CHIKYU+10 INTERNATIONAL WORKSHOP

CHIKYU REPORT

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Chiyoda-ku, Tokyo, Japan)

CHIKYU+10 International Workshop Report

Written by

CHIKYU+10 Steering Committee

Edited by

Holly K. Given

IODP Management International and

Scripps Institution of Oceanography

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EXECUTIVE SUMMARY

High-priority projects using the technique of scientific ocean drilling enabled by the Deep Sea Drilling Vessel (D/V) *Chikyu* were discussed by nearly 400 participants from over 20 nations at the international workshop CHIKYU+10 in Tokyo, 21-23 April 2013. D/V *Chikyu* uses riser technology developed by the hydrocarbon industry to achieve new capability to drill, sample, log, and monitor the subseafloor towards the ultimate goal of more fully understanding planet Earth. Over the next ten years, D/V *Chikyu's* unique capability will contribute to the goals described in the science plan *Illuminating Earth's Past, Present, and Future* of the International Ocean Discovery Program (IODP): Exploring the Earth under the Sea. At the CHIKYU+10 Workshop, the international science community identified eight fundamentally important "flagship projects" for which engineering and management planning are ready to begin. All require the uniquely available capabilities of D/V *Chikyu* to maximize the potential of scientific discovery. The Steering Committee of CHIKYU+10 organized the workshop discussion around five scientific themes that can be investigated using D/V *Chikyu*. The Dynamic Fault Behavior theme seeks to understand the causes and methodologies of destructive earthquakes and tsunamis. Two flagship projects, the *Nankai Trough Seismogenic Zone Experiment* (currently underway) and the *Costa Rica Seismogenesis Project*, bracket the variation of convergent margin characteristics that control earthquake behavior. A third flagship project, *Slow Slip at the Hikurangi Margin*, New Zealand, will investigate the role that the newly-discovered slow slip process plays in the earthquake cycle and its causal relationship to great earthquakes. In the Ocean Crust and Earth's Mantle theme, researchers agreed on a flagship project to sample a complete section of oceanic crust and *Drill to Earth's Mantle* in order to address key questions on ocean crust formation and the origin of plate tectonics, a dream born over 50 years ago as Project Mohole, with emphasis on a Pacific Ocean site. A second-priority flagship project would study the *Life Cycle of the Oceanic Lithosphere* as it is transformed by interaction with the hydrosphere while making the slow journey from creation at ocean ridges to reabsorption into the mantle and recycling water and gases from Earth's surface. In the Deep Life and Hydrothermal Systems theme, the community recommends improving methods of regular sample collection and storage germane to microbiological research, so that all D/V *Chikyu* expeditions – even those not specifically focusing on microbiology – will contribute to discovering the limits of the subseafloor's *Habitable Zone*. In the Continent Formation theme, the community fully supports the well-defined science of the flagship project *Island Arc Origin: Izu-Bonin-Mariana*, which will explore how the continental crust upon which terrestrial life depends is created from primeval origin. In the Sediment Secrets theme, the flagship project *Ocean Basin Desiccation* offers a unique opportunity to study the still-unexplored history of an extreme climate crisis when most of the then-vast Mediterranean Sea rapidly evaporated. The motivation for these projects and their relevance to society are described in the Report. The Steering Committee notes that these meritorious projects can keep D/V *Chikyu* fully occupied making fundamental discoveries about the Earth far beyond the five months per year that is under discussion for the IODP. Workshop participants enthusiastically discussed many additional and exciting project ideas. The CHIKYU+10 Workshop emphasized that *Chikyu* is a unique platform for planetary discovery. Without D/V *Chikyu*, these explorations have little or no chance of being brought to fruition.

INTRODUCTION

The international scientific workshop CHIKYU+10 was convened to discuss high-priority science projects requiring the use of scientific ocean drilling for the next long-term plan of the Deep Sea Drilling Vessel (D/V) *Chikyu*. The April 2013 workshop was held at the Hitotsubashi Hall of Hitotsubashi University in Tokyo, drawing 397 participants from 21 countries. The workshop was funded by the Japan Agency for Marine-Earth Science and Technology (JAMSTEC) with contributions from national programs that supported travel by participating scientists. Participants included researchers in many scientific disciplines (e.g. marine geology, petrology, geochemistry, sedimentology, climate change and paleoceanography, microbiology, geomagnetism, seismology and earthquake hazards), representatives of international funding agencies, engineers and managers from industry, technical staff from JAMSTEC's Center for Deep Earth Exploration (CDEX), and many students. 136 participants came from outside Japan. In total, approximately 180 institutions were represented.

Launched in 2002, D/V *Chikyu* has been Japan's contribution to the international Integrated Ocean Drilling Program (IODP, 2003-2013), and will continue its agenda of discovery under the International Ocean Discovery Program (IODP 2013-2023): Exploring the Earth Under the Sea. The International Ocean Discovery Program's science plan, *Illuminating Earth's Past, Present, and Future,* guides multidisciplinary international collaboration in science discovery carried out in four science plan themes: Climate and Ocean Change; Biosphere Frontiers; Earth Connections; and Earth in Motion.

This was first international workshop to specifically consider the range of science to be carried out with D/V *Chikyu* since the ship began drilling IODP expeditions in 2007. Under the organizational framework of the International Ocean Discovery Program, a new *Chikyu* IODP Board (CIB) will consider the range of possible science missions and make recommendations to JAMSTEC about annual implementation plans, long-term implementation strategies, workshops that lead to project proposals, international partnerships, and similar issues. The CHIKYU+10 Workshop Report will provide input to the CIB's inaugural meeting in July 2013.

An international Steering Committee of 19 members (ref list) met in November 2012 to plan the workshop themes, format, and agenda. Considering community interest and D/V *Chikyu's* unique focus and capabilities, the Steering Committee formulated five workshop-specific themes:

Dynamic Fault Behavior (termed Active Faults at the workshop): Seismogenic zones pose lethal hazards to humans and civilization through seismic shaking, deformation, and tsunamis. D/V *Chikyu* will help scientists understand the mechanisms that control fault behavior by sampling and monitoring conditions in the crustal earthquake zone.

Ocean Crust and Earth's Mantle: The largest part of Earth's interior, the mantle, lies within reach of D/V *Chikyu*. Direct observations will fundamentally change our understanding of early Earth, present-day mantle dynamics, and evolution of the ocean crust, with wider implications for our solar system.

Deep Life: The mostly unmapped microbial ecosystem beneath the seafloor is a new frontier of biology. Deep sampling will revolutionize our concept of life: its origins and co-evolution with the physical Earth, its diversity, its adaptation to extreme environments, and its depth limits.

Continent Formation: How Earth's continental and oceanic crust became differentiated, and how continents originated through time can be studied by deep drilling at island arcs, oceanic plateaus, and magmatic divergent continental margins where continental crust is forming today.

Sediment Secrets: Drilling deep sections of marine sediments will explore past ocean environments, reveal changes in large-scale oceanic, atmospheric, and continental conditions, and illuminate the effects of cataclysmic events such as episodic flood magmatism and bolide impacts.

Project ideas in these themes were invited from the community in the form of white papers that would be discussed at the workshop. The community was invited to suggest other science areas for exploration by D/V *Chikyu*'s deep riser drilling capability in a "Blue Sky" category. 127 white papers were received and organized into 18 sub-theme discussion panels. The Steering Committee also invited 12 keynote speakers to give overview presentations, and organized informational panels from CDEX and co-chief scientists of completed D/V *Chikyu* IODP expeditions.

The workshop took place over three days. The first day featured keynote talks to provide context and background; the second day had panel discussions of the community white papers, and the third day had small group discussions to identify high-priority science on the basis of discovery, need for D/V *Chikyu*, feasibility, opportunity for related research, and technical advancement. Invited speakers are listed in Table 1, and the detailed Daily Programs are found in Appendix 1.

In introductory remarks, JAMSTEC officials asked the workshop participants to consider future science that only D/V *Chikyu* can do – for example, targets requiring deep riser drilling, or riserless drilling in very deep water. CDEX presentations highlighted advanced systems aboard D/V *Chikyu* that add new dimensions to sub-seafloor research. *Chikyu's* well logging capability and analysis of drill cuttings and mud gas made possible by the riser system provide a comprehensive picture of the drilled section through core-log integration. *Chikyu's* current marine riser can operate in 2,500 meters water depth for a target depth (water depth + penetration depth) of 9,000 meters. Plans are underway to upgrade to a riser system that could operate in at least 4,000 meters of water and provide a total possible target depth of up to 12,000 meters.

One keynote talk summarized the decadal planning process (2013-2023) used by the U.S. space agency NASA to arrive at priorities by size of mission. NASA uses a categorization of size/cost/complexity to classify missions as Discovery (small), New Frontiers (medium), or Flagship (large). In generating the Workshop Report, the CHIKYU+10 Steering Committee found this terminology useful in summarizing the theme group discussions. In this report, large complex projects are referred to as flagships, and smaller projects having a more contained scope and shorter implementation schedule as referred to as discovery missions, although this classification was not used for all themes. In reality, JAMSTEC will need different styles of projects to develop a flexible portfolio that offers multiple options when the important aspects of engineering readiness, available budget, safety, and operational constraints are factored in.

The CHIKYU+10 workshop identified a portfolio of exciting projects to address top priorities of Earth system science. Flagship (multiyear) projects will investigate the conditions and limits of microbial life at depth, the dynamics of fault behavior that lead to great earthquakes, the island arc origins of continents, the composition of the mantle and oceanic crust, and sedimentation and ecosystem change during ocean basin desiccation. Several of these programs are ready to implement now. In addition, discovery (partial year) projects that may be interleaved in the schedule target hydrothermal systems of arc volcanoes, extreme fault slip of great earthquakes, environment-altering large volcanic eruptions, and global anoxic events. Together, these ambitious projects – achievable only through *Chikyu* drilling - will illuminate Earth's past, present and future and constitute a major contribution to the International Ocean Discovery Program in the coming decade. The portfolio identified by the 400 international participants warrants at least twice the currently available scientific drilling time planned for D/V *Chikyu* of 5 months per year.

In discussing potential drilling projects, participants took into account the potential for discovery, the project's uniqueness, its overall feasibility and readiness, whether it would provide opportunity for synergistic or follow-on studies, and whether it would help build *Chikyu's* capability through new engineering developments. For example, drilling ideas that could be accomplished as well (or in some cases, better) with other IODP platforms receive less emphasis in this Report.

Workshop participants also discussed project ideas that are not likely to be implemented in the next ten years, but that are the natural follow-on to the recommended missions. Some of these are limited by yet-to-be-done preparation, for example, detailed seismic site surveys. Others are studies that would complement the priority project and leverage science results into a more comprehensive understanding of a wider topic; e.g. the lifecycle of oceanic crust, the diversity of deep life, or the role of sediments in varying subduction settings. This report includes these longer-term possibilities to illustrate that the importance of D/V *Chikyu's* capabilities for new discoveries about planet Earth extends far into the future.

Dynamic Fault Behavior

Introduction

One of the major goals in the new IODP science plan is an increased understanding of the dynamic processes of the Earth, including the causes of destructive earthquakes and tsunamis. Over the last decade, and following a 40 year hiatus, a series of Magnitude ≥9.0 earthquakes and tsunami have ruptured at subduction zones around the world: 2004 Sumatra-Andaman, 2010 Chile-Maule, 2011 Tohoku-oki (Japan). In the case of both the 2004 Sumatra-Andaman and the 2011 Tohoku-oki earthquakes, unexpectedly shallow slip took place. An unprecedented magnitude of fault slip occurred in parts of the fault plane during the 2011 Tohoku-oki earthquake (≥50 m), and as a margin with low sediment input, it was not expected to have the potential for M≥9 earthquakes. In addition, over these same ten-plus years the discovery of episodic slow slip events at subduction margins around the world has led to an explosion of new theories about fault rheology and slip behavior along subduction megathrusts (Figure 1). Both these recent earthquakes and the finding of slow slip are generating a major reassessment of our understanding of slip behavior in the shallow subduction zone and of how different materials should behave in terms of fault slip. These recent developments in active faulting and seismology have spawned a variety of compelling project proposals for *Chikyu* expeditions.

A total of 42 white papers were submitted and 36 of those were discussed in detail and provided the basis of the following report.

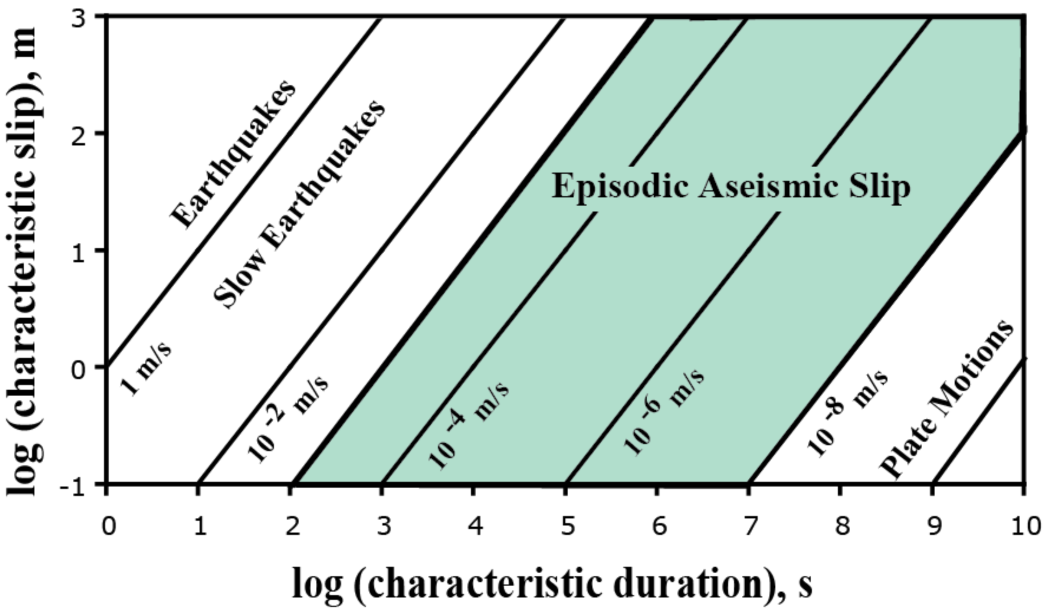


Figure 1. Plot of characteristic slip magnitude versus slip duration for various deformational processes. Normal and slow earthquakes both radiate seismic energy and occur at the fast end while plate tectonic motions occur at the slow end of the velocity spectrum. Most episodic aseismic slip (shaded region) occurs at intermediate velocities. Figure from Schwartz, 2007.

Flagship Project: Great earthquakes at an Accretionary Margin: Nankai Trough Seismogenic Zone Experiment (NanTroSEIZE)

The Nankai Trough is the typical end member accretionary margin and is characterized by regular M~8 tsunamigenic megathrust earthquakes. The NanTroSEIZE drilling experiment began in 2007 marking the beginning of the D/V Chikyu drilling program. The transect of boreholes and associated geophysical datasets have resulted in the best characterized subduction zone margin transect in the world. To date, the project has drilled, sampled and logged at ~ 12 sites from the incoming oceanic plate to the forearc, in order to characterize the input material properties, measure fault zone properties at shallow depths and stress state across the forearc (Figure 2). Targeted fault structures include the frontal thrust/shallow plate boundary fault and the shallow megasplay fault (thought to bring seismogenic slip to the seafloor during megathrust earthquakes). In addition, the first long-term borehole observatory has been successfully installed and connected to the DONET (Dense Oceanfloor Network system for Earthquakes and Tsunamis) seafloor network and is delivering real-time pore pressure, temperature, tilt, strain, and seismicity data. Drilling at the deep riser site which ultimately targets the deep seismogenic megasplay fault, has started (reaching 2,000 mbsf, Exp. 338, Site C0002). Key results of the project include: quantification of input sediment and basement properties at the décollement level; documentation of the state of stress across a forearc transect where strain is accumulating pre-earthquake; identification of young and probably high velocity slip along the megasplay fault and frontal thrust at very shallow depths (<500 mbsf: i.e., rapid slip close to the seafloor); developing techniques for recognizing frictional heating along faults; successful observatory installation and data recording; and expertise development in riser cuttings and gas handling.

Scientific Objectives, Rationale and Global Scientific Impact: The primary remaining drilling objective within the NanTroSEIZE project is to sample, log and monitor the composition, physical properties, hydrology and structure of the seismogenic part of the megasplay fault/plate boundary structure (Figure 2). These data would be the first from a M≥8 earthquake-generating fault zone. Drilling of this deep hole has begun, and requires deepening to a depth of ~5,200 mbsf with a program of complete logging-while-drilling, cored sections (including a sidetrack cored section across the fault zone) and downhole in situ pressure and stress measurements. Installation of a deep borehole observatory at this site is planned, in addition to observatories at two shallow fault targets (frontal thrust and shallow megasplay fault). Since project initiation, new earthquake phenomena have been identified globally and within the Nankai margin, e.g., Very Low Frequency (VLF earthquakes): these now provide exciting new targets for monitoring, for understanding the spectrum of earthquake slip modes, and for determining their spatial and temporal interactions and feedbacks. Additional, externally funded seismic experiments (Vertical Seismic Profiling) will image and resolve further the structure and physical properties of the forearc and megasplay/plate boundary fault across a wider area beyond the borehole itself.

Societal Relevance: The Nankai margin has historically generated M~8 tsunamigenic earthquakes causing significant damage and fatalities (including the most recent earthquakes in 1944 and 1946), and hence understanding the earthquake-generating process at this margin and monitoring activity and behavior of the fault zone is of significant regional relevance, as well as for the subduction zone earthquake rupture process globally. Very few active faults have been accessed within their seismogenic zone so retrieval of samples and monitoring fault behavior is critical for progress in earthquake science and hazard analysis.

Rationale for Deep Drilling and Technical Challenges: The depth of the borehole (~5,000 mbsf) requires riser drilling. Technical challenges include highly deformed and potentially overpressured sediments at depth. Additionally, the site lies in an area of periodically high velocity currents of the Kuroshio current system and seasonal typhoons. Further technological development of observatory instruments is still required.

White Papers: Araki *et al.* (WP-59), Tobin *et al.* (WP-93), Kimura *et al.* (WP-74), Park *et al.* (WP-82).
Project Templates: PI-40, PI-52, PI-53.

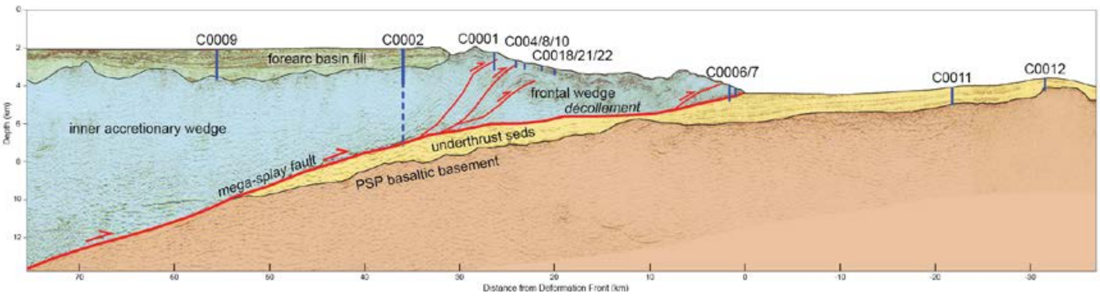


Figure 2. Cross section of the Nankai margin. Cross section shows existing riser holes (C0009 and C0002) plus riserless holes. Dashed portion of C0002 to be completed to reach megasplay fault during the remainder of the NanTroSEIZE project. Figure from Moore *et al.*, 2013.

Flagship Project: Erosional Subduction Processes - Influence on Seismogenesis: Costa Rica Seismogenesis Project (CRISP)

The Costa Rica subduction zone is generally non-accretionary with the thin incoming sediments mostly subducted beneath the margin; subsidence of the upper plate indicates that it is being tectonically eroded at the base. This contrasts markedly with the copious incoming sediments of the rapidly growing Nankai accretionary prism. The Costa Rica subduction zone commonly has M_w 6.0-7.7 earthquakes repeating about approximately every 50 years, whereas M_w 8.0 earthquakes, repeating about every 100 years, are common beneath and within the Nankai accretionary prism. The contrasting geologic and geophysical characteristics of the Nankai and Costa Rican convergent margins provide an opportunity to understand their differing seismogenic behavior.

Scientific Objectives, Rationale and Global Scientific Impact: CRISP is designed to investigate a plate boundary thrust dominated by subduction erosion. Riserless drilling IODP Expeditions 334 and 344 have explored the nature of incoming sediments and oceanic crust, and the materials of the upper plate to depths of 981 mbsf. The CRISP riser drilling plan consists of a penetration of about 5 km in 500 m water depth, within the shallow seismogenic zone just up-dip from the hypocenter of the M_w 6.4 earthquake that occurred in 2002. A recently acquired 3-D seismic grid will provide clear geological context for the riser hole. The four major goals of CRISP riser drilling, monitoring, and laboratory experiments, linked to riserless and seismic experiment results, are: 1) To quantify effective stress and plate boundary migration via focused investigation of fluid pressure gradient and fluid advection across the erosional plate boundary; 2) To determine the structure and fault mechanics of an erosional convergent margin and identify the processes that control the up-dip limit of seismicity; 3) To constrain how fluid-rock interactions affect seismogenesis by studying fluid chemistry and residence time, basement alteration, diagenesis, and low grade metamorphism; and 4) To obtain physical properties of a 3-D volume that spans the seismogenic zone. The subduction zone offshore the Osa Peninsula provides the tectonic setting to achieve these goals because the shallow subduction angle and high temperatures bring processes that elsewhere occur at greater depth (and beyond the reach of drilling) to shallow depths.

Societal Relevance: In September of 2012 the Nicoya Peninsula of Costa Rica, ~ 200 km to the northwest of the CRISP site, was shocked by a M_w 7.6 earthquake that caused about $50 million in damage destroying many schools, homes and businesses. This earthquake appears to be a repeat of a similar earthquake that occurred in the same area about 50 years ago. Although this may be a characteristic earthquake of this subduction zone, substantially larger earthquakes could be possible on a millennial time scale, such as was the pattern in the Tohoku-oki M_w 9.0 earthquake region in northern Japan.

The CRISP drilling program has particular relevance for understanding earthquake behavior along margins of tectonic erosion, which, in this area, extend north through Central America to southern Mexico. Overall, investigation of seismogenic processes of the Costa Rican margin and their comparison to other subduction zones will allow better global assessment of earthquake hazard potential based on fundamental geological and geophysical character and processes.

Rationale for Deep Drilling and Technical Challenges: Earthquakes nucleate at substantial depths. The CRISP locality requires about 5 km of penetration to reach the seismogenic zone of the 2002 M_w 6.4 earthquake (Figure 3). Fortunately, the site is located in 500 m of water depth, minimizing the total drill string length. Moreover, the ocean current velocity in the drilling area is typically low with calm sea state. The availability of 3-D seismic results and completed riserless drilling indicates that CRISP is ready for riser drilling with D/V *Chikyu.* Under the previous IODP management structure, the CRISP program was transferred to the Operations Task Force for scheduling. The CRISP program is described in IODP proposals 537 CDP, 537A, and 537B (Ranero *et al.*, 2004); however the details of the site location and drilling program should be reconsidered in light of the 3-D seismic survey and the results from riserless drilling.

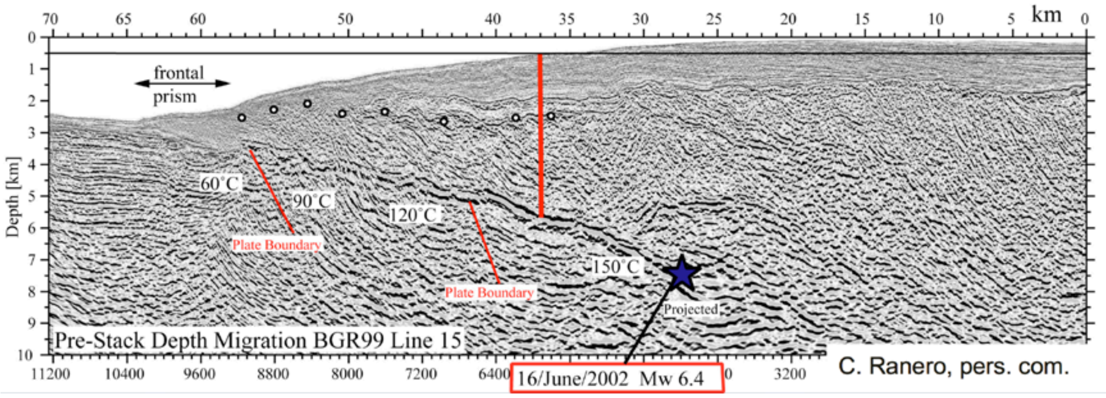


Figure 3. Cross section through the CRISP riser site. The proposed drill site is up-dip of the hypocenter of the 2002 earthquake, but in a thermal realm (> 120 deg. C) that lies in the upper limits of the traditional seismogenic zone. Figure provided by C. Ranero.

White Papers: Ranero *et al.* (WP-85), Vannucchi *et al.* (WP-96).
Project Template: PI-27.

Flagship Project: Slow Slip at the Hikurangi Margin, New Zealand

Slow slip events (SSEs) involve accelerated, transient aseismic slip across a fault lasting for days, weeks or even years. Only since the advent of dense, plate boundary-scale geodetic networks has the importance of these events been recognized. A full understanding of the mechanics of the shallow earthquake-generating portion of the subduction interface, or mega-thrust and how it evolves through the earthquake cycle involves study of both earthquake and slow slip behavior (Figure 1). In fact, the short recurrence interval of most SSEs provides one of the few opportunities to make observations over a complete plate-boundary-locking-to-slipping cycle. Slow slip has also been suggested to precede several large to great earthquakes including the 2011 Tohoku-oki event and it may be an important preparatory process in earthquake nucleation.

Although SSEs appear to bridge the gap between typical earthquake behavior and steady, aseismic slip on faults, the physical mechanisms that lead to SSEs and their relationship to destructive, seismic slip on subduction thrusts are poorly known. This is partly due to the fact that most well-studied subduction zone SSEs are too deep for high-resolution imaging or direct sampling of the source region. The northern Hikurangi margin, New Zealand, is a notable exception. Here, well-characterized SSEs occur every one to two years, over a period of 2-3 weeks at depths <5-15 km below the seafloor (Figure 4). Drilling, down-hole measurements, and sampling of the northern Hikurangi SSE source area would provide a unique opportunity to definitively test hypotheses for the physical conditions and rock properties leading to SSE occurrence. It would also allow a comparison of the structural character and frictional properties of a subduction interface dominated by aseismic slip and moderate subduction thrust earthquakes (Hikurangi), with, for example, the Nankai interface which is characterized by stick-slip behavior and great megathrust earthquakes.

Scientific Objectives, Rationale and Global Scientific Impact: The primary riser drilling objectives of the slow slip Hikurangi project are a single riser hole to intersect the source area of SSEs at ~5-6 km below seafloor in ~1000 meters of water to recover sediments, rocks, and pore fluids, collect geophysical logs, and make downhole measurements (Figure 4). The objectives of this program are to document the lithology, geometry, mechanical and structural character of the fault that hosts slow slip and to determine the stress and pore pressure regime and the hydrogeological, thermal, and chemical properties of the upper plate and slow slip source fault. Ultimately, long-term borehole monitoring at the SSE source in the deep riser drill hole is a goal of this project. The NanTroSEIZE and CRISP Flagship Projects would drill into, sample, and monitor the seismogenic portion of a subduction plate boundary thrust fault. In contrast, the northern Hikurangi subduction interface is dominated by slow slip and aseismic creep. To fully understand physical mechanisms that control the diverse spectrum of strain release observed along subduction mega-thrusts, it is essential to directly observe slow slip source regions and test hypotheses for their origin.

Societal Relevance: The Hikurangi margin has historically generated "tsunami" earthquakes. Moreover, the full slow slip earthquake cycle including the slip event itself can be observed along the Hikurangi margin. Understanding the full spectrum of slip processes at this, and other margins dominated by aseismic processes is required to accurately evaluate their great earthquake potential. Slow slip has been documented to precede many large earthquakes and may be an important precursory earthquake process that could enhance earthquake forecasting.

Rationale for Deep Drilling and Technical Challenges: The depth of the borehole (>5000 mbsf) requires riser drilling. Technical challenges will include highly deformed and potentially over-pressured sediments at depth; however, riser drilling with circulating mud provides pressure balance at depth, improving hole conditions. Although good quality 2-D seismic data exists, a 3-D survey will likely be required for riser drilling. Further technological development of observatory instruments is required.

IODP proposal 781-B Full for a riser hole (Wallace *et al.*, 2013) was submitted April, 2013.

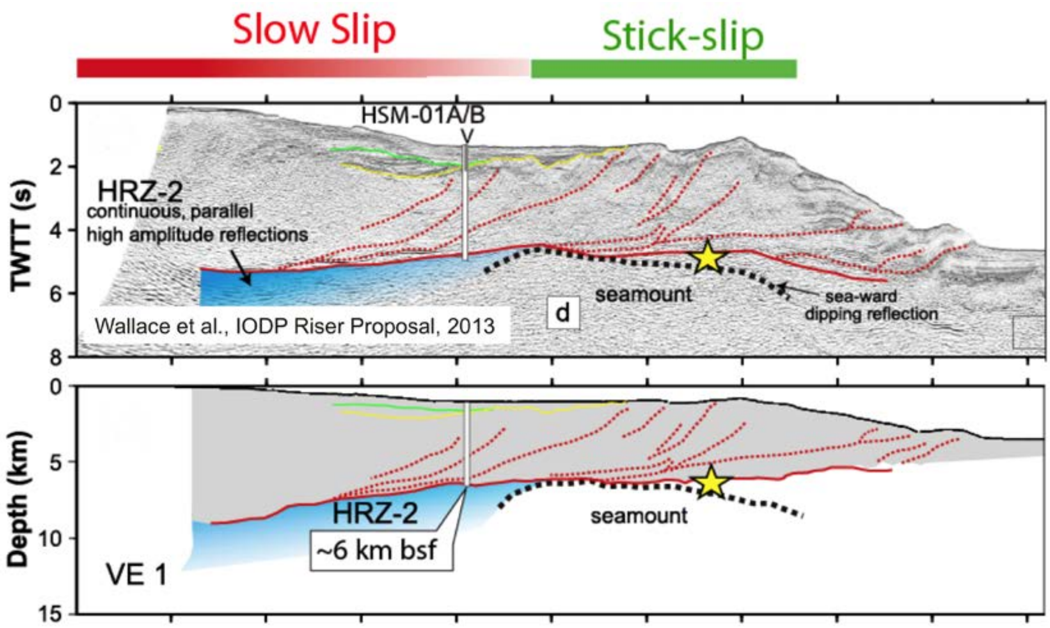


Figure 4. Time section and depth section across the proposed riser drilling locality at the Hikurangi Margin with the proposed deep hole penetrating the area of slow slip. Yellow star denotes location of 1947 tsunami earthquake. Figure provided by L. Wallace.

White Papers: Wallace *et al.* (WP-99).
Project Template: PI-48.

Discovery Project: Shallow and Extreme Slip (Japan Trench)

Following the 2011 Mw 9.0 Tohoku-oki earthquake and tsunami on the Japan Trench margin, a successful rapid response drilling project (Expedition 343: JFAST) drilled and sampled the décollement plate boundary fault. The coring and logging at one site close to the trench (Site C00019) was in the region of greatest fault slip. The program installed and successfully retrieved temperature loggers to record the post-seismic signal. Significantly, the program operated in deeper water (7-8 km) than any previous drilling project and clearly demonstrated the capability and potential of D/V *Chikyu* in this extreme environment.

Scientific Priorities, Rationale and Global Scientific Impact: Utilizing the ultra deep water capabilities of *Chikyu*, a new drilling project proposes to investigate further the shallow plate boundary fault zone properties and incoming input material properties, and determine the record of great earthquakes at three transects along the Japan Trench. The project would test the following hypotheses: (i) that subduction zones have mega-earthquake super-cycles not covered in instrumental and historical data, and (ii) that the occurrence of earthquake slip-to-trench is governed by the structure or physical properties of the slip layer or by the geometry of the incoming plate. Scientific questions include: 1) How often does this fault zone slip in great earthquakes? 2) What is the nature of slip along strike related to this large earthquake? 3) What are the present post-seismic deformation rates and how are they related to the earthquake cycle? 4) What physical properties and deformation mechanisms govern strain energy accumulation and release at shallow depths? 5)

What are the current hydrologic conditions that characterize this active high-slip fault zone?

To address these questions, input materials at the level of the plate boundary fault, the frontal sedimentary prism, and the décollement zone would be logged and sampled for structure, physical properties, and hydrogeology. In addition, a series of short (50-100 m) trench cores would be used to build a paleoseismological record based on earthquake-generated turbidites. Observatories should also be established at one or two key sites for monitoring post-seismic behavior of the plate boundary fault. The project will bear importantly on other convergent margins where tsunamigenic great earthquakes have a high potential of occurrence and for a globally relevant evaluation of what drives shallow slip at subduction margins.

Societal Relevance: The unusual and extreme characteristics of the 2011 Tohoku-oki earthquake have resulted in a dramatic re-evaluation of earthquake mechanisms. Consequently, it is of great societal relevance to understand the nature of this earthquake rupture. The structural makeup of this margin bears many similarities to other low sediment input and/or erosional margins, and therefore this behavior could occur elsewhere. An understanding of past earthquake ruptures of this kind on the margin and what might drive them is therefore critical both for Japan and for regions located near similar margins.

Rationale for Deep Drilling and Technical Challenges: The proposed boreholes are all located in deep water (~7000-8000 m) necessitating the use of D/V *Chikyu* in riserless drilling mode. While there are technical challenges drilling in this water depth, drilling during Expedition 343 was successful. Drilling at these sites should be relatively straightforward and rapid, with flexibility in timing for individual sites/transects in order to work around other *Chikyu* projects.

The project is at the stage of proposal preparation with likely submission for Fall 2013. Additional site survey data collection is planned by JAMSTEC for site selection.

White Papers: Kodaira and Nakamura (WP-78), Kodaira *et al.* (WP-79), Sample *et al.* (WP-88), Hirose (WP-66), Ikehara (WP-68), Kanamatsu (WP-73), Strasser *et al.* (WP-91), Morita (WP-51), Ujiie *et al.* (WP-95).
Project Templates: PI-49, PI-50.

Discovery Project: Slow and Fast Slip in Close Proximity- Kanto Region Japan: Kanto Asperity Project (KAP)

Scientific Objectives, Rationale and Global Scientific Impact: Both seismogenic and slow slip behavior have been documented to occur in close proximity at shallow depth along the Sagami Trough, offshore the Kanto region of Japan. The 1923 Kanto earthquake devastated Tokyo, killing 105,000 people. The recurrence interval of this type of event is thought to be 200-400 years. In 1703 an even larger event ruptured this region with an ~2000 year recurrence interval. To the east, offshore the Boso Peninsula, large, shallow slow slip events recur about every 6 years. The Kanto Discovery project proposes deep drilling to intersect the plate boundary at the Boso slow slip and the 1923 Kanto earthquake source regions to investigate why different types of fault behavior occur so close to one another at similar depths and therefore similar pressure and temperature conditions. This project seeks to obtain samples of fault material failing in large earthquakes and slow slip events and to use their measured physical properties as the input to a realistic earthquake generation model. In addition, the program would use shallower riserless drilling to install a comprehensive monitoring network. Finally, a just-submitted proposal focuses on sediment inputs including sampling in very deep water of the Izu forearc where exotic rock types, including serpentine, may be incoming to the Boso slow slip zone.

Societal Relevance: The southern Kanto region of southeastern Japan includes the Tokyo Metropolitan Area. It is an important and densely populated economic center that has been subjected to repeated great (M~8.0) earthquakes. An understanding of the physical properties of the plate boundary that underlie this region and establishing a realistic earthquake-generation model are of critical importance for mitigating the danger posed by earthquake hazards. In its final stage, a monitoring program consisting of a seafloor cable network with connected observatories is proposed. This cable will enable real-time transmission of data to onshore stations. Real-time monitoring of the plate boundary is critical to hazard assessment and mitigation.

Rationale for Deep Drilling and Technical Challenges: The proposed deep boreholes are all located at depths 6.5-7.0 km below seafloor, requiring the use of *Chikyu* for riser drilling. Technical challenges will include highly deformed and potentially over-pressured sediments at depth. Unique challenges to this site include the high level of ship traffic that may make it difficult to obtain the 3-D seismic data required to identify an optimal deep drilling target. The sediment input proposal is partly in very deep water, requiring the capabilities of D/V *Chikyu*. The monitoring sites do not require riser drilling.

The umbrella 707-MDP proposal (Kobayashi *et al.*, 2006), as well as proposals 782 (riser drilling) and 770 (monitoring) have been submitted and iterated.

White Papers: Kobayashi *et al.* (WP-76, 77), Sato *et al.* (WP-89).
Project Templates: PI-32, PI-45.

Other Projects:

Faulting in Oceanic Crust

Although there are no existing IODP drilling proposals to investigate faulting in oceanic crust, several white papers were of interest to the CHIKYU+10 participants. A concept to trigger earthquakes by pumping fluid into a transform fault was of broad interest (Mori and Kano, WP-81). Additionally, a program to drill very deeply through the zone of faulting of the subducting plate just seaward of the trench (outer rise) was of considerable interest and provides a synergistic link between studies of oceanic crust and mantle and active faults (Morgan and Vannucchi, WP-115; see Ocean Crust and Mantle section for further discussion). The ocean drilling community would welcome development of formal proposals in these areas.

White Papers: Mori and Kano (WP-81), Morgan and Vannucchi (WP-115).
Project Templates: PI-20; PI-11, PI-38.

Long-term Monitoring of Boreholes

A critical element of riserless and riser drilling within the Dynamic Faults theme is monitoring physical and chemical changes and dynamic processes over medium-long timescales ("4-D"). Monitoring is accomplished primarily using borehole observatories, but repeat active source seismic experiments (e.g., vertical seismic profiles) are also valuable. A number of white papers were presented on or related to this topic, emphasizing different potential methodologies, what could be achieved, and some specific applications. Measuring and monitoring formation pressure as a proxy for volumetric strain and the role of pore pressure in prism deformation were discussed (Davis *et al.*, WP-60; Hyndman, WP-67), including a proposal to install spatial observatory arrays around existing and future drilling transects on subduction margins. Stress measurements are becoming commonplace and will allow us to determine stress variations before and after earthquakes and for different slip modes (e.g., slow slip), potentially requiring rapid response drilling (Lin *et al.*, WP-80). Utilizing VSP experiments with borehole instrumentation for 4-D examination of physical property changes, including fluid pressure and fault properties would increase the spatial and temporal extent of information gained by drilling (Hashimoto, WP-63; von Huene, WP-98). The majority of these approaches are contingent on external funding and in some cases, significant technology development, therefore present challenges in the new IODP structure which should be addressed because of the importance of 4-D measurements.

White Papers: Davis *et al.* (WP-60), Hashimoto (WP-63), Hyndman (WP-67), Lin *et al.* (WP-80), von Huene (WP-98).

Nicoya Peninsula, Costa Rica

The Nicoya Peninsula, Costa Rica, ~200 km northwest of the CRISP proposed deep drilling site, may be a completely unique locale in that both the upper limit of its seismogenic zone, which ruptures in large earthquakes about every 50 years, and regions generating slow slip and tremor are within the range of scientific drilling using *Chikyu* capabilities. This site provides an alternative location to accomplish the scientific objective laid out in the CRISP and Hikurangi Flagship and Kanto Region Discovery projects. Reaching the seismogenic zone at 5-6 km and slow slip regions at shallower depth below the seafloor and the opportunity for year-round drilling make this an attractive alternate site to CRISP and Kanto. Significant geophysical data exist for the Nicoya Peninsula but a more modern 3-D seismic survey would be required prior to deep drilling.

White Paper: Protti and Kaneda (WP-84).
Project Template: PI-1.

Ocean Crust and Earth's Mantle

Introduction

The IODP science plan for 2013-2023 addresses key challenges in Ocean Crust and Earth's Mantle studies, which are elucidations of the composition, structure, and dynamics of Earth's upper mantle, including interconnections between mantle melting and ocean plate formation, drivers of plate tectonics, and Earth's chemical cycles. A major goal in Earth science is to understand the differentiation of the planet into layers and the causative mechanism of plate tectonics. This requires an understanding of the oceanic lithosphere, which covers about 70% of the Earth's present-day surface. The oceanic crust and underlying mantle play a major role in the tectonic process, both as source material during formation of new oceanic lithosphere and as the feeder material for the subduction process. This essential geological material ultimately acts as a key ingredient in mantle convection, depleting the mantle at zones of new oceanic plate creation and enriching the mantle at subduction zones. This planetary process has likely been occurring only on Earth in the solar system for the last 3.5 billion years, creating the habitable planet that we see today.

The nature and architecture of the oceanic crust and underlying lithospheric mantle have been described through seafloor geology, prior scientific ocean drilling, and geophysical imaging, combined with studies of ophiolites (exhumed ancient pieces of oceanic crust and mantle). Yet, their overall complexity and variability are far from being fully understood. Direct sample return with *in situ* geophysical observations of the entire ocean crust-uppermost mantle remains an essential scientific goal. D/V *Chikyu* offers now the possibility to reach deeper targets in the ocean lithosphere, and will eventually accomplish a complete crustal penetration project to cross the crust/mantle boundary, and sample the *in situ* Earth's mantle.

The goal of deep drilling through the ocean crust and into the Earth's mantle was the original inspiration for scientific drilling more than 50 years ago (e.g., Bascom, 1961; Teagle and Ildefonse, 2011). However, over the course of the Deep Sea Drilling Project (DSDP), the Ocean Drilling Program (ODP), and the Integrated Ocean Drilling Program (IODP), the number of deep sections successfully drilled in the ocean lithosphere has been very limited. Only 4 holes have penetrated more than 1 km into both fast- and slow-spread crust (Figure 5). These represent only a minor fraction (<1%) of total drill cores recovered by scientific ocean drilling programs, and only about 6% of total drilling time to date. So far, the deepest ocean crust drilled continuously from the seafloor was in Hole 1256D in the Cocos plate fast-spread crust, which reached through the sheeted dike/gabbro transition zone. The other drill holes terminated at a shallower level, or dug from a deeper level tectonically exposed on the seafloor in slow-spread crust. Therefore, the grasp of the entire nature and architecture of intact ocean crust remains elusive, as is understanding the oceanic lithospheric mantle.

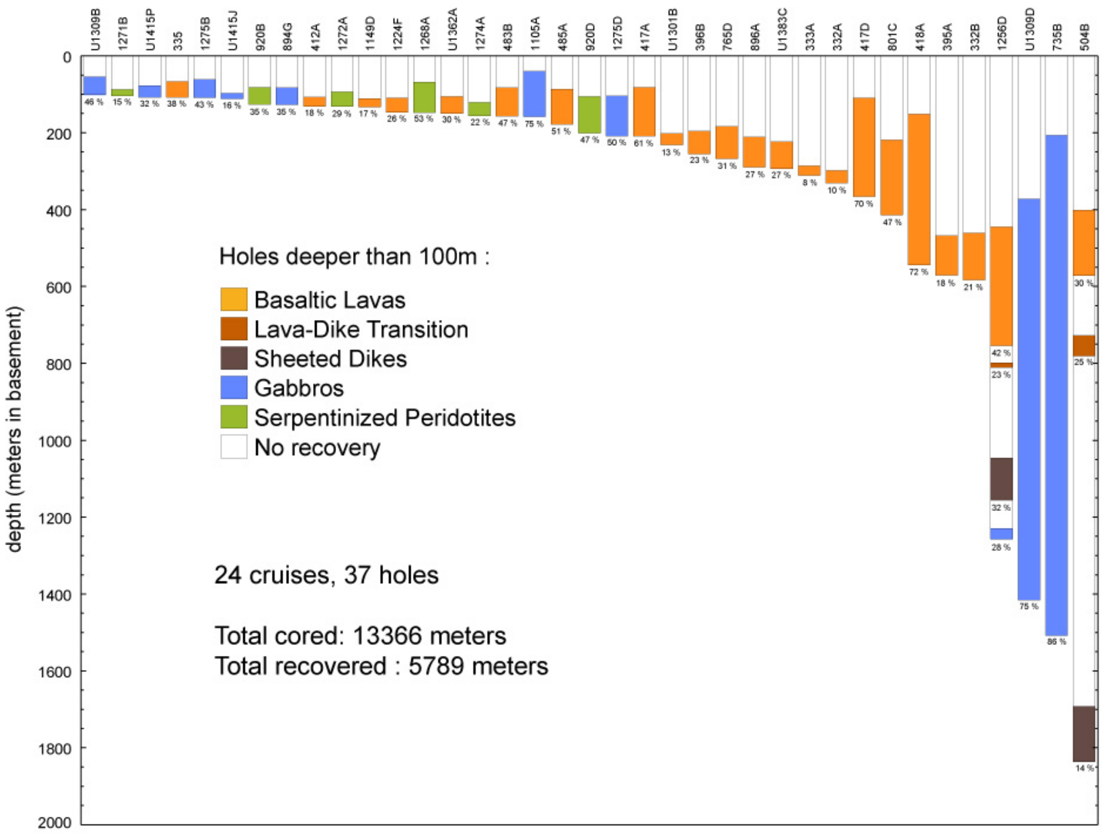


Figure 5. Compilation chart showing holes drilled deeper than 100 m (into basement, i.e., in hard rocks below sediments), intact crust, and tectonically exposed lower crust and upper mantle from 1974 to 2013. For each hole are indicated the hole number and the core recovery (in percent) for each lithology. This compilation does not include "hard rock" drill holes in oceanic plateaus, arc basement, hydrothermal mounds, or passive margins. Figure modified from Teagle *et al.*, 2012.

A total of 26 white papers were discussed at the workshop under subthemes of Drilling to the mantle: ocean plate formation and architecture (12), Ocean plate modification, aging, and recycling (6), and Large igneous provinces: deep mantle dynamics and environmental impact (8). The scientific objectives of these white papers contribute to several major challenges as described in the IODP science plan, such as Challenges 5, 6, 8, 9, 10, 11, and 13.

Discussion participants identified two major decadal goals: reaching the Earth's mantle in the Pacific Ocean for the top priority project, and studying the evolution of the oceanic lithosphere over its complete life cycle for the second priority project (see below). While the top priority project is being planned, hard rock targets in shallower water offer significant science returns and would provide valuable experience with D/V *Chikyu's* riser drilling system. The participants also discussed the longer range direction (far beyond the next decade) of deep hard-rock drilling with *Chikyu* to meet the ultimate goal of documenting and understanding the global variability of the architecture of the ocean lithosphere. This would include full penetration of igneous crust in the Atlantic for complementary study with the Pacific, drilling into different Large Igneous Provinces (LIPs) to study the variability of their origins, and drilling various age stages of the oceanic lithosphere. With the understanding that *Chikyu* should primarily been used for its unique riser, deep-drilling capability, it is hoped that within the next 20 years or more, the community will be able to achieve a spectrum of projects with multiple drilling and sampling platforms for focused study of the ocean lithosphere.

Flagship Project (top priority): Sampling complete oceanic crust and reaching Earth's mantle

Workshop participants agreed that drilling through an entire section of intact, igneous ocean crust and sampling the shallow mantle was the top priority decadal *Chikyu* project in this workshop theme, preferring a target site in fast-spreading crust in the Pacific Ocean. This recommendation is based on the scientific rationale developed since 2006 at various community workshops, and detailed in the IODP proposal Mohole to the Mantle (M2M) by Umino *et al*. (2012) (Figure 6). M2M is a mature proposal with over sixty international participants, which makes the case for an ultra-deep hole in the ocean lithosphere and discusses three potential sites in the Pacific Ocean with water depths between 3650 - 4300 meters and target depths between 6100 - 6700 meters.

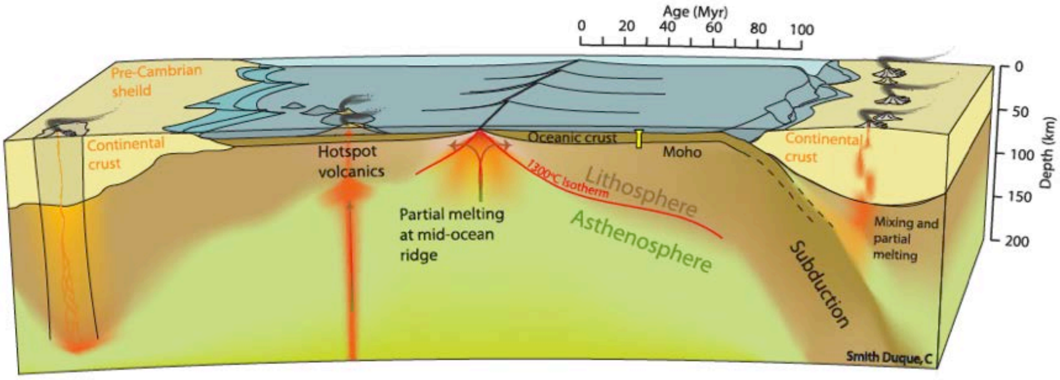


Figure 6. Sketch of the plate tectonic cycle showing the upwelling and partial melting of asthenospheric mantle to form new ocean crust at a mid-ocean ridge and the progressive growth of the lithospheric mantle as the plate conductively cools away from the ridge until it is subducted back into the mantle. Beneath the continental shields there is commonly a deep keel of continental lithospheric mantle that has been isolated from mantle convection since the Pre-Cambrian. The MoHole (thick yellow line) will sample the upper part of the oceanic mantle lithosphere, which is eventually recycled at subduction zones. Figure from Umino *et al*., 2012.

Scientific Objectives, Rationale and Global Scientific Impact: Samples of upper mantle peridotites that, in the near-geologic past, resided in the convecting mantle soon after experiencing partial melting at a fast-spread mid-ocean ridge will provide heretofore unobtainable information on mantle composition, deformation and physical properties, and the degree of heterogeneity in the uppermost mantle. This information is essential to understand the formation and evolution of Earth, its internal heat budget, planetary differentiation, reservoir mixing by mantle convection, mantle melting, and other fundamental characteristics of the planetary interior. Related areas of inquiry include the structure and formation processes of the igneous oceanic crust, the depth limit and controls on the microbial life in an entire section of oceanic crust, the geologic nature of the Mohorovičić seismic discontinuity (Moho) and mantle/crust boundary, and the mantle and crustal abundances of important trace volatile elements like carbon and hydrogen. Once established, the cased M2M hole may be utilized as a unique reference window to the mantle for subsequent experiments in a variety of scientific domains (petrology, geochemistry, geophysics, and biology). Fast-spreading crust is targeted in priority because it exhibits relatively uniform bathymetry and seismic structure, and is representative of the great majority of oceanic crust recycled back into the mantle by the past 200 million years of subduction. Comparative studies between *in situ* sections with reference sections in the Oman (and other) ophiolite(s) will be useful to further test the validity (or limitation) of the analogy between ophiolites and present-day ocean lithosphere, and provide a three-dimensional context to drill holes.

Societal Relevance: Reaching Earth's mantle - the next deepest layer of our layered planet – is considered as the Earth science analogy of Apollo, bringing rocks back from an as-of-yet unexplored part of the solar system. It is a fundamental mission of human exploration and record-setting requiring international collaboration in the spirit of discovery.

Rationale for Deep Drilling and Technical Challenges: Hard rock expeditions with scientific ocean drilling's traditional riserless ships have had significant, but still very limited success when trying to drill deep in the crust. This drove the development of the riser platform now known as D/V *Chikyu* through Japan's OD21 initiative: *Chikyu* was built primarily for the scientific goal of reaching the mantle. *Chikyu* has not yet drilled hard igneous rock targets in riser mode, but the well control possible through riser operations is expected to open the door to a project that has been deemed beyond the logistical or operational capabilities of other scientific ocean drilling platforms. Because of the combination of large water depth and extreme target depth, any change out of downhole equipment adds significant time and therefore cost, making considerations such as drill bit life an important part of the engineering strategy. Reaching the mantle in the Pacific will require extension of D/V *Chikyu's* current water depth capability beyond 2500 m. Based on recent feasibility studies, a MoHole in the Pacific is arguably within reach of the scientific drilling community. It will require substantial investment of time and resources, approaching the scale of a space project. Seismic site surveys are urgently required of all potential drill sites for M2M, and met-ocean surveys (to characterize variables such as weather, sea state, and currents) are advisable.

White Papers: Umino *et al.* (WP-126), Natland (WP-118), Kawamura (WP-111), Koepke (WP-112), Akizawa and Arai (WP-102), Fujiwara (WP-105), Day (WP-103).
Project Templates: PI-7, PI-35.

Related recommendation: Shallow water riser drilling of valuable hard rock scientific targets

During the extensive planning that will be required to reach the mantle at a Pacific Ocean site, valuable hard rock targets within reach of *Chikyu's* current riser capability can be explored. Such projects would provide experience and confidence with hard-rock riser drilling while addressing important scientific goals. Drilling through the serpentinization front inferred to be the crust-mantle boundary at Atlantis Bank in the Indian Ocean (Figure 7) would document *in situ* ocean crust formation at slow-spreading ridges, ideally complementing the science in M2M. Deep plutonic rocks of the lower crust and serpentinized upper mantle are generally more exposed in slow-spread crust than in fast-spread environments where they are overlain by thicker lavas and sheeted dikes, making for more straightforward drilling and recovery, based on past riserless drilling experience.

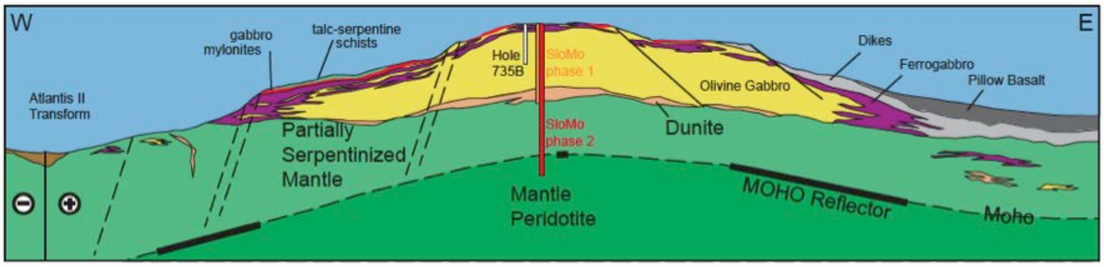


Figure 7. Cross section of Atlantis Bank through ODP Hole 735B and planned SloMo drilling (modified from a figure by H. Dick). Projected onto this line, ROV & submersible dives, over-the-side rock drills, Hole 735B and dredges show continuous gabbro outcrop, locally covered by a thin detachment fault zone assemblage of talc-serpentine schist, diabase cataclasite and weathered pillow basalt, and cataclasized gabbro mylonites where the original fault surface is uneroded. The best guess model for the Moho and crust-mantle boundary are shown. Deep drilling at the Atlantis Bank (Dick *et al.*, 2012) aims to test this model.

The deep basaltic crust of the Ontong Java Plateau in the southern Pacific Ocean is also a valuable *Chikyu* target, offering the chance to study rock generated during the most vital stage of the emplacement of this Large Igneous Province (LIP) (Figure 8). This would better document the mantle source variability of these large volcanic events. Drilling the deep middle crust of the Izu-Bonin Margin (see Continent Formation section of this Report) would provide a similar opportunity to test riser drilling in a hard rock environment with the current riser. Deep, riserless hard rock drilling to study the Godzilla Megamullion oceanic core complex in the Parece Vela Basin in the Philippine Sea would address lithospheric architecture and fluid circulation therein, mantle dynamics and melt migration at slow spreading ridges, and physical properties in the lower serpentinized crust.

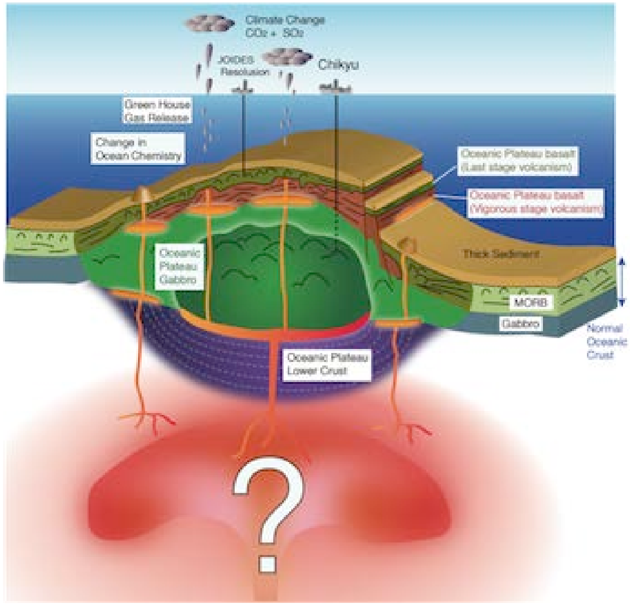


Figure 8. Schematic cross section of a Large Igneous Province (LIP), and targeted depth for *Chikyu* drilling. Figure provided by C. Neal.

By including drilling by other riserless platforms in an integrated strategy for studying the oceanic lithosphere, much can be learned from a variety of targets in the short term. This includes, for example, sampling the heterogeneous mantle exposed at the Gakkel ridge in the Arctic, deepening the existing deep Hole 1256D in the superfast spread crust of the Cocos plate in the Pacific, or realizing the first riserless drilling phase of the "SloMo" project (Dick *et al.*, 2012) to reach serpentinized peridotites underneath the gabbroic section already sampled at the Atlantis Massif in the Indian Ocean (Figure 7).

White Papers: Abe (WP-101), Dick *et al.* (WP-104), Hellebrand *et al.* (WP-108), Ohara *et al.* (WP-120), Harigane *et al.* (WP-107), Sato (WP-123), Sano *et al.* (WP-122), Tejada *et al.* (WP-125), Neal (WP-119), Zhao (WP-127), Maeno (WP-113), Nakanishi *et al.* (WP-117), Miura *et al.* (WP-114), Hanyu *et al.* (WP-106), Kawahata (WP-110).
Project Templates: PI-4, PI-6, PI-8, PI-9, PI-14, PI-16, PI-28, PI-37.

Flagship Project (second priority): Life Cycle of the Oceanic Lithosphere

The second priority goal, but no less ambitious, is to understand the transformation of the oceanic lithosphere and the associated global cycle of volatiles as the lithosphere is altered by seawater before it is recycled in the mantle at subduction zones.

Scientific Objectives, Rationale and Global Scientific Impact: Drilling through the oceanic plate just prior to subduction at the outer rise, where bending-related faulting is documented, is proposed to elucidate low temperature weathering, hydrothermal alteration, faulting, carbonation and hydration of the oceanic igneous crust and upper lithospheric mantle. Two white papers discussed this from both sides of the Pacific Ocean (Costa Rica subduction zone, and the outer rise of the Japan Trench). The Costa Rica subduction zone location links to the well-studied East Pacific Rise (plate formation), bending and faulting of the Cocos Plate, and subduction in the Costa Rica Seismogenesis Project (CRISP); the Japan Trench location links to the studies of Tohoku-oki Earthquake including JFAST drilling (see Dynamic Fault Behavior section of this Report). The working hypothesis to be tested there is that the lithospheric upper mantle is physically and chemically transformed by interaction with aqueous fluids before returning to the asthenosphere via subduction. The implications for the dynamics of the subduction/arc system and the global geochemical cycles are obviously profound. Coupled with the M2M project, and with integrated studies at the East-Pacific Rise and on the subduction zone, a deep hole in the outer rise would eventually contribute to fully understand the evolution of oceanic crust and upper mantle, including the natural storage of H_2O and C via serpentinization-related processes, and eventually document the complete life cycle of the oceanic lithosphere from creation to recycling (Figure 9). This is also relevant to studying the deep biosphere.

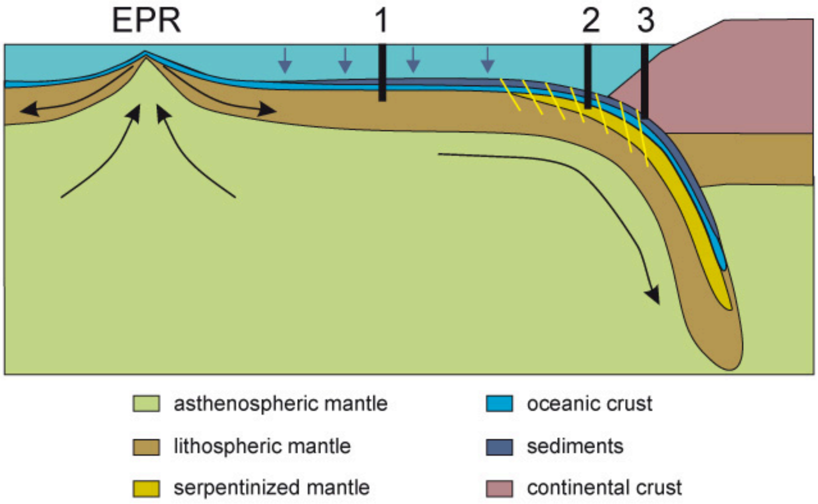


Figure 9. Schematic cross section of the Cocos plate from the East Pacific Rise to the Costa-Rica subduction zone, illustrating the concept of studying the complete life cycle of an oceanic plate. 1: M2M, 2: outer rise deep drilling, going through bent fault and reaching the serpentinized mantle, 3: CRISP (Figure modified from Morgan and Vannucchi, WP-115).

Societal Relevance: Understanding hydration and carbonation during serpentinization in ultramafic rocks is essential to estimate the long-term role of the shallow Earth's mantle in the global water and carbon budgets. While such processes have been documented in mantle rocks exposed on the seafloor, the importance of fluid-rock interaction in the deep basaltic ocean crust and *in situ* upper mantle in fast-spread ocean plate remains highly speculative in the absence of samples. This limits fundamental understanding of the role of the deep mantle as a carbon sink for the greenhouse gas CO_2. In contrast, subducted water dehydrates to a greater extent in subduction zones and may contribute to seismicity both at the plate boundary and in the slab (see Dynamic Fault Behavior section of this Report). Improved estimates of volatile inputs to subduction will help understand the causal mechanisms of these earthquakes.

Rationale for Deep Drilling and Technical Challenges: An ultra-deep, ~6 km deep hole would be required to fully address the science related to hydration of the upper mantle at the outer rise and the recycling of volatiles in subduction zones. Both the eastern and the western Pacific targets need deep-water riser drilling capability, although the water depths of the Pacific plate outer rise offshore Japan are too deep for this to be considered in a foreseeable future. An additional level of complexity is the need for drilling through a major fault zone in hard rock, along with the technology to drill into fractured hard rock.

White Papers: Morgan and Vannucchi (WP-115), Johnson and Hellebrand (WP-109), Morishita *et al.* (WP-116) ; Sakuyama *et al.* (WP-121).
Project Templates: PI-11, PI-13, PI-36, PI-42, PI-51.

Deep Life and Hydrothermal Systems

Introduction

The transfers of mass and energy between the solid Earth and the oceans are strongly affected by the flow of water and typified by the presence of microbial life. IODP's new science plan identifies questions revolving around the presence, activity, and ecology of the deep biosphere as a major frontier in biology and Earth sciences. Likewise, hydrothermal systems are assigned a key role in the science plan theme Earth Connections, because they constitute a major interface between the deep Earth and the oceans, transporting heat and mass, forming metal deposits, supporting autotrophic life, and acting as sinks or sources of CO_2.

One particularly obstinate challenge in deep biosphere and hydrothermal research is our inability to understand the ecological and physicochemical constraints that affect the limits of life. The habitable zone may be constrained by temperature, pH, or the availability of permeability/porosity, free energy, nutrients and micronutrients, water, etc. These parameters define ecosystem functioning and life's limits; they will vary drastically between the vast range of sub-seafloor environments in terms of substrate, transport regime, heat flow, and energy/nutrient availability.

These ecosystems comprise hydrothermal up-flow zones as well as vast aquifers within the ocean crust, which may constitute Earth's largest microbial habitat. In many settings, such as forearcs, bend faults, rifted margins, and mid-ocean ridge detachment faults, the circulation of seawater will lead to serpentinization of Earth's mantle and produce copious amounts of dihydrogen, the most potent energy source for chemosynthetic microbial life. There are also large accumulations of hydrocarbons, coal, and massive sulfide in the deep sub-seafloor, which may provide metabolic energy for microbial life and fuel hotspots of deep life.

Given this tremendous variability of sub-surface habitats, it is imperative for deep life research that high-quality core material is retrieved from a large range of settings. With its ultra-deep drilling capabilities, D/V *Chikyu* can make a crucial contribution to answer the following critical questions:

1. Which parameters determine the limits of the habitable zone in different settings?
2. How do diversity, ecology, and activity change within the habitable zone?
3. How do processes in the underlying abiotic zone affect life in the habitable zone?
4. Can high energy supply expand the habitable zone by offsetting physiological stress?

Hydrothermal systems support the most significant primary production of biomass on Earth outside of the photic zone. Yet, the processes controlling the flux of energy (reduced metals and gases) from the magmatic source to the seafloor are very poorly understood. Sub-seafloor mixing zones may act as traps for metals and as microbial incubators, due to prevailing strong geochemical gradients. In addition to deep life questions, submarine hydrothermal systems are of great societal interest, because they are modern analogs for some of the largest copper and gold deposits mined on land

and they constitute sources of metals, minerals, and biochemical compounds that may help satisfy our society's growing need for resources in the future.

Flagship of Opportunity

Many *Chikyu* expeditions under discussion for the next decade will penetrate all the way through the habitable zone, sampling the full range of parameters that control life's limit in different sub-seafloor environments. The *flagship of* opportunity for deep life research is to use these deep holes for addressing the most pressing questions in deep life studies to the maximum extent possible. Doing so requires improved sampling and analytical techniques as well as minimizing contamination. A persistent issue of cornerstone importance in deep life research is the difficulty to precisely determine the extent of microbial biomass and the level of microbial activity in deep sub-seafloor environments.

The habitable zone on Earth may be limited by temperature, pH, or the availability of permeability/porosity, free energy, nutrients and micronutrients, and water (Figure 10). Furthermore, we do not understand how energy flux supplied by deep reactions (diagenetic, hydrothermal, and magmatic) supports overlying microbial ecosystems in these different geotectonic settings. Nor can we comprehend the consequences of deep microbial activities for biogeochemical cycling of carbon and other elements on Earth.

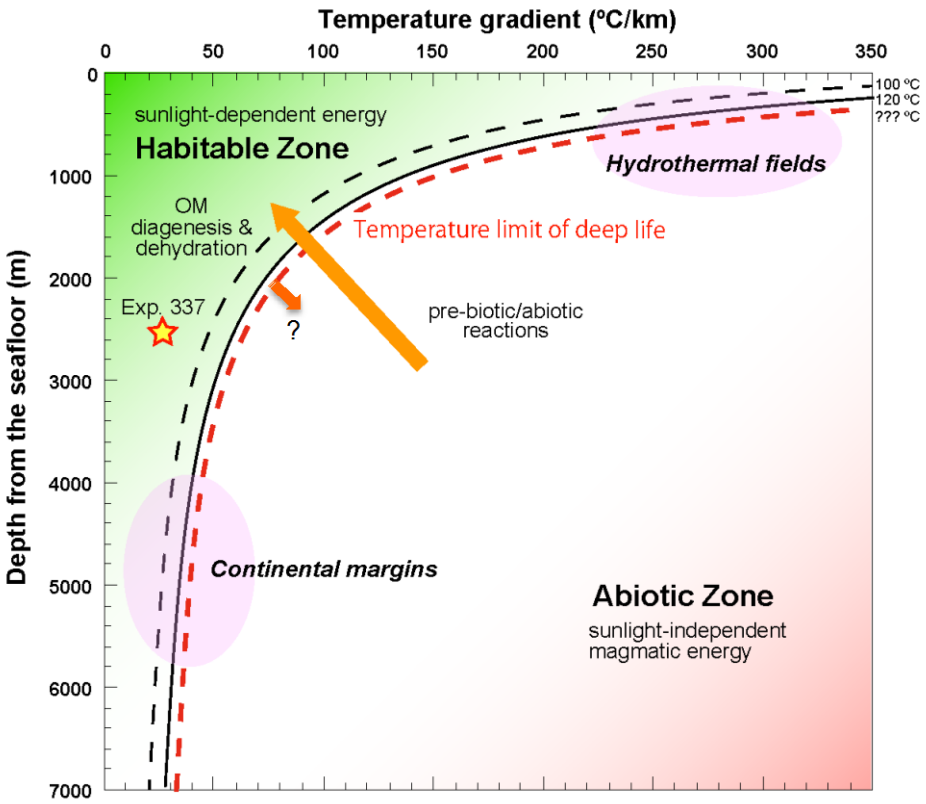


Figure 10. The transition between the habitable and abiotic zones is determined by temperature and may be very deep in areas of low heat flow such as continental margins. Hydrothermally active areas mark another end-member in the spectrum of habitats. The affect of energy input from the abiotic zone

into the habitable zone is greatly variable and how this flux affects deep life is poorly understood. Figure provided by F. Inagaki.

The deep life and hydrothermal community has produced a number of white papers and project idea templates, which identify a number of settings covering a large range of environmental conditions, stress factors, and energy availability that constrain the habitable zone (Figure 11).

Setting	Energy	Transport	Stress factors	WP/PI	Expeditions
Hydrothermal upflow zones	high	advective	Temperature, toxic elements	WP- 25, 23, 27, 22, PI-17, 18, 26	331
Hard rock basement	low	advective	Energy and nutrient availability	WP-12, 19, PI-8, 13	336
Serpentinization systems	high	advective	High pH, low CO_2	PI-2, 11, 42	
C_{org}-poor sediments (e.g., volcanic ash)	low	diffusive	Energy and nutrient availability	WP-24, PI-28	350-352
Sediments in high heat flow	high	diffusive	temperature	PI-25, 34	
Subducting sediments	high	variable	unknown	PI-10, WP-14	
Fluid and gas seepage (mud volcanoes, gas seeps)	high	advective	unknown	PI-38, 46, WP-20	
Buried energy (coal bed, massive sulfide)	high	diffusive	low permeability, high temperature	PI-47, WP-13	337
Deep salt	high	diffusive	high salt, low water	PI-31	

Figure 11. Overview of the range of sub-seafloor environments for which project ideas exist. Microbial life and its limiting factors are likely to differ considerably between these environments. WP = white paper; PI = project idea template (see Appendices).

Many of these systems will be drilled, but the number of dedicated microbiology expeditions will be small. Deep life researchers wish to improve sampling and measuring protocols to the extent needed to improve the quality and quantity of data. While the standard of microbiological sampling and sample storage has much improved in the current IODP with the specialized DeepBIOS core curation (WP-21), improved legacy sampling and measurements are absolutely critical for deep life research. This includes *regular sample collection and storage for microbiological research*, as well as biogeochemical measurements of pore waters, including nutrients and basic microbial metabolites (H_2, acetate). This is already in place to some extent through DeepBIOS, but needs to be expanded. Drill fluid samples should be added to this improved set of routine analyses. *Cleaner drilling mud* for riser drilling is a must (WP-17). Drilling mud during Expedition 337 had 10^8 cells cm^{-3} while some of the deeper layers studied had *in situ* populations of 10^2 cells cm^{-3}. Hence there is a strong need to develop cleaner muds, just like cleaner CORK casings were developed for Expedition 336.

The sooner these developments are implemented, the stronger the microbiology and biogeochemistry outcomes will be from future expeditions such as the large-scale projects identified elsewhere in this report (e.g. NanTroSEIZE, IBM-4, SloMo, and M2M). Investment in this can start immediately and run in parallel with other operations. Developing standardized sampling protocol for DeepBIOS samples requires communication with all disciplines and understanding of needs from all groups involved. Details of some technical issues have been designed based on the recommendation of IODP's Scientific Technology Panel. Further details of molecular and specific microbial and geochemical analyses must be discussed and summarized again through a small and mission-focused workshop.

Microbiological analyses from every core taken during D/V *Chikyu* expeditions are strongly recommended to develop a more thorough understanding of the distribution of deep life and its ecological functioning in the various sub-seafloor environments. Besides prokaryotes, fungi and viruses may play significant role in dark and anoxic deep environment. Likewise, quantification of microbial necromass (WP-18) and spores are required. Legacy samples should be made available to the larger scientific community to bring in new people and help broadening and strengthening deep life science.

Specifically, recent advances in cell enumeration technologies can provide a standard measurement of the microbial biomass within the subsurface biosphere. Previous arguments in opposition to such a goal were based on limited manpower and expertise. Morono *et al.* (2009) describes an automated method that can and should become routine onboard. While this will require time for a technician to run the machine and prepare samples, this is no more labor intensive than what is currently done for routine geochemical analyses. The described method uses an automated system that will help reduce the overall time devoted to collecting these highly valuable data. Automating the counting method also reduces human-introduced variations between expeditions. Routine sampling for cell enumeration will provide baseline biosphere comparisons between lithologies and locations, while also providing additional data points to better estimate the extent of the subsurface biomass.

Specific project ideas for Deep Life that could develop into Discovery Projects

There are no dedicated deep life or hydrothermal systems proposals currently in IODP review for the use of D/V *Chikyu*; however, a number of very promising ideas that would make distinct use of the ship's unique capabilities were discussed. Workshop participants felt strongly that, in addition to improvements in sampling and analysis methods, novel dedicated deep life expeditions in the coming decade would be vital for IODP and timely considering the growing importance of deep life questions in ocean and Earth sciences. The deep life researchers attending CHIKYU+10 hence issue a strong endorsement of specific "Deep Life" projects for consideration in this decade's scheduling.

A number of projects could be developed into full drilling proposals within a fairly short amount of time. One particularly exciting project idea is that of extending the search for the depth limit of life by drilling a **4,500 m hole off Hachinohe**, where Expedition 337 recently set a new record for documenting deep life. More deeply buried coalbed-methane zones could be sampled in a renewed ultra-deep drilling effort, providing first insights into very deep life tied to high energy availability in a diffusion controlled environment (PI-47).

Another ambitious project idea for **ultra-deep drilling** of potential flagship magnitude targets the **Izu-Bonin-Mariana forearc**, which contrasts with the Nankai forearc in terms of sediment accretion and subduction erosion processes. Such a drilling project would be of considerable interest, not only in terms of hydrology, fluid geochemistry, microbiology, and abiotic chemical processes and alteration, but also from the perspective of igneous petrology, seismology, and general subduction zone geology. Forming a project scoping team is recommended to develop a truly multidisciplinary proposal for the ultra-deep drilling of the IBM forearc.

Apart from these potential projects, a set of distinct project ideas for discovery-type missions has been discussed. Common to all these project ideas is that the relationships between hydrogeology, fluid chemistry and microbial activity are at the core of the science questions to be addressed. Furthermore, all of these potential projects share a very high feasibility and a very large potential for breakthrough discoveries in deep life research. Specifically, these ideas are:

Project 1: Temperature limits of life in sediments (Shikoku Basin, Sites 1173/1174)
The high heat flow Shikoku Basin is an area where the temperature limit of life is expected at around a kilometer below the seafloor while the critical zones of the biotic fringe may be studied in expanded intervals of a few hundred meters length. Moreover, the influence of basement hydrothermal circulation on life in the deeply buried sediments could be assessed (PI-34).

Project 2: Décollement hydrology effects on deep life (JFAST site)
Investigation of how microbial life is affected by fluid flow within the décollement and possibly within the subducting ocean crust in a zone of shallow and extreme slip, such as the JFAST Expedition 343 site in the Japan Trench.

Project 3: Mud volcanoes in the Kumano Basin: windows to deep life, Kumano Basin, Nankai
Advective delivery of energy from great depths takes place in mud volcanoes, such as those in the Kumano Basin. *Chikyu* drilling there would retrieve unprecedented samples of the feeding system of mud volcanoes and could be developed into a sub-seafloor observatory that could be tied into the DONET network being established in this particular area (PI-46).

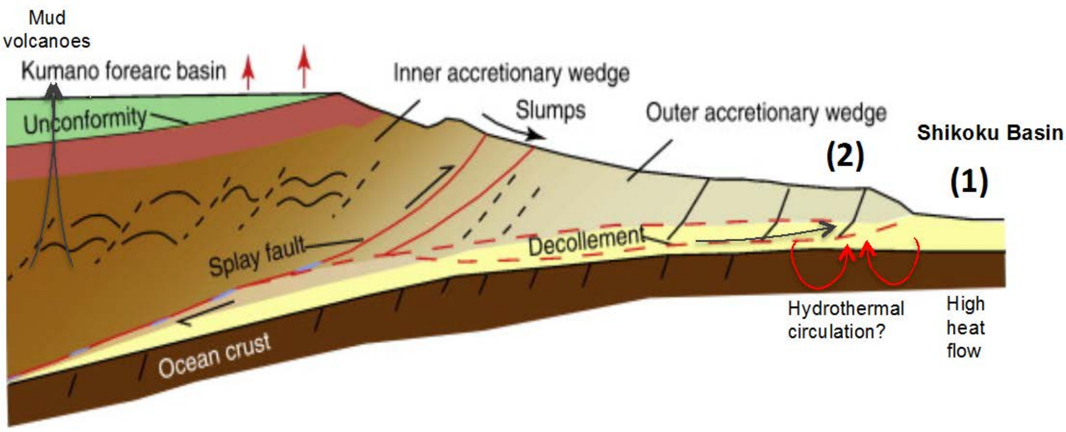


Figure 12. Schematic view of the setting of three of the discovery-type project ideas revolving around deep life in drastically different settings in convergent margins.

These potential projects would provide the deep life community with the unique opportunity of sampling three radically different environments in convergent margins (Figure 12), using the much-improved protocols for sampling and analysis advised above. These environments are:

1. Shallow and hot, diffusion-controlled (Shikoku Basin)
2. Deep and affected by fluids from the down-going slab, diffusion-controlled grading into advection-controlled (JFAST-like site), and
3. Shallow and controlled by advection of energy-rich deeply sourced fluids from the accretionary prism (Kumano Basin mud volcanoes).

Global impact of these project ideas: Life near the limit of habitability has developed specific adaptation mechanisms, including biochemical pathways unknown from other forms of life. The potential for making fundamental discoveries in biology is large. The role played by deep life in global biogeochemical cycles is unknown, due to the scarcity of dedicated microbiology drilling endeavors.

Societal Relevance: Deciphering the cycles of materials and life on Earth is of fundamental importance for understanding our planet, which in turn is essential in developing concepts for the future use of marine resources. The role of the sub-seafloor biosphere in the cycles of carbon and other elements is unknown, although the sub-seafloor is a significant microbial habitat on Earth.

Specific project ideas for Hydrothermal Systems hosted in arc volcanoes

Hundreds of active hydrothermal systems in >7000 km of submarine arcs on Earth are major players in global geochemical exchange budgets. Arc hydrothermal systems are geochemically extremely diverse, which is a surface expression of high versus low sulfidation systems in the sub-seafloor. These systems are direct communication ports between magma systems influenced by plate tectonics, and seafloor processes. As such, they constitute unique geo-bio interfaces in which temporal and spatial gradients may be higher than anywhere else on Earth.

The hydrothermal systems in arc volcanoes are modern analogs for world-class polymetallic sulfide deposits. Examining these systems by deep drilling will provide an unprecedented opportunity to understand how these deposits form. A particularly important issue in the metallogenesis of these deposits is understanding how sub-seafloor fluid mixing processes control metal transport between magma reservoirs and the seafloor. Moreover, learning how the formation of massive sulfides is controlled by magmatic processes and volcanic facies will be vital for assessing metal resources in the oceans.

Two specific project ideas for **arc hydrothermal system drilling** were presented at the workshop: Drilling the Brothers Volcano in the Kermadec Arc (WP-22), and drilling neo-volcanic structures in the eastern Manus Basin (WP-27). Both systems host contrasting types of hydrothermal venting, comprising acid-sulfate as well as black smoker type. The large geochemical diversity of the vent fluids is an expression of high- and low-sulfidation systems in the sub-seafloor. These systems cause contrasting alteration types in the volcanic basement. Seawater-entrainment in the high- and low-sulfidation up-flow zones will affect sulfide precipitation and zone refining, leading to fractionation of metals discharging from the degassing magma reservoir. These processes create habitats for microbial life, which harnesses metabolic energy in strong redox gradients. The systems are rich in CO_2, heat and potential metabolic energy. High temperature and low pH as well as high toxic metal and metalloid concentrations may impose limits on life. The principal energy sources are reduced metals, as well as hydrogen sulfide and elemental sulfur.

Global Impact: Arc-derived fluxes of metals and metalloids (also C- and S-species gases) to the oceans are very large. Although hydrothermal heat flux in arcs is only 10% of that along mid-ocean ridges, the role they play in the geochemical budget of the ocean is large for many elements, because their enrichment in the fluids is orders of magnitude greater than in similarly hot fluids issuing along the mid-ocean ridges. A large number of these systems are in water depths shallow enough for hydrothermally discharged metals to reach the photic zone and affect productivity there. Also, the impact of hydrothermal venting on the global budget and distribution of metals in the oceans is being increasingly recognized. Furthermore, the low pH of the discharged plume waters slows down the oxidation kinetics of iron, allowing iron and metals that are scavenged when Fe-hydroxide precipitates in the plume to be dispersed over much greater distances when compared to mid-ocean ridge derived plumes.

Rationale for Deep Drilling and Technical Challenges: Riser drilling has several distinct advantages, including mud-line gas analyses, continuous sample retrieval from cuttings stream, and large diameter coring. *Chikyu* therefore will overcome many of the problems encountered when drilling hydrothermal systems using riserless systems (e.g., low sample recovery, lack of fluid sampling capability). Technical challenges include high temperatures and low pH in the target zone, and fractured basement.

Societal Relevance: Understanding how volcanogenic massive sulfide deposits form will facilitate exploration for metals on land. It will also help assessing metal resource in the oceans. Furthermore, isolation and cultivation of extremophile microorganisms may lead to biotechnological developments.

Other projects

Serpentinization systems represent another potential setting for deep life in the spectrum of physicochemical variability in water-rock systems in the oceans. They are associated with fluids featuring high pH, low CO_2, and low to moderate temperatures. The fluids are enriched in dihydrogen and methane such that the availability of energy is very high in serpentinization systems; yet the high pH and the virtual lack of CO_2 impose potential limits of chemolithoautotrophic life. Serpentinization affects mud volcanoes in the Mariana forearc (WP-19), fluids circulating in bend faults in the outer rise (PI-2, PI-12, PI-42) and troctolite-basalt systems in the Uraniwa hills / Hakuho knolls area on the Central Indian Ridge (WP-25, PI-12). While drilling these systems with *Chikyu* may not be feasible within the time frame relevant here, they are very important science targets for ocean drilling in general. The development of drilling proposals should be encouraged to enable exploration of serpentinization-related processes and life in the not too distant future.

Continent Formation

Introduction

Continents constitute 40% of the Earth's crust and provide the platform on which terrestrial life evolved. The formation process of continents, however, remains one of the important challenges in modern Earth science. The silica content of the bulk continental crust is 60 wt% (weight percent), closely resembling the composition of andesite, whereas the mantle-derived oceanic crust generated at mid-ocean ridges and above mantle plumes is basaltic. No other known planet has developed such a large volume of silica-rich crust, so the existence of continents is one of the defining features of what makes the Earth unique in the solar system.

It is widely thought that continental crust has been created, or at least recycled, along convergent margins for the last ~3.5 billion years ago. The rapid growth of continental crust in the geological past certainly increased the transport of terrestrial material from land to ocean, changing ocean chemistry and controlling the evolution of Earth's environment and life. Since approximately 1 billion years ago, continent formation has occurred continuously along subduction zones, forming island arcs. Water supply to the lithosphere from the subducting oceanic plate is essential to create continental crust. Continents could not be formed without the ocean, and the existence of continental crust has changed the ocean. Understanding continent formation is therefore essential to understand the Earth's evolution.

Flagship Project: Island Arc Origin, Izu-Bonin-Mariana

The continental crust we observe on the surface of the Earth has been deformed, metamorphosed, and otherwise processed perhaps several times from its creation in subduction zones to the present. The study of island arc origin is therefore the best way to answer the key question of how the continental crust is formed, although the process is a little bit far from the past geological setting. The significance of island arc origin is clearly described in IODP science plan as *How do subduction zones initiate, cycle volatiles, and generate continental crust?* (IODP Science Plan, *Challenge 11*).

Scientific Objectives, Rationale and Global Scientific Impact: The overarching objective of the flagship project ***Island Arc Origin*** is to understand how juvenile arc crust forms and differentiates. The project has a high potential to result in a fundamentally new understanding of Earth's history. In the modern Earth, island arcs and Andean margins, that are the convergent plate boundaries, are the site of continental crust formation. The middle crust beneath arcs, with seismic *P* wave velocities of 6.0-6.8 km/s, shows characteristics of intermediate-felsic plutonic/metamorphic rocks, geophysically identical to the middle crust of continent. Deep drilling to the middle layer of juvenile arc crust will provide the opportunity to study an intact, undeformed continental crust as it forms *in situ*, which cannot be resolved only by studying mature continents or exposed ancient arcs on land. It will constrain the petrologic and chronological relationship between middle crust and the overlying upper crustal arc volcano, allowing exploration of the active processes of continental crust growth below arc volcanoes.

Appropriate site location*: *Izu-Bonin-Mariana (IBM)

The Izu-Bonin-Mariana (IBM) arc system, extending 2800 km to the south of Japan, is uniquely suited to the study of arc evolution and continental crust formation. It is a juvenile intra-oceanic arc with no pre-existing continental crust, yet a thick middle crust layer with 6.0-6.8 km/s V_p is widely distributed in this arc (Figure 13). IBM is the most intensively studied island arc in the world; drilling there will provide a much needed reference section for other arcs and correlation between geophysics and petrologic observations.

Three IODP expeditions by the *JOIDES Resolution* have already been scheduled in 2014. IBM-1 (Expedition 351) will drill the pre-existing oceanic crust west of the remnant arc to reveal the nature of the original crust and mantle prior to arc inception. IBM-2 (Expedition 350) will drill through the volcanic stratigraphy of the outer forearc, studying early processes in magmatic evolution associated with subduction initiation. IBM-3 (Expedition 352) will drill the rear arc crust to elucidate the spatial and temporal evolution of arc magmatism. In order to reach comprehensive understanding of arc evolution and continental crust formation, an ultra-deep drilling site with *Chikyu* (IBM-4) is proposed in the northern Izu arc. The hole will penetrate through a complete sequence of intra-oceanic arc upper crust and into the *in situ* middle crust that may be a nucleus of continental crust.

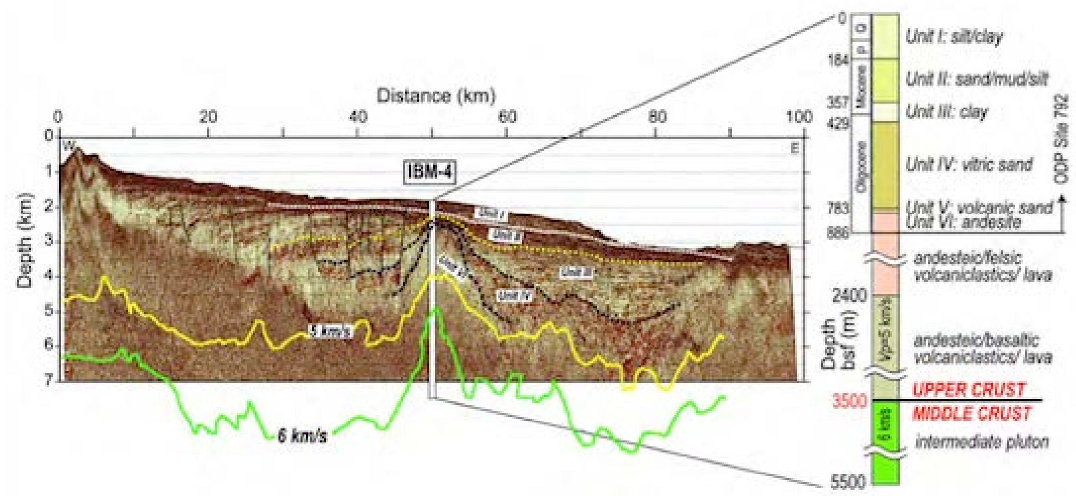


Figure 13. Lithological interpretation of the seismic image across the IBM-4 proposed site based on the results of ODP site 792, Leg 126 (Taylor *et al.*, 1992). Iso-V_p contours of 5 km/s and 6 km/s are also shown. Figure from Tatsumi *et al.*, 2010.

Societal Relevance: The IBM arc consists of numerous islands with active volcanoes and submarine volcanoes, having the potential to cause significant damage to society. Although understanding middle crust formation may not directly contribute the mitigation of volcano disasters, post-drilling long-term measurements will provide valuable data for monitoring and predicting volcanic and seismic activity. The active arc and back-arc rift areas are also known to host hydrothermal ore deposits, hence understanding the alteration of crust likely increases our knowledge about the mineralization process and possible existence of natural resources.

Rationale for Deep Drilling and Technical Challenges: The proposed site for IBM-4 is the place where ODP site 792 reached the top of the basement. The site survey is finished and riserless expeditions are scheduled, and the scientific relevance is approved in current IODP framework. The goal of the project is to reach the intact middle crust at 5,500 mbsf. This ultra-deep drilling can be achieved only by riser drilling with D/V *Chikyu*. The ultra-deep drilling at the proposed site is achievable with *Chikyu's* current technical capability. The water depth is 1,800 m and the planned penetration is 5,500 mbsf. The temperature at the base of the hole is estimated as 150-175°C. There is no risk of shallow gas or similar hazards. A geotechnical hole for IBM-4 will be drilled by the *JOIDES Resolution* in 2014. Ultra-deep drilling at IBM-4 aims to drill through hard rock to depths as of yet unreached in scientific ocean drilling. Although the coring is preferable, a realistic drilling plan with usage of logging-while-drilling (LWD), cutting, and side-wall coring is required. Deep riser drilling in hard rock in IBM-4 will build confidence and provide engineering data for other ultra-deep projects, such as drilling to the mantle in the future.

Opportunity beyond the expedition: Ultra-deep drilling to the middle crust is a unique opportunity to carry out many important post-drilling studies, such as fluid flow monitoring in arc crust and vertical seismic profiling using boreholes. The ultra-deep drilling, logging and post-drilling investigations at IBM-4 also provide a valuable opportunity to investigate a deep biosphere that has never been reached. The IODP science plan clearly infers the significance, as *What are the origin, composition, and global significance of deep sub-seafloor communities and what are the limits of life in the sub-seafloor realm (*IODP Science Plan, *Challenges 5 and 6*).

White Papers: Stern (WP-9), Tatsumi (WP-10), Tamura *et al.* (WP-39), Kimura *et al.* (WP-35), Gill (WP-31), Nichols *et al.* (WP-36), Kelley *et al.* (WP-34), Freymuth *et al.* (WP-30), Straub *et al.* (WP-37), Takai and Nakamura (WP-38)
Project Templates: PI-41

A longer-term project: The Aleutian end member of arc crust

Ultra-deep drilling of IBM-4 offers a unique opportunity to directly compare the seismic velocity model with rock types and structure within the deep arc crust. Many active arcs have a middle crust with seismic velocities of 6.0-6.5 km/s which are interpreted as intermediate to felsic plutonic rocks. The Aleutian arc lacks a comparable middle crust layer with these velocities. Instead, its middle crust has seismic *P* wave velocities of 6.5-7.3 km/s, interpreted to be predominantly mafic rock. Other intra-oceanic arcs lie within a range of velocity structures that fall between IBM and the Aleutian (Figure 14). Deep drilling in the central Aleutians will then provide a record of initiation and evolution of the mafic end member of intra-oceanic arc, allowing a comprehensive understanding of subduction initiation and continent formation through arc volcanism (IODP Science Plan, *Challenge 11*). Site characterization is not advanced enough for detailed planning of drilling at the present time. Further pre-drilling studies are required.

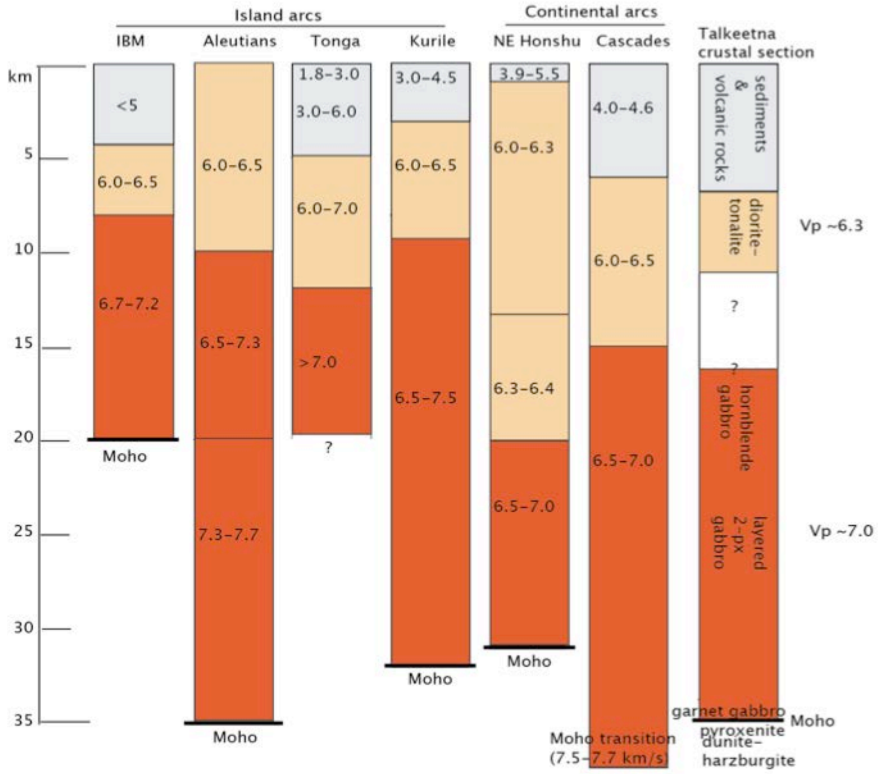


Figure 14. Seismic velocity models of various modern island arcs and continental arcs. Figure from DeBari and Greene (2011).

White Papers: Jicha *et al.* (WP-33), Ishizuka and Tani (WP-32), Busby and DeBari (WP-28), DeBari *et al.* (WP-29), Yogodzinski *et al.* (WP-40)

Sediment Secrets

Introduction

D/V *Chikyu* offers opportunities for safely recovering deeply buried sediments through riser drilling, and may be used also to recover shallower sediments with potentially high gas content. Drilling these important sediment archives allows exploration of past ocean environments, reveals changes in large-scale oceanic, atmospheric, and continental conditions, and illuminates the effects of cataclysmic events such as episodic flood magmatism and bolide impacts.

16 white papers involving sediment archives were discussed during the workshop. The topics were wide-ranging, including the evolution of ocean basins, high-resolution records of climate, Mesozoic paleoceanography, and salt and sub-salt environments. Drilling deep sections will also provide the opportunity to address questions related to evolution and adaptation of life to Earth's extreme environments.

The scientific objectives of these white papers contribute to several major challenges as described in the IODP science plan for 2013-2023, such as *How does Earth's climate system respond to elevated levels of atmospheric* CO_2*?* (IODP Science Plan, *Challenge 1*), *How do ice sheet and sea level respond to a warming climate?* (*Challenge 2*), *How resilient is the ocean to chemical perturbations?* (*Challenge 4*), and *How sensitive are ecosystems and biodiversity to environmental change?* (*Challenge 7*).

One general recommendation from the workshop is that extending the drilling capacity of D/V *Chikyu* beyond 2,500 meters water depth would be extremely beneficial for research utilizing deep sediment sections.

Discussions during the Sediment Secrets workshop theme identified one Flagship project and several assemblages of Discovery projects with similar themes that could start being developed for *Chikyu* implementation through workshops and dialog with potential national and regional partners.

Flagship Project: Extreme environments: Ocean Basin Desiccation (Mediterranean)

Miocene sediments in the present-day Mediterranean Sea offer a unique opportunity to study continental margin formation, deep life, and extreme climate change in a previously unexplored subsurface environment. About 6 million years ago, a period of extreme environmental change transformed the Mediterranean Sea into a giant saline basin. Sea level fell about 1,500 meters as much of the sea evaporated, leaving the basin almost desiccated and resulting in a huge sequence of salt deposits. This extreme environmental event is referred to as the Messinian salinity crisis (MSC). 95% of the offshore Messinian salinity crisis deposits are unexplored, and the geology underlying these deposits has never been sampled.

Scientific Objectives, Rationale and Global Scientific Impact: Drilling through this Messinian salt sequence at several places in the Mediterranean will address questions about the causes, processes, timing, and regional and global consequences of this extreme environmental event, which can only be studied through deep water drilling. Drilling also explores the impact of salt bodies on surrounding sediments (fluid, diagenesis, geochemistry, and geomechanics) and may lead to the discovery of unique life within and below the salt-related deep biosphere. Recovering samples from beneath the massive salt deposit will provide new information about the Neogene history of the Mediterranean basin, which is now based largely on terrestrial studies.

Societal Relevance: New knowledge about the cause of the Messinian environmental crisis in the Mediterranean region can help to understand the mechanisms involved in extreme environmental change. Analysis of these and older sedimentary deposits could provide potential new knowledge about natural resources in the Mediterranean.

Rationale for Deep Drilling and Technical Challenges: The origin and pre-history of the Messinian Salinity Crisis can be studied only through drilling the deep Mediterranean basins (Figure 15). Technical challenges for this project include the excessive water depth beyond the current riser capability, and known challenges with drilling salt formations, such as borehole stability and salt deformation in the hole. Exploring the even deeper sub-salt environment raises concerns with compaction disequilibrium and overpressure, and would require a deep hole (to 6 km). *Chikyu's* riser capability is essential to safely access and recover these deep sediments.

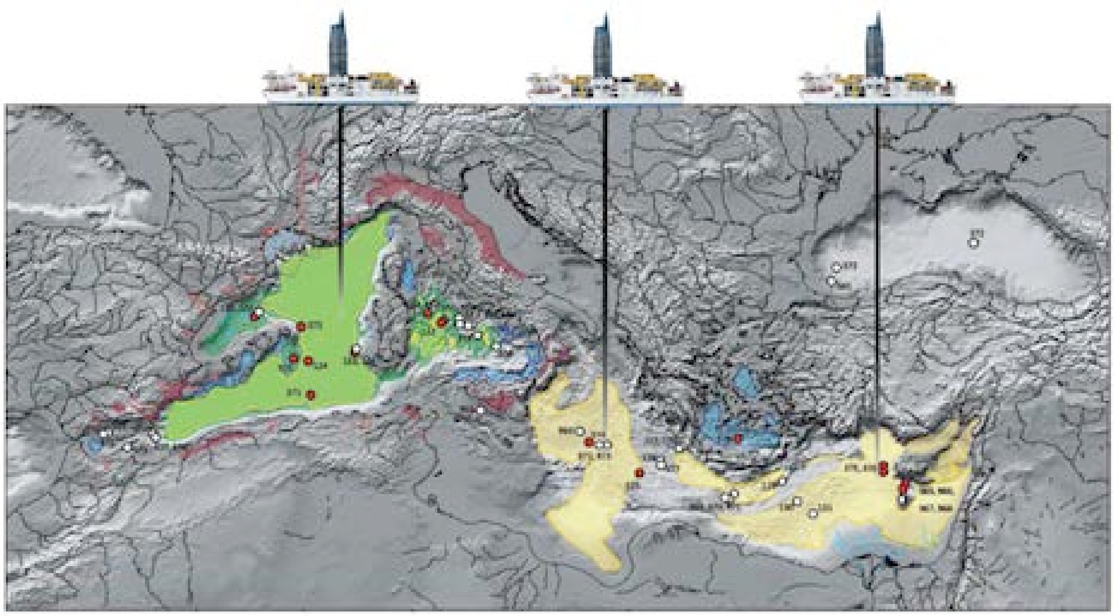


Figure 15. Multiple drilling locations are proposed to resolve the enduring questions concerning the Mediterranean salinity crisis. Figure from Camerlenghi *et al*. (WP-43).

A large proponent group is actively working on a drilling proposal. They have identified one potential site in 2,300 meters of water depth in the western Mediterranean (N41º45.92, E 05º00.10) and are seeking two additional sites in water depths between 1,000 and 2,500 m. Other additional sites could be located in water depths between 2,500 and 4,000 m when the new riser capability becomes available.

White Papers: Rabineau *et al.* (WP-53), Camerlenghi *et al.* (WP-43).
Project Template: PI-31.

Potential Discovery Projects: Exploring basin evolution in the southwestern Pacific (Lord Howe Rise, Pegasus Basin, Challenger Plateau, South China Sea, Santos Basin, and Aleutian Basin)

***Lord Howe Rise*:**
The Lord Howe Rise region between New Zealand and eastern Australia is one of the world's largest remaining offshore frontiers for scientific research and resource exploration outside the polar regions. Deep drilling into the pre-Late Cretaceous sediments will provide essential information to unlock the geological history of the Mesozoic break-up of eastern Gondwana and its effects on regional and global tectonics, environmental change, ocean basin formation, and micro-continent formation. Discovery of expected late- to mid-Cretaceous petroleum source rocks and confirmation of petroleum systems will support regional and global energy security.

Rationale for Deep Drilling and Technical Challenges: Riser drilling is required due to possible occurrence of hydrocarbons. Drilling sites will necessarily be located off-structure so as to minimize potential of encountering hydrocarbons. A challenge is that the area is quite remote. Lord Howe Island is the closest port for mobilization and has helicopter facilities. An austral summer drilling campaign is preferred to minimize the potential of encountering winter storms and East Coast low pressure systems. This study has the potential to attract national funding leading to a Complementary Project Proposal (CPP).

***Challenger Plateau*:**
Sediments of the Challenger Plateau southeast of the Lord Howe Rise could constrain the development of the Cretaceous rift margin formed during the breakup of eastern Gondwana and the formation of the Tasman Sea (Figure 16). Objectives in this drilling proposal are comparable but not equivalent to the Lord Howe Rise project idea (above). New 2-D seismic data in the area have indicated a considerable amount of Cretaceous sediment on the northern flank of the Challenger Plateau that has the potential for hydrocarbons. Comparable rocks are observed in the Gippsland Basin southeast of Victoria, Australia, an offshore oil and gas region. Because there has been no significant deep drilling in this area, all current geological understanding is based on seismic records. Drilling would add considerably to the understanding of the paleogeographic setting and the tectonic evolution of this area during Cretaceous breakup. Previous DSDP holes 592 (to the northwest) and 593 (to the southwest) provide regional context. Currently there is petroleum production from the Taranaki basin further to the east, largely in shelf water depths.

Rationale for Deep Drilling and Technical Challenges: Riser drilling is required due to the possible occurrence of hydrocarbons. A location within helicopter range of mainland New Zealand would be required, the most likely base being the deep water port of New Plymouth, center for the local offshore petroleum industry with good infrastructure facilities including a helicopter base and commercial airport.

***Pegasus Basin*:**

Neogene to Paleogene sediments forming a thick stratigraphic section within the Pegasus Basin (offshore eastern New Zealand, between North and South Islands) are relatively undeformed, yet are part of a Neogene convergent margin (Figure 17). The Pegasus Basin is located within the Hikurangi margin, a site for other proposal Chikyu drilling, but in contrast to the deformation seen to the north, its Paleogene and Neogene sections are undeformed. Virtually nothing is known about these sediments, which have the potential to be oil and/or gas bearing. The basin lies to the east of mainland New Zealand and west of ODP Sites 1125 and 1123. It lies just north of the subtropical front dominated by subtropical waters. The water mass within the basin comprises a local gyre at the southern margin of the East Coast Current (Pacific Ocean) with mixing from the D'Urville Current (from the Tasman Sea). The Neogene paleoclimatic record should provide indications of the mixing of Pacific and Tasman waters through time, controlled by tectonic opening of seaways between North and South Island New Zealand, as well as possible mixing of colder sub-Antarctic waters from the south.

Rationale for Deep Drilling and Technical Challenges: Riser drilling is required due to possible occurrence of deep-seated oil and gas as well as hydrates at shallower depths. The section is more than 3 km thick and drilling would target key stratigraphic intervals that had previously been recognized in seismic imaging as worthy of coring. Wellington, the capital city of New Zealand, would provide a local base for helicopter and logistic support.

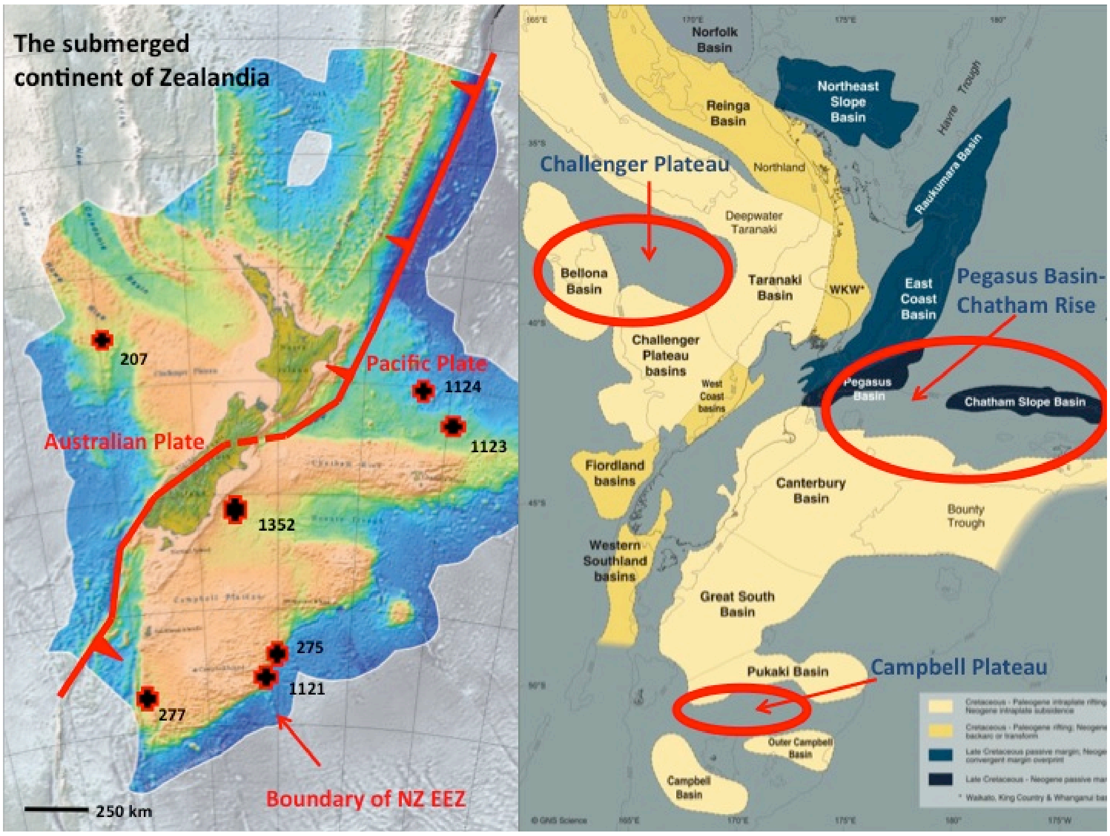


Figure 16. On the left, Boundary between the Australian and Pacific Plates in the southwest Pacific Ocean. On the right, locations of possible drilling explorations in the southwest Pacific Ocean. Figure from Browne and Hollis (WP-42).

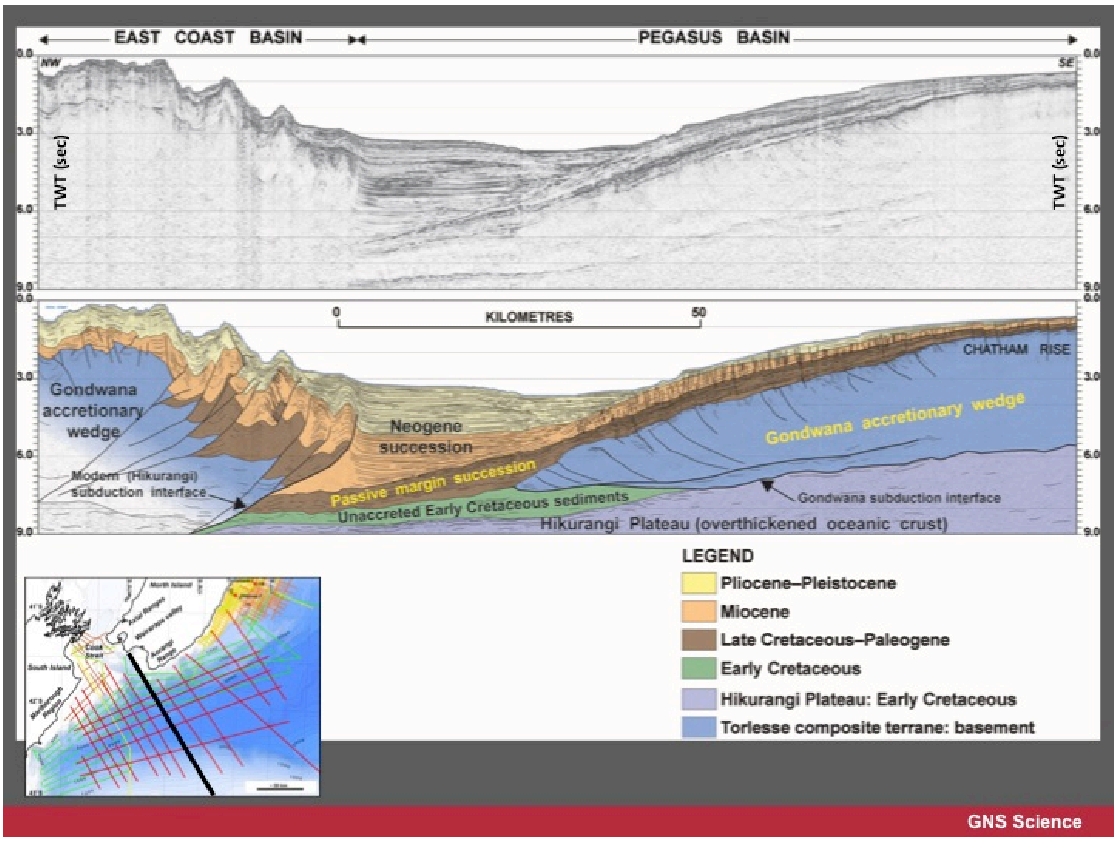


Figure 17. NW-SE seismic line showing the main sedimentary sequences of the Pegasus Basin and the modern Hikurangi subduction interface. Figure from Browne and Hollis (WP-42).

***South China Sea*:**
A dedicated drilling program with D/V *Chikyu* is an opportunity to improve understanding of the regional formation of the South China Sea. New drilling may provide materials to address questions related to east Asian geology and fundamental issues regarding continental breakup and basin formation. Important targets in the region include pre-rifting and syn-rifting sequences, ocean ridges and basin basalts.

Rationale for Deep Drilling and Technical Challenges: Riser drilling is required because of the thickness of the sequence and the possible occurrence of hydrocarbons.

***Santos Basin*:**
Recently acquired deep seismic data in the Santos Basin indicate several potential scientific drilling targets in order to better constrain the early phases of South Atlantic opening, oceanic crust formation and paleoecology of the magnetically quiet Aptian-Albian transition, notable because a wide microbial-rich lacustrine shallow water carbonate environment evolved to a very thick salt basin.

Rationale for Deep Drilling and Technical Challenges: Riser drilling is required because of the thickness of the sequence and the possible occurrence of hydrocarbons.

***Bering Sea*:**
The tectonic evolution of the Aleutian convergent margin and surrounding regions is poorly understood. Drilling in the Aleutian Basin may recover a record of overlying sediments as well as good penetration (>200 m) into magnetic basement. Drilling

aims to test competing hypotheses for the origin of the Aleutian Arc and flanking ocean basins in the Bering Sea.

Rationale for Deep Drilling and Technical Challenges: Riser drilling is required because of the thickness of the sequence and the possible occurrence of hydrocarbons.

White Papers: Hashimoto *et al.* (WP-47), Browne and Hollis (WP-42), Zhao and Li, (WP-58), Viana *et al.* (WP-56), Daigle and Dugan (WP-46), Stern *et al.* (WP-54).
Project Templates: PI-19, PI-21, PI-22, PI-23.

Potential Discovery Projects: Deep Mesozoic sedimentary section (Pacific guyots, the deep Pacific, Somali Basin, and Eastern Mediterranean)

The Mesozoic sedimentary archive will address major challenges described in the IODP science plan. Specifically: 1) long-term and short-term climate changes and Earth system functioning under low and high levels of CO_2; 2) oceanic anoxic events; 3) response to ocean acidification and fertilization; 4) oceanic ecosystem dynamics during paleoenvironmental ephemeral adaptations and permanent evolutionary change; 5) dating and exploring links between LIP construction and environmental consequences.

The Mesozoic Era is important due to the global emergence of terrestrial vertebrates and their speciation, evolution, and extinction. The position of continents and large-scale eruptions altered sea levels, ocean chemistry, and global climate, controlling conditions for life. Much of the terrestrial Mesozoic record has been erased from the planet by erosion and tectonics. Mesozoic sediments in the deep sea provide essential records for reconstructing global climate conditions and understanding how these conditions develop, persist, and change.

Chikyu drilling of Pacific guyots, such as the Resolution Guyot between Wake and Midway Islands, can enable high-resolution studies of shallow-water ecosystems (atolls) and their response to known perturbations in the early Cretaceous period. These perturbations include ocean anoxic events, ocean acidification, and greenhouse climate conditions. *Chikyu* drilling in deep basins of the western Pacific Ocean (> 5,000 meters water depth) may recover sections from the mid-Cretaceous ocean anoxic events to define the vertical extent of anoxia. Coring of a complete section through Cretaceous and Jurassic sediments in the West Somali Basin, offshore the Horn of Africa, may provide an expanded archive of the climatic, oceanic and biosphere history of an area very poorly sampled so far. Water depths here are between 3,500-5,000 meters, and a penetration depth of 2,500 meters would be needed to recover the target sediments. Finally, the Ionian Abyssal Plain of the eastern Mediterranean might be the oldest *in situ* ocean fragment of the world, with ocean crust of late Triassic age. This location is key to fill the gap between the Tethys-Atlantic Ocean and the Indo-Pacific Ocean. *Chikyu* is the only platform capable of recovering such a thick and deeply buried Mesozoic section. However, this requires drilling in at least 4,000 meters of water depth and penetration to about 6,000 meters (Figure 18).

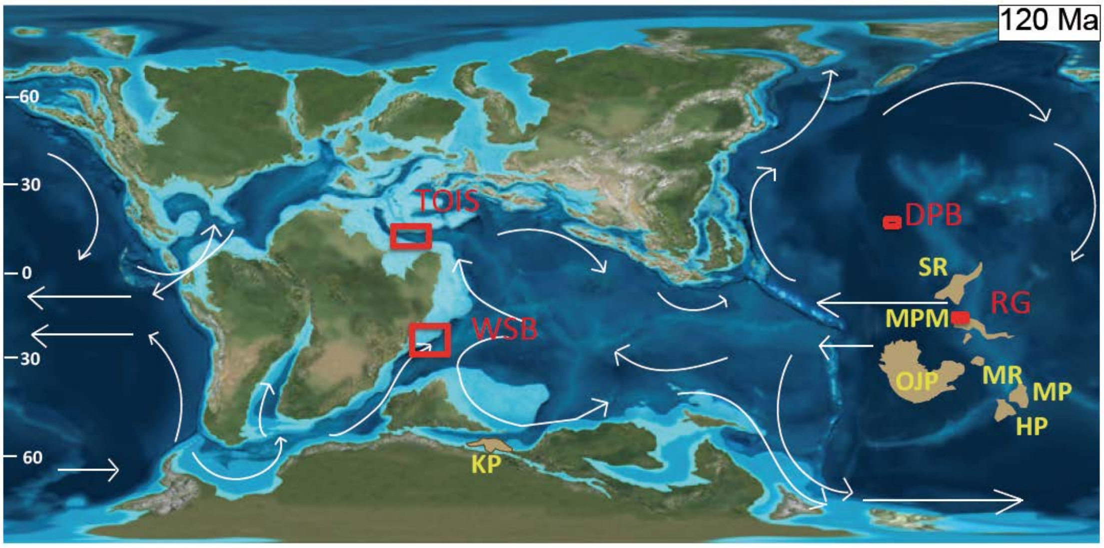


Figure 18. Palaeogeographic and oceanographic reconstructions of the Cretaceous world at about 120 Ma (source http://www2.nau.edu/rcb7/globaltext2.html). Key areas are in yellow: OJP=Ontong Java Plateau; SR=Shatsky Rise; MPM=Mid-Pacific Mountains; MR=Magellan Rise; MP=Manihiki Plateau; HP=Hikurangi Plateau; KP=Kerguelen Plateau. Key drilling areas proposed in the white papers are in red: TOIS=Tethys Ocean in Situ; WSB=West Somali Basin; DPB=Deep Pacific Basin; RG=Resolution Guyot. Figure modified from Erba (WP-1).

White Papers: Kuroda and Ohkouchi (WP-50), Ohkouchi and Kuroda (WP-52), Coffin (WP-45), Erba (WP-1).
Project Templates: PI-29, PI-44.

Potential Discovery Projects: Exploring climate change (Santa Barbara Basin, West Caroline Basin, Bohai Sea, and Dronning Maud Land)

Development of high quality, well-dated climate reference sites, spanning a broad and continuous range of climate conditions, is an essential prerequisite for testing hypotheses driving rapid climate change. These hypotheses include: (1) changes in deep and intermediate thermohaline circulation related to the Northern Hemisphere ice sheet and shelf ice instabilities; (2) changes in tropical heat distribution; and (3) increase in greenhouse gas concentrations in the atmosphere from reservoirs of CO_2 and CH_4.

Several white papers proposed using D/V *Chikyu* to access important climate records distributed around the world. Some relate to drilling natural archives found in marginal seas. One widely celebrated high-resolution archive is found in the Santa Barbara Basin. Previous riserless drilling there revealed a remarkable correlation between proxy climate records and the Greenland Ice Sheet record for the last 70,000 years (Figure 19). This record has not been extended further back in time with deeper drilling due to safety concerns in this known hydrocarbon area, but *Chikyu's* capabilities now make this feasible. The Bohai Sea is another high-resolution archive proposed for *Chikyu* drilling with similar objectives.

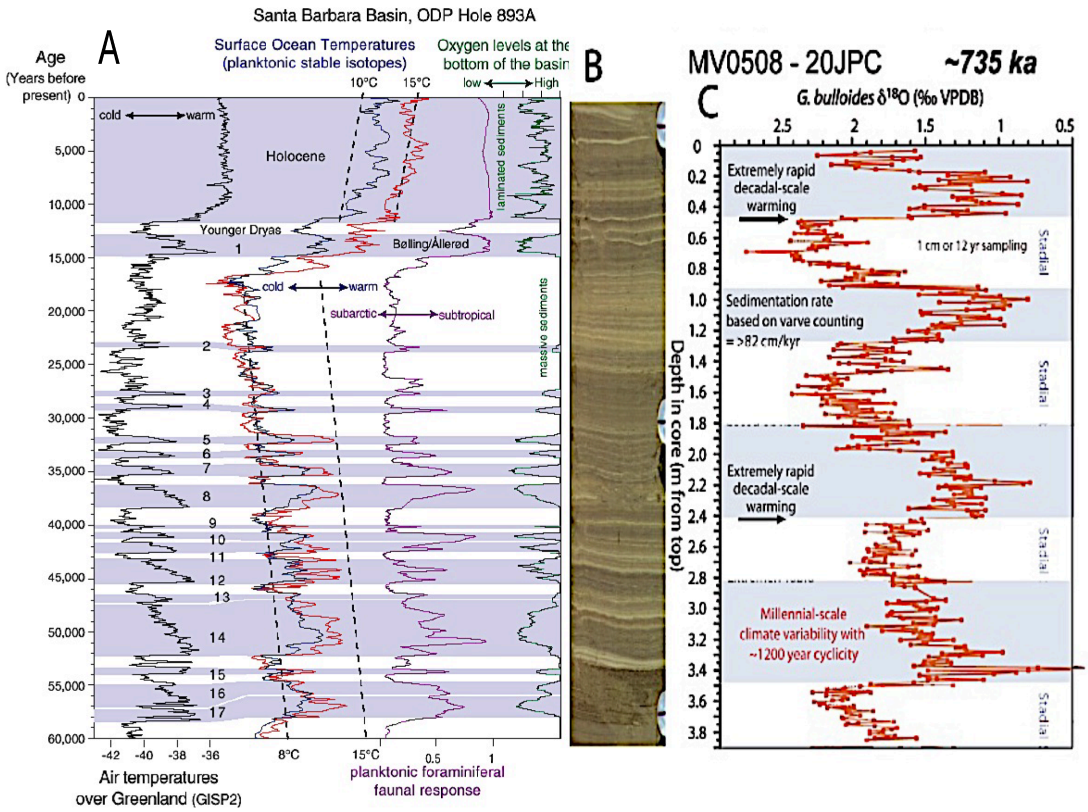


Figure 19. (A) Comparison of $\delta^{18}O$, planktonic assemblages, and laminations from ODP Site 893 in Santa Barbara Basin with air temperature over Greenland; (B) Section of Core MV0508-7 (~300,000 years ago) showing annual (varved) laminations; (C) isotopic record from Core MV0508-20 (~735,000 years ago) showing a distinct 1,200-yr stadial-interstadial oscillation that had not been previously recognized owing to a previous lack of paleoclimate data of comparable age and resolution. Figure from Behl *et al.* (WP-41).

Other climate-related white papers propose drilling in specific areas. For instance, the West Caroline Basin may contain the ideal paleointensity record of the geomagnetic field, and the Antarctica's margin at Dronning Maud Land may reveal the history and behavior of the East Antarctic ice sheet.

White Papers: Behl *et al*. (WP-42), Chen *et al.* (WP-44), Yamazaki *et al.* (WP-57), Suganuma *et al.* (WP-55).

Project Idea Templates: PI-3, PI-5, PI-24, PI-33.

CONCLUSIONS

Participants at the CHIKYU+10 Workshop identified many exciting areas where the Deep Sea Drilling Vessel *Chikyu* can contribute to major new discoveries about the dynamic Earth. These discoveries will enlighten us not only about our home planet, but also will provide insights into the deep mysteries of the cosmos, including the origin and nature of life itself. The Earth beneath the sea holds secrets about how the whole Earth behaves.

Workshop participants identified eight flagship (multi-year) projects that compare the nature and hazards of earthquake faults, explore the deep oceanic lithosphere and uppermost mantle while illuminating global geochemical cycles of carbon and hydrogen, examine how Earth differentiated its continental crust, scrutinize the rich planetary history preserved in seafloor sediments, and define the habitable zone of microbial life on Earth. Workshop participants additionally identified smaller scale projects that will actively address the challenges identified in *Illuminating Earth's Past, Present, and Future*, the science plan for 2013-2023 of the International Ocean Discovery Program: Exploring the Earth under the Sea. All projects highlighted in this Report require the unique capabilities of D/V *Chikyu* to control the drilling environment through its riser system and/or provide ultra-deep or hard-rock drilling in either riser or riserless mode. These projects cannot be fully realized by any other drilling platform.

The societal relevance of projects discussed at CHIKYU+10 has multiple dimensions. Flagship and other projects speak to the variation and underlying causes of earthquake and tsunami hazards, the emplacement mechanisms of valuable ore deposits, and the global balance and reservoirs of essential substances like carbon and hydrogen. Microbiological studies address the pervasiveness and energy balance of life on Earth and could eventually have implications for pharmaceuticals, energy, and the prospect of life elsewhere in the solar system and beyond. Work with sediment archives can offer a view of possible future climate scenarios in the Anthropocene, where societal behavior will increasingly affect our habitat on a planetary scale. As with many missions of fundamental discovery, eventual societal relevance could be serendipitous and unforeseen. Beyond health, safety, or direct economic return, any addition to the body of knowledge about the natural world increases the overall benefits of living in an informed and educated society.

Workshop discussions also emphasized how advances in engineering capability, investment in technology, and incorporation of new analytical methods will accelerate scientific discovery. Considering that several flagship projects will require drilling in water depths greater than 2,500 meters, an expanded-capability riser system is a necessary engineering improvement for the next decade. Improved drill bit technology will make ultra-deep hard rock drilling less time-consuming. Participants also recommended using *Chikyu* to define a new leading edge of biosphere research by investing in clean technology and incorporating automated methods of microbiological analysis for all samples, regardless of the primary science focus of the expedition. Long-term engineering and management planning and forward-looking policies that will maximize the potential for discovery are encouraged, and background work such as site surveys should begin now.

In conclusion, international scientists at the CHIKYU+10 Workshop clearly conveyed their vision and enthusiasm for new exploration by D/V *Chikyu* that are not achievable by other contemporary scientific ocean drilling platforms. The CHIKYU+10 Workshop Steering Committee endorses these community-identified projects and recommendations, and provides this report as background information for the Chikyu IODP Board and other decision-making entities. Acknowledging that the projects in totality will require more ship time than is anticipated to be available in the next decade, the Steering Committee advocates for this community perspective to be incorporated into long-term planning for D/V *Chikyu*, a unique and invaluable resource for discovery.

REFERENCES

Bascom, W. (1961). A Hole in the Bottom of the Sea: The Story of the MoHole Project, 352 pp, Doubleday & Co., New York.

DeBari, S.M., and A. Greene (2011). Vertical stratification of composition, density, and inferred magmatic processes in exposed arc crustal sections, in Brown, D., P. Ryan (eds.) Arc-continent collision, Frontiers in Earth Sciences, DOI 10.1007/978-3-540-88558-0_2, Springer-Verlag Berlin Heidelberg 2011, p. 121-144.

Dick, H.J.B., S. Arai, J.H. Natland, C. J. MacLeod, P.T. Robinson, M. Tivey, and the SloMo proponent group (2012). The Nature of the Lower Crust and Moho at Slower Spreading Ridges (SloMo), IODP proposal 808.

Kobayashi, R., Y. Yamamoto, and the Kanto Asperity proponent group (2006). Kanto Asperity Project: Geological and geophysical characterization of the source regions of great earthquakes and slow slip events, IODP proposal 707-MDP.

Moore, G.F., Kanagawa, K., Strasser, M., Dugan, B., Maeda, L., Toczko, S., and the IODP Expedition 338 Scientists, 2013. IODP Expedition 338: NanTroSEIZE Stage 3: NanTroSEIZE plate boundary deep riser 2: Scientific Drilling, No. 16 (in press).

Morono, Y., T. Terada, N. Masui, and F. Inagaki (2009). Discriminative detection and enumeration of microbial life in marine subsurface sediments. The ISME Journal 3:503–511.

Ranero, C., C. Marone, and the CRISP Program B proponents (2004). CRISP Program B: The transition from stable to unstable slip at erosional convergent plate boundaries, IODP proposal 537B-Full4.

Science Plan Writing Committee, INVEST Steering Committee, and Additional Contributors (2011), E. Kappel and J. Adams (eds). *Illuminating Earth's Past, Present, and Future, The International Ocean Discovery Program: Exploring the Earth under the Sea, Science Plan for 2013-2023*. Available at www.iodp.org/science-plan-for-2013-2023.

Schwartz, S.Y. (2007). Episodic aseismic slip at plate boundaries, Treatise on Geophysics, v.4, p. 445-469.

Tatsumi, Y., Kelly, K. *et al.* (2010). Continental crust formation at intra-oceanic arc: Ultra-deep drilling to the middle crust of the Izu-Bonin-Mariana Arc, IODP proposal 698-Full3.

Taylor, B., K. Fujioka, T.R. Janecek, and the Leg 126 Scientists (1992). Proc. ODP Vol 126 Sci Results, Texas A&M University, doi:10.2973/odp.proc.sr.126.1992.

Teagle, D., Ildefonse, B. (2011). Journey to the mantle of the Earth, Nature 471, 437–439. doi: 10.1038/471437a.

Teagle, D.A.H., Ildefonse, B., Blum, P., and the Expedition 335 Scientists (2012). Proc. IODP, Vol 335, IODP Management International, Inc., doi:10.2204/iodp.proc.335.2012

Umino, S., Ildefonse, B., P.B. Kelemen, S. Kodaira, K. Michibayashi, T. Moroshita, D.A.H. Teagle, and the MoHole proponents (2012). MoHole to the mantle (M2M), IODP proposal 805.

Wallace, L., Y. Ito, S. Henrys, P. Barnes, D. Saffer, S. Kodaira, H. Tobin, M. Underwood, N. Bangs, A. Fagereng, H. Savage, S. Ellis, and the Hikurangi Margin Working group (2013). Unlocking the secrets of slow slip by drilling at the northern Hikurangi subduction margin, New Zealand: Riser drilling to intersect the plate interface, IODP Proposal 781B.

APPENDIX 1
Steering Committee Members

Steering Committee Members

Mike Coffin (Chair); University of Tasmania
Wolfgang Bach; University of Bremen
Elizabetta Erba; University of Milan
Brian Horsfield; GFZ German Research Center of Geosciences
Benoit Ildefonse; University of Montpellier
Kenji Kato; Shizuoka University
Jun-Ichi Kimura; Japan Agency for Marine-Earth Science and Technology
Dick Kroon; University of Edinburgh
Lisa McNeill; University of Southampton
Kenneth Nealson; University of Southern California
Kyoko Okino; The University of Tokyo
Susan Schwartz; University of California, Santa Cruz
Nobukazu Seama; Kobe University
Sean Solomon; Columbia University
Brian Taylor; University of Hawaii
Kazuhiko Tezuka; Japan Petroleum Exploration Co., Ltd.
Pinxian Wang; Tongji University
Uli Harms; GFZ German Research Center of Geosciences
Casey Moore; University of California, Santa Cruz

APPENDIX 2
Workshop Program

Workshop schedule: CHIKYU+10 Workshop

	Sunday, 21 April	Monday, 22 April	Tuesday, 23 April
	ORIENTATION	PANELS: IDEAS EMERGE	DISCUSSION: PROJECTS EMERGE
09:00-09:10	Registration	Doors open 09:00	Doors open 09:00
09:10-09:30		Keynotes: Projects from IODP IBM (Tatsumi), CRISP (Ranero)	CHIKYU Project Implementation
09:30-10:00	Opening remarks by MEXT / JAMSTEC	Panel: Deep Life and Hydrothermal Systems	
10:00-10:30	Introduction to program; Chikyu Capabilities Talk		Scribe Reports
10:30-11:00	Break / Discussion		Break / Discussion
11:00-11:30	Panel: Chikyu's First 10 Years (Expedition Co-Chiefs)	Break / Discussion	Finish Scribe Reports and Instructions for Small Groups
11:30-12:00		Parallel Panels: Continent Formation / Sediment Secrets	
12:00-12:30			Working Lunch: Work in Small Groups on project templates
12:30-13:00	Lunch / Posters / Discussion		
13:00-13:30		Lunch / Posters / Discussion	
13:30-14:00			
14:00-14:30	Keynotes: Vane, Horsfield, Pandey, Nealson Theme Overviews (DL, HYD)	Parallel Panels: Active Faults / Ocean Crust and Earth's Mantle	Work in Small Groups; complete templates
14:30-15:00			
15:00-15:30			
15:30-16:00	Break / Discussion	Break / Discussion	Break / Discussion
16:00-16:30	Keynotes: Manning, Neal Theme Overviews (EM, AF)	Parallel Panels: Active Faults / Ocean Crust and Earth's Mantle	Discussion: Community Issues, Concerns, and Recommendations
16:30-17:00			
17:00-17:30			
17:30-18:00	Keynotes: Stern, Erba Theme overviews (CF,SS)	Short Break to re-align panels	JAMSTEC: Concluding Remarks
18:00-18:30		Panel: Active Faults	
18:30-19:00	Reception		
19:00-19:30			

NOTE

AF: Active Faults
EM: Ocean Crust and Earth's Mantle
CF: Continent Formation
SS: Sediment Secrets
DL: Deep Life
HYD: Hydrothermal Systems

CHIKYU+10 INTERNTIONAL WORKSHOP DAILY PROGRAM

Sunday, 21 April ***Doors Open at 09:00***

09:00 – 09:30: Registration; audience is seated by 09:30

09:30 – 10:00: (Logistical Announcements: 5 minutes)
Opening Remarks by MEXT and JAMSTEC
Moderator: Hitoshi Hotta, Executive Director, JAMSTEC

10:00 – 10:20: Introduction to the Deep-sea Drilling Vessel CHIKYU
Moderator: Wataru Azuma, Director, CDEX
Presenters: T. Saruhashi and CDEX staff

10:20 – 10:30: Introduction to Scientific Program / Goals of Workshop
Mike Coffin, Chair, CHIKYU+10 Steering Committee

10:30 – 11:00: Coffee Break / Discussion

11:00 – 12:30: **PANEL: CHIKYU's First 10 Years: Remarks by Expedition Co-Chiefs**
Moderator: Kiyoshi Suyehiro, President and CEO, IODP-MI
Panelists: H. Tobin (NanTroSEIZE), K. Takai (Exp 331),
F. Inagaki (Exp 337), J. Mori (Exp 343)

12:30 – 14:00: Lunch / Posters

14:00 – 15:30 **Keynote Talks and Theme Introductions**
Moderator: M. Coffin, University of Tasmania
NASA's Decadal Planning of Solar System Exploration
G. Vane, Caltech / Jet Propulsion Laboratory
Chikyu and ICDP: Partners in Scientific Drilling
B. Horsfield, GFZ German Research Centre for Geosciences
Scientific Drilling in the Indian Ocean to Unravel Complex Geo-Scientific Issues
D. Pandey, National Centre for Antarctic and Ocean Research, India
Microbial Expectations for the Marine Deep Subsurface
K. Nealson, University of Southern California
Workshop Theme Overview: Deep Life and Hydrothermal Systems
K. Kato, Shizuoka University and W. Bach, University of Bremen

15:30 – 16:00: ***Coffee Break / Discussion***

16:00 – 18:30: **Keynote Talks and Theme Introductions**
Moderator: M. Coffin
Exploring the Solar System with Scientific Ocean Drilling
C. Neal, University of Notre Dame
Ocean Crust / Mantle and the Deep Carbon Cycle
C. Manning, University of California, Los Angeles
Workshop Theme Overview: Ocean Crust and Earth's Mantle
J. Kimura, IFREE/JAMSTEC
Workshop Theme Overview: Active Faults
C. Moore, University of California, Santa Cruz
<Change Speaker Seating>
Challenges in Mesozoic Paleoceanography
E. Erba, University of Milan
Formation of Continental Crust at Convergent Margins
R. Stern, University of Texas at Dallas
Workshop Theme Overview: Sediment Secrets
D. Kroon, University of Edinburgh
Workshop Theme Overview: Continent Formation
K. Okino, University of Tokyo

19:00 – 20:45 **RECEPTION at Gakushi-kaikan**

CHIKYU+10 INTERNTIONAL WORKSHOP DAILY PROGRAM

Monday, 22 April ***Doors Open at 09:00***

09:10 – 09:30: **Keynote Talks: Projects from IODP**

Moderator: H. Given, Deputy to President, IODP-MI

Ocean Creates Continent: Deep Drilling in Izu-Bonin Margin

Y. Tatsumi, Kobe University and IFREE/JAMSTEC

Costa Rica Seismogenesis Project CRISP

C. Ranero, Barcelona Center for Subsurface Imaging, Spain

09:30 – 11:00: **Thematic Panels: Deep Life and Hydrothermal Systems**

Deep Biosphere Exploration
(30 min; Moderator K. Kato)
Panelists: H. Mills (119), R. Hayman (076), F. Inagaki (112), Takai (023)
Associated Posters: N. Xiao (090), Y. Morono (054), G. Ramirez (096)

Some Ideas on Hydrogen and Hydrocarbons
(30 min; Moderator K. Nealson)
Panelists: H. Tomaru (053), J. Kim (103), S. Kawagucci (033)

Hydrothermal Systems
(30 min; Moderator G. Wheat, Univ of Alaska Fairbanks)
Panelists: M. Jutzler (036), C. deRonde (122), C. Yeats (120), H. Kumagai (082)
Associated Posters: J. Ishibashi (097), T. Toki (035)

11:00 – 11:30: ***Coffee Break / Discussion***

11:30 – 13:00: **ATTENTION! 2 PARALLEL SESSIONS**

Thematic Panels: Continent Formation
11:30 – 13:00:
IBM4: Perspective and Strategy
(60 min; Moderators Y. Tamura and K. Kelley)
Panelists: Y. Tamura (013), S. Straub (074),
K. Kelley (046), H. Freymuth (071)
with Y. Tatsumi
<short discussion>
Panelists: A. Nichols (034), K. Takai (101),
J. Kimura (019)

Comparative Studies, Continent Formation
(30 min, Moderator R. Stern)
Panelists: B. Jicha (021), G. Yogodzinski (117),
O. Ishizuka (022), S. DeBari (038),
C. Busby (029)

Thematic Panels: Sediment Secrets
11:30 – 13:00:
Tectonics and Climate / Sedimentation
(20 min; Moderator G. Browne)
Panelists: R. Stern (089), X. Zhao (100),
G. Browne (124)

High-Resolution Climate Archives
(25 min; Moderator M. Chen)
Panelists: R. Behl (017), T. Yamazaki (083),
MT. Chen (024), Y. Suganuma (095)

Cretaceous Paleoceanography
(25 min; Moderator J. Kuroda)
Panelists: M. Coffin (057), N. Ohkouchi (018),
C. Foster (069), J. Kuroda (025)
with E. Erba

Sub-Salt Environments
(20 min; Moderator A. Camerlenghi)
Panelists: H. Daigle (028), A. Camerlenghi (067),
M. Rabineau (115)

13:00 – 14:00: ***Lunch / Posters***

General Posters: U. Udrekh (073), A. Rodnikov (010), S. Wu (042),
S. Planke (114), YG. Kim (104)

14:00 – 19:30: ATTENTION! 2 PARALLEL SESSIONS

Thematic Panels, Ocean Crust and Earth's Mantle
14:00 – 15:45:
Drilling to the Mantle; Ocean Plate Formation and Architecture Part 1
(45 min; Moderator N. Seama and B. Ildefonse)
Panelists: J. Natland (093), Y. Kawamura (123), S. Umino (015), J. Koepke (126), N. Akizawa (56)

Drilling to the Mantle; Ocean Plate Formation and Architecture Part 2
(60 min; Moderator E. Hellebrand)
Panelists: T. Fujiwara (040), J. Day (045), H. Dick (050), E. Hellebrand (085), Y. Ohara (052), Y. Harigane (059), T. Sato (061)

15:45 – 16:15: Coffee Break / Posters

16:15 – 17:45:
Ocean Plate Modification, Aging, and Recycling
(50 min; Moderator J. Morgan)
Panelists: N. Abe (098), K. Johnson (077), J. Morgan (011), T. Morishita (084), T. Sakuyama (094)

Large Igneous Provinces: Deep Mantle Dynamics and Environmental Impact
(45 min; Moderator C. Neal)
Panelists: T. Sano (008), M. Tejada (032), X. Zhao (002), C. Neal (047), F. Maeno (068)
Associated Posters: M. Nakanishi (055), S. Miura (060), T. Hanyu (058), H. Kawahata (113)

17:45 – 19:00:
Ocean Crust and Earth's Mantle Posters / Discussion
(or re-join Active Faults, Long-Term Monitoring panel)

Thematic Panels, Active Faults
14:00 – 15:30:
Investigating Slow Slip Events
(45 min; Moderators Y. Ito and L. Wallace)
Panelists: L. Wallace (030), Y. Ito (092), R. Kobayashi (105)
Associated Posters: R. Kobayashi (106) and T. Sato (031)

Japan Trench
(45 min; Moderators S. Kodaira and J. Sample)
Panelists: S. Kodaira (064), K. Ujiie (066), J. Sample (048), Hino (041), Hirose (039): 30 min
K. Ikehara (001), M. Strasser (063), T. Kanamatsu (102), Morita (110): 10 min
Associated Posters: K. Ikehara (001), M. Strasser (063), T. Kanamatsu (102), S. Morita (110)

15:30 – 16:00: Coffee Break / Posters

16:00 – 17:15:
Costa Rica Subduction Zone Studies
(40 min; Moderator P. Vannuchi)
Panelists: P. Vannuchi (003), A. Sakaguchi (107), Tanigawa (037), Protti (005) with C. Ranero

Faulting in Oceanic Crust
(30 min; Moderator: J. Mori)
Panelists: G. Fujie (079), P. Henry (128), J. Mori (78), A. Ishiwatari (108), X. Gao (088)

17:15 – 18:00 Break / Posters / Discussion

18:00 – 19:00:
4D Instrumentation and Long-Term Monitoring
(30 min; Moderator K. Becker)
Panelists: R. Hyndman (004), E. Davis (026), Y. Hashimoto (051), W. Lin (080)
Associated Posters: I. Song (116)

Nankai Trough Seismogenic Zone Experiment (NanTroSEIZE)
(30 min; Moderators G. Kimura and H. Tobin)
Panelists: G. Kimura (065), JO. Park (070), H. Tobin (075), E. Araki (111)
Associated Posters: M. Iwai (087), S. Horozal (091)

19:00 – 19:30:
Active Faults Posters / Discussion

APPENDIX 3

Workshop Attendees

List of attendees (Alphabetical order)

Name	Institution
Natsue Abe	IFREE, JAMSTEC
Jonathan Aitchison	University of Sydney
Norikatsu Akizawa	Department of Earth Sciences, Kanazawa University
James Allan	National Science Foundation
Ryo Anma	University of Tsukuba
Nobuhiro Anraku	Marine Works Japan
Kan Aoike	CDEX, JAMSTEC
Yuzo Arai	GEOPHYSICAL SURVEYING CO.,LTD.(GSC)
Yohei Arakawa	Marine Works Japan, Ltd.
Eiichiro Araki	JAMSTEC
Juichiro Ashi	University of Tokyo
Wataru Azuma	CDEX, JAMSTEC
Wolfgang Bach	University of Bremen
Chiharu Bada	CDEX, JAMSTEC
Masao Ban	Yamagata University
Rodey Batiza	NSF
Keir Becker	University of Miami - RSMAS
Jan Behrmann	GEOMAR, Kiel. Germany
Greg Browne	GNS Science
Cathy Busby	University of California at Santa Barbara
Timothy Byrne	University of Connecticut
Angelo Camerlenghi	OGS National Institute of Oceanography and Applied Geophysics Trieste Italy
Chanh Caominh	Schlumberger
Rebecia Jane Carey	University of Tasmania
Qing Chang	IFREE, JAMSTEC
Min-Te Chen	National Taiwan Ocean University
Yan Chen	China University of Geosciences
Hao Cheng	School of Ocean and Earth Science, Tongji University
Tae Woong Chung	Sejong University
Millard Coffin	IMAS/University of Tasmania
Hugh Daigle	University of Texas at Austin
James Day	Scripps Institution of Oceanography
Jan de Leeuw	NIOZ Royal Netherlands Institute for Sea Research
Cornel de Ronde	GNS Science
Susan DeBari	Western Washington University
Henry Dick	Woods Hole Oceanographic Institution
Hisashi Dobashi	JAMSTEC
Brian Dreyer	University of California, Santa Cruz
Katrina Edwards	university of southern california
Nobu Eguchi	CDEX, JAMSTEC

(Continued)

Guillermo Eichentopf	Halliburton
Elisabetta Erba	Dept. Earth Sciences, University of Milan, Milan, Italy
Jochen Erbacher	BGR Hannover, Germany
Oliver L. Fabbri	University of Franche-Comte France
Heye Freymuth	Bristol Isotope Group, University of Bristol
Gou Fujie	IFREE, JAMSTEC
Akihiko Fujihara	Marine Works Japan LTD.
Masakazu Fujii	The University of Tokyo
Toru Fujiki	Marine Works Japan
Hidtoshi Fujimori	JAMSTEC
Toshiya Fujiwara	IFREE, JAMSTEC
Rina Fukuchi	University of Tokyo
Akiko Fuse	CDEX, JAMSTEC
Hiroyuki Futamata	University of Shizuoka
Yuji Fuwa	Marine Works Japan Ltd.
Xiang Gao	Institute of Oceanology, Chinese Academy of Sciences
Biswajit Ghosh	Kanazawa University
Holly Given	IODP-MI
Shinya Goto	CDEX, JAMSTEC
Lallan Gupta	KCC/JAMSTEC
Morihisa Hamada	IFREE, JAMSTEC
Yohei Hamada	JAMSTEC
Mari Hamahashi	University of Tokyo
Sebastian Hammerschmidt	MARUM, University of Bremen
Takeshi Hanyu	IFREE, JAMSTEC
Yumiko Harigane	Geological Survey of Japan/AIST
Kihachi Hasebe	Press D/JAMSTEC
Yoshitaka Hashimoto	Kochi University
Kentaro Hatakeda	Marine Works Japan
Kiyoshi Hatakeyama	CDEX, JAMSTEC
Nicholas Hayman	Institute for Geophysics
Andrew Heap	Geoscience Australia
Eric Hellebrand	University of Hawaii
Pierre Henry	CEREGE (Aix-Marseille University and CNRS)
Stuart Henrys	GNS Science
Verena Heuer	MARUM , University of Bremen
Shinji Hida	CDEX, JAMSTEC
Kai-Uwe Hinrichs	University of Bremen, MARUM & Dept. of Geosciences
Yuka Hirahara	IFREE/JAMSTEC
Satoshi Hirano	Marine Works Japan, Ltd.
Takehiro Hirose	JAMSTEC Kochi
Yuya Hitomi	MARINE WORKS JAPAN LTD.

(Continued)

Senay Horozal	Korea Institute of Geoscience and Mineral Resources
Brian Horsfield	ICDP
Hiroshi Hoshino	Marine Works Japan, Ltd.
Tatsuhiko Hoshino	JAMSTEC
Hitoshi Hotta	JAMSTEC
Shu-Kun Hsu	Department of Earth Sciences, National Central University, Taiwan
Roy Hyndman	Pacific Geoscience Centre, Geol. Survey Canada
Mituteru Idehara	Unviersity of Tokyo
Chiaki Igarashi	CDEX, JAMSTEC
Eri Igata	Tokyo Insititute of Technology
Koichi Iijima	SRRP/JAMSTEC
Akira Ijiri	JAMSTEC
Ken Ikehara	Geological Survey of Japan, AIST
Minoru Ikehara	Kochi University
Daiji Ikenomoto	CDEX, JAMSTEC
Benoit Ildefonse	CNRS - Universite Montpellier 2
Hiroyuki Imachi	JAMSTEC
Ryo Imai	IGraduate School of Science, Tohoku University
Fumio Inagaki	JAMSTEC
Tomoya Inoue	CDEX, JAMSTEC
Jun-ichiro Ishibashi	Kyushu University
Teruaki Ishii	Fukada Geological Institute
Tsuyoshi Ishikawa	JAMSTEC Kochi
Akira Ishikawa	University of Tokyo/IFREE/JAMSTEC
Akira Ishiwatari	CNEAS, Tohoku University
Osamu Ishizuka	Geological Survey of Japan/AIST
Yoshio Isozaki	JAMSTEC
Yoshihiro Ito	Tohoku University
Masao Iwai	Kochi University
Thomas Janecek	US National Science Foundation
Tamara Jeppson	University of Wisconsin-Madison
Brian Jicha	University of Wisconsin-Madison
Francisco Jimenez-Espejo	Graduate School of Environmental Studies, Nagoya University
Kevin Johnson	University of Hawaii at Manoa
Martin Jutzeler	University of Otago, New Zealand; National Oceanographic Centre of Southampton, UK
Issa Kagaya	IODP-MI
Yuko Kambe	CDEX, JAMSTEC
Kyuichi Kanagawa	Chiba University
Toshiya Kanamatsu	IFREE, JAMSTEC
Kyoko Kanayama	Kanazawa University
Kyohei Kaneko	MEXT
Masahori Kaneko	JAMSTEC

(Continued)

Miriam Kastner	Scripps Institution of Oceanography
Sho Kataoka	CDEX, JAMSTEC
Kenji Kato	Shizuoka University
Hodaka Kawahata	Atmosphere and Ocean Research Institute, The University of Tokyo
Tatsuya Kawai	Marine Works Japan Ltd.
Kenji Kawamura	JAMSTEC (BG), NIPR
Yoshi Kawamura	IODP-MI
Daiki Kawata	Marine Works Japan LTD.
Tezuka Kazuhiko	JAPEX
Myra Keep	University of Western Australia
Katherine Kelley	Graduate School of Oceanography, University of Rhode Island
Yoshiki Kido	Marine Works Japan Ltd.
Yukari Kido	CDEX, JAMSTEC
Eiichi Kikawa	JAMSTEC
Hiroyuki Kikuta	CDEX, JAMSTEC
Jinwook Kim	Dept of Earth System Sciences, Yonsei University
Taewoon Kim	IODP-MI
Young-Gyun Kim	Seoul National University
Ken Kimlicka	Springer Japan KK
Gaku Kimura	The University of Tokyo
Jun-Ichi Kimura	IFREE, JAMSTEC
Yuzuru Kimura	MEXT
Hajimu Kinoshita	JAMSTEC
Masataka Kinoshita	KCC/JAMSTEC
Hiroko Kitajima	National Institute of Advanced Industrial Science and Technology
Yujin Kitamura	Dept. Earth and Planetary Sci., University of Tokyo
Manami Kitamura	Hiroshima University
Shomei Kobayashi	CDEX, JAMSTEC
Reiji Kobayashi	Kagoshima University
Shuichi Kodaira	IFREE, JAMSTEC
Jurgen Koepke	Leibniz Universitaet Hannover
Hiroaki Koge	The University of Tokyo
Mika Komatsu	University of Tokyo Press
Dirk Kroon	University of Edinburgh
Yusuke Kubo	CDEX, JAMSTEC
Hidenori Kumagai	IFREE/ Precambrian Ecosystem Lab., JAMSTEC
Shin'ichi Kuramoto	CDEX, JAMSTEC
Junichiro Kuroda	JAMSTEC
Koji Kusaka	Schlumberger
Yuki Kusano	Kanazawa University
Sang-Mook Lee	Seoul National University
Chao Li	Tongji University

(Continued)

Weiren Lin	JAMSTEC Kochi
Jiwen Liu	Ocean university of China
Guido Lueniger	German Research Foundation / ECORD
Qing Luo	Institute of Oceanology, Chinese Academy of Sciences
Kuo-Fong Ma	Department of Earth Sciences, National Central University, Taiwan
Shusuke Machida	CDEX/JAMSTEC
Hideaki Machiyama	Submarine Resources Res. Project, JAMSTEC
Lena Maeda	CDEX, JAMSTEC
Fukashi Maeno	Earthquake Research Institute, University of Tokyo
Craig Manning	Dept. of Earth and Space Sciences, University of California, Los Angeles
Hideki Masago	CDEX, JAMSTEC
Shigemi Matsuda	CDEX, JAMSTEC
Shiro Matsugaura	JAMSTEC/CDEX
Ryo Matsumoto	Meiji University
Tetsuo Matsuno	National Institute of Polar Research
Lisa McNeill	University of Southampton
Jun Meng	School of Earth Sciences and Resources, China University of Geosciences
Charna Meth	Consortium for Ocean Leadership
Katsuyoshi Michibayashi	Shizuoka University
Heath Mills	Texas A&M University
Seiichi Miura	IFREE, JAMSTEC
Motoyuki Miyamoto	Marine Works Japan LTD.
Eigo Miyazaki	CDEX, JAMSTEC
Takashi Miyazaki	IFREE, JAMSTEC
Shinichi Mizumoto	JAMSTEC
Kimihiro Mochizuki	Earthquake Research Institute, The University of Tokyo
Kyaw Moe	CDEX, JAMSTEC
Gregory Moore	University of Hawaii
James Moore	Univ California Santa Cruz
Jason Morgan	Royal Holloway, University of London
Sally Morgan	Borehole Research Group, University of Leicester
James Mori	Disaster Prevention Research Institute, Kyoto University
Tomoaki Morishita	Kanazawa University
Sumito Morita	Geological Survey of Japan, AIST
Soichi Moriya	Marine Works Japan
Yuki Morono	JAMSTEC Kochi
Yuichi Morozumi	Graduate University for Advanced Studies / KEK
Samuel Mukasa	University of New Hampshire
Hiroaki Muraki	Marine Works Japan Ltd.
Masafumi Murayama	Kochi University
Edward Murdy	National Science Foundation
Shigemi Naganawa	University of Tokyo, Frontier Research Center for Energy and Resources

(Continued)

Yasuyuki Nakamura	IFREE, JAMSTC
Yuki Nakamura	Atmosphere and Ocean Research Institute , The University of Tokyo
Jun-ichi Nakanishi	OYO Corporation, Instruments & Solutions Division
Masao Nakanishi	Graduate School of Science, Chiba University
Mariko Namiki	CDEX, JAMSTEC
James Natland	RSMAS University of Miami
Tomohisa Nawate	CDEX, JAMSTEC
Clive Neal	University of Notre Dame
Kenneth Nealson	University of Southern California
Alexander Nichols	IFREE, JAMSTEC
Craig Nicholson	University of California - Santa Barbara, USA
Shigako Nigi	Marine Works Japan
Hiroshi Nishi	Tohoku University
Masahiro Nishimura	Marine Works Japan Ltd.
Yoshiro Nishio	JAMSTEC
Tetsuo No	JAMSTEC
Taryn Noble	University of Tasmania
Yoshifumi Nogi	National Institute of Polar Research
Takuro Nunoura	JAMSTEC
Hirokuni Oda	Geological Survey of Japan, AIST
Jae Ho Oh	Korea Institute of Geoscience and Mineral Resources
Yasuhiko Ohara	Hydrographic and Oceanographic Department of Japan
Atsushi Ohashi	Marine Work Japan ltd.
Naohiko Ohkouchi	JAMSTEC
Hisashi Oiwane	National Institute of Polar Research
Takanori Ojima	Atmosphere and Ocean Research Institute, University of Tokyo
Yoko Okamoto	Marine Works Japan Ltd.
Kyoko Okino	Atmosphere and Ocean Research Institute, University of Tokyo
Hikaru Okutsu	JAMSTEC
Kentaro Omura	National Research Institute for Earth Science and Disaster Prevention
Kiyokazu Oohashi	Graduate School of Science, Chiba University, Japan
Shinji Oshima	JAMSTEC
Miyuki Otomo	IODP-Management International
Dhananjai Pandey	IODP-India, National Centre for Antarctic and Ocean Research, Goa, India
Jin-Oh Park	Atmosphere and Ocean Research Institute, University of Tokyo
Katerina Petronotis	IODP-USIO/Texas A&M University
Nicolas Pilisi	Blade Energy Partners
Werner Piller	Institute for Earth Sciences, University of Graz
Vivian Pistre	Schlumberger D&M
Sverre Planke	VBPR
Jorge Protti	OVSICORI-Universidad Nacional
Ning Qiu	South China Sea Institute of Oceanology

(Continued)

Marina Rabineau	CNRS Univ. Brest
Gustavo Ramirez	University of Southern California
Cesar Ranero	CREA at CSIC-ICM, Barcelona Center for Subsurface Imaging
Andrew Philip Roberts	Australian National University
Gideon Rosenbaum	The University of Queensland
Saneatsu Saito	IFREE, JAMSTEC
Satomi Saito	Marine Works Japan Ltd.
Arito Sakaguchi	JAMSTEC
Masumi Sakaguchi	Marine Works Japan Ltd.
Tetsuya Sakuyama	JAMSTEC
James Sample	Northern Arizona University
Kazuo Sano	SASC JAPAN INC
Takashi Sano	National Museum of Nature and Science
Tomokazu Saruhashi	CDEX, JAMSTEC
Takeshi Sato	IFREE, JAMSTEC
Tomoki Sato	JAMSTEC
Toshinori Sato	Graduate School of Science, Chiba University
Ikuo Sawada	CDEX, JAMSTEC
Ritsuko Sawada	MARINE WORKS JAPAN LTD.
C Schipper	IFREE, JAMSTEC
Jeffrey Schuffert	Consortium for Ocean Leadership
Susan Schwartz	University of California Santa Cruz
Elizabeth Screaton	University of Florida
Nobukazu Seama	Kobe University
Ryoko Senda	IFREE, JAMSTEC
Bunichiro Shibazaki	International Institute of Seismology and Earthquake Engineering, Building Research Institute
Toru Shigetomi	JAMSTEC
Mayuko Shimizu	University of Tokyo
Kenji Shimizu	IFREE, JAMSTEC
Kazuko Shinohara	National Science Foundation Tokyo
Masanao Shinohara	Earthquake Research Institute, The University of Tokyo
Yoshihisa Shirayama	JAMSTEC
Hiromichi Soejima	Marine Works Japan
Insun Song	Korea Institute of Geoscience and Mineral Resources
Teh-Ru Alex Song	IFREE, JAMSTEC
Gordon Southam	The University of Queensland
Ruediger Stein	Alfred Wegener Institute for Polar and Marine Research, Bremerhaven, Germany
Robert Stern	U Texas at Dallas
Michael Strasser	ETH Zurich
Susanne Straub	Lamont Doherty Earth Observatory of Columbia University
Daisuke Suetsugu	IFREE, JAMSTEC
Yusuke Suganuma	National Institute of Polar Research

(Continued)

Toshikatsu Sugawara	Marine Works Japan Ltd.
Takamitsu Sugihara	CDEX, JAMSTEC
Hiroko Sugioka	JAMSTEC
Kazuhiro Sugiyama	Marine Works Japan Ltd.
Zhilei Sun	Qingdao Institute of Marine Geology
Kiyoshi Suyehiro	IODP Management International
Katsuhiko Suzuki	IFREE, JAMSTEC
Takahiro Suzuki	Marine works japan LTD.
Yohey Suzuki	The University of Tokyo
Jason Sylvan	University of Southern California
Asahiko Taira	JAMSTEC
Arata Takahashi	CDEX, JAMSTEC
Kazuma Takahashi	Marine Works Japan Ltd.
Toshiro Takahashi	IFREE, JAMSTEC
Ken Takai	JAMSTEC
Yoshinori Takano	JAMSTEC
Koji Takase	CDEX, JAMSTEC
Eiichi Takazawa	Niigata University
Omata Tamano	CDEX, JAMSTEC
Takamasa Tamura	JAMSTEC
Yoshihiko Tamura	IFREE, JAMSTEC
Aki Tanaka	CDEX, JAMSTEC
Tomoyuki Tanaka	Marine Works Japan Ltd
Kenichiro Tani	IFREE, JAMSTEC
Noritaka Taniguchi	CDEX, JAMSTEC
Wataru Tanikawa	JAMSTEC Kochi
Masaharu Tanimizu	JAMSTEC
David Tappin	British Geological Survey
Kenji Tara	Atmosphere and Ocean Research Institute
Yoshiyuki Tatsumi	Kobe University
Brian Taylor	SOEST, University of Hawaii
Maria Luisa Tejada	IFREE, JAMSTEC
Harold Tobin	University of Wisconsin - Madison
Sean Toczko	CDEX, JAMSTEC
Tomohiro Toki	University of the Ryukyus
Hidekazu Tokuyama	Kochi University
Hitoshi Tomaru	Department of Earth Sciences, Chiba University
Masako Tominaga	Michigan State University
Mitsuhiro Toriumi	JAMSTEC
Takeshi Tsuji	WPI-I2CNER, Kyushu University
Hiroshi Tsuruoka	Earthquake Research Institute, The University of Tokyo
Joanne Tudge	University of Wisconsin-Madison

(Continued)

Shouting Tuo	The IODP-China Office/Tongji University, Shanghai, China
Udrekh Udrekh	Agency for The Assessment and Application of Technology - Indonesia
Shigehito Uetake	Mantle Quest Japan, Co., Ltd.
Kohtaro Ujiie	University of Tsukuba
Keita Umetsu	CDEX, JAMSTEC
Susumu Umino	Department of Earth Sciences, Kanazawa University
Mariko Uno	JAMSTEC
Bogdan Vaglarov	IFREE, JAMSTEC
Gregg Vane	Jet Propulsion Laboratory, California Institute of Technology
Paola Vannucchi	Royal Holloway, University of London
John Walker	Schlumberger Drilling Domain for East Asia and China GeoMarkets
Laura Wallace	University of Texas, Institute for Geophysics
FengPing Wang	Shanghai JiaoTong University
Pinxian Wang	Tongji University
Chris Ward	BAKER HUGHES
Yoshiyasu Watanabe	School of Marine Science and Technology, Tokai University
Charles Wheat	University of Alaska Fairbanks
William Whitney	Blade Energy Partners
Dean Wilson	University of Southampton
Hung Yu Wu	JAMSTEC
Shiguo Wu	Institute of Oceanology, Chinese Academy of Sciences
Nan Xiao	JAMSTEC Kochi
Toshikuni Yabuki	Marine Works Japan Ltd.
Kazuhiro Yagasaki	Atmosphere and Ocean Research Institute, University of Tokyo
Yasuhiro Yamada	Kyoto University
Yasuo Yamada	CDEX, JAMSTEC
Asuka Yamaguchi	Atmosphere and Ocean research Institute, The University of Tokyo
Yasuhiko Yamaguchi	The University of Tokyo
Michiko Yamamoto	IODP-MI
Aiko Yamamoto	JAMSTEC
Kaji Yamamoto	Japan Oil, Gas and Metals National Corporation/JOGMEC
Nagisa Yamamoto	Marine Works Japan
Toshiya Yamamoto	GEOPHYSICAL SURVEYING CO.,LTD.(GSC)
Yuzuru Yamamoto	IFREE, JAMSTEC
Yuhji Yamamoto	Kochi University
Makoto Yamano	Earthquake Research Institute, University of Tokyo
Masaoki Yamao	CDEX, JAMSTEC
Mikiya Yamashita	IFREE, JAMSTEC
Toshitsugu Yamazaki	Atmosphere and Ocean Research Institute, University of Tokyo
Quanshu Yan	First Institute of Oceanography, State Oceanic Administration
Duoxing Yang	Institute of Crustal Dynamics,Chinese Earthquake Administration
Shouye Yang	Tongji University

(Continued)

Yang Yang	Guangzhou Institute of Geochemistry, Chinese Academy of Sciences
Masaru Yasunaga	Marine Works Japan, Ltd.
Gregory Yaxley	The Australian National University
Christopher Yeats	CSIRO Earth Science and Resource Engineering, Australia
Gene Yogodzinski	University of South Carolina
Takahiro Yokoyama	CDEX, JAMSTEC
Yusuke Yokoyama	Atmosphere and Ocean Research Institute, University of Tokyo
Toshihiro Yoshimura	JAMSTEC
Xiang Zeng	The third institute of oceanography,SOA,PRCHINA
Ai Zhang	Guangzhou Institute of Geochemistry, Chinese Academy of Sciences
Jie Zhang	Xia Men University
Qiang Zhang	South China Sea Institute of Oceanology, Chinese Academy of Sciences
Xiaohua Zhang	Ocean University of China
Xixi Zhao	University of California Santa Cruz

APPENDIX 4
Project Ideas

Chikyu +10 Workshop: Drilling Project Idea

Workshop Theme (*bold/italicize* main theme and underline other relevant themes)			
AF (Active Faults), OC/EM (Ocean Crust/Earth's Mantle), CF (Continent Formation), SS (Sediment Secrets), DL (Deep Life), HYD (Hydrothermal Systems)			
Project Title: Drilling the Seismogenic Zone of Large Subduction Earthquakes off Nicoya Peninsula, Costa Rica			
Affiliated proposal? Yes (number) Not Yet			
Contact Person and Principal Supporters			
Marino Protti (Universidad Nacional, Costa Rica) (OVSICORI-UNA) Yoshiyuki Kaneda (JAMSTEC)			
Scientific Objectives and Global Impact			
Penetrate the source of large interplate subduction earthquakes to better understand the process that originate catastrophic failure at these plate interfaces. Sample the interface and instrument the fault zone. Contribute to earthquake potential assessment and earthquake prediction. Sample also the source of slow slip events, tectonic tremor, low frequency and very low frequency events on the updip limit of the seismogenic zone at a subduction zone with fast convergence rate.			
Site Coordinates	**Approximate Water Depth (m)**	**Approximate Penetration Depth**	
		Sediment (m)	**Basement (m)**
9.6 N, 85.5 W	1000 mbsl	1000	4500
Rationale for Deep Drilling			
The source of large (Mw>7.0) subduction earthquakes lies beyond non-riser drill capabilities and there are very few regions in the world where it can be reach even with riser drilling. The Nicoya segment of the Middle American Trench off Nicoya peninsula, in Costa Rica is one of them and logistically easy with year round conditions for drilling. The shallow portion of the seismogenic zone at this segment of the Middle American Trench also generates slow slip earthquakes, tectonic tremor, low frequency and very low frequency events. While the deeper portion ruptured in 2012 with a Mw=7.6 earthquake, this shallow portion remains locked.			
Technical Challenges (if already known)			
None known. Potential for a shallow underthrust earthquake to occur at the site while drilling.			
Potential for Discovery and Societal Relevance			
Water content on the plate interface and its role in earthquake generation is one of the key parameters that could help understand the processes that combined results in the genesis of large earthquakes. Sampling the lithology and physical properties and state of the fault zone at the seismogenic zone of large earthquakes in subduction zones can advance the understanding of earthquake occurrence and contribute to earthquake prediction. Monitoring the changes in the fault conditions, fluid flow and deformation in and around the fault zone will help comprehend the processes that lead to failure at the fault.			

Chikyu +10 Workshop: Drilling Project Idea

Workshop Theme (*bold/italicize* main theme and underline other relevant themes)

AF (Active Faults), OC/EM (Ocean Crust/Earth's Mantle), CF (Continent Formation), SS (Sediment Secrets), DL (Deep Life), HYD (Hydrothermal Systems)

Project Title: Plate bending and Serpentinization of the crust and upper mantle near the Costa-Rica-Nicaragua Trench.

Affiliated proposal? Yes (number) Not Yet **x**

Contact Person and Principal Supporters

Miriam Kastner, I expect the following to be strong supporters, but have to discuss it with them: P. Vannicchi, C. Ranero, R. Hyndman, j. Morgan

Scientific Objectives and Global Impact

To determine the rate and extent of the serpentinization process of the incoming oceanic crust and upper mantle, caused by plate bending and faulting near the trench. It has major implications on the water budget in the subduction zone and on the physical properties of the incoming plate. as well as on the global water cycle and the deep biosphere. It will require drilling a deep hole with CHIKYU into the mantle just before the trench.

Site Coordinates	Approximate Water Depth (m)	Approximate Penetration Depth	
		Sediment (m)	Basement (m)
~ 8.5° N and ~ 84° W	~3 km, too deep for the present CHIKYU	~400 m	> 3 km

Rationale for Deep Drilling

The depth of penetration in ocean crust and mantle will require a ship with the capabilities CHIKYU has. The depth of penetration of seawater through the bending faults and the % hydration of the ocean crust and upper mantle will have to be determined.

Technical Challenges (if already known)

Drilling in ~ 3 to 3.5 km of water depth.

Potential for Discovery and Societal Relevance

The importance of serpentinization near trenches, the amount of water involved, thus the amount of water available for deep cycling in subduction zones and the impact of this process on the global water cycle. In addition, the implication of serpentinization on seismogenic zone behavior.

Chikyu +10 Workshop: Drilling Project Idea

Workshop Theme (*bold/italicize* main theme and <u>underline</u> other relevant themes)

AF (Active Faults), OC/EM (Ocean Crust/Earth's Mantle), CF (Continent Formation), ***SS (Sediment Secrets)***, DL (Deep Life), HYD (Hydrothermal Systems)

Project Title: Evolution of the East Antarctic Ice Sheet and Southern Ocean at Dronning Maud Land, Antarctica

Affiliated proposal? Yes (number) Not Yet

Contact Person and Principal Supporters

Yusuke Suganuma (National Institute of Polar Research)

Scientific Objectives and Global Impact

(1) The history and behavior of the East Antarctic ice sheet (EAIS) at Dronning Maud land, (2) The responses of the Antarctic Circumpolar Current (ACC) and Weddel Gyre (WG) to the evolution of the EAIS and Southern Ocean, (3) Tectonic influences on climatic changes.

Site Coordinates	Approximate Water Depth (m)	Approximate Penetration Depth	
		Sediment (m)	Basement (m)
25°58'E, 66°32'S (RL)	4500 m	2500 m	0 m
33°50'E, 66°6'S (GR)	1000 m	500 m	~50 m
3°06'E, 64°31'E (689)	2080 m	400 m	~50 m
5°1'E, 53°2'S(1094)	2800 m	800 m	~50 m
11°30'E, 68°15'S{AR}	1700 m	500 m?	~50 m

Rationale for Deep Drilling (Chikyu)

Stable platforms against the rough southern seas and more developed drilling technology, for example, the Chikyu riser drilling vessel, make it possible to obtain deep (long) continental glacial marine sedimentary sequences with excellent core recovery.

Technical Challenges (if already known)

These historical drilling projects on Antarctica's margins have been hampered by the technological challenges associated with achieving adequate core recovery in inhomogeneous glacial marine sedimentary sequences in very strong consolidated sediments such as porcellanites or diamictites intercalated with highly porous biosiliceous one.

Potential for Discovery and Societal Relevance

The key scientific objectives will reveal the role of the Antarctic cryosphere, the dynamics of the EAIS, and its future stability in a high CO_2 world. These issues are urgently needed from both a scientific and societal point of view.

Chikyu +10 Workshop: Drilling Project Idea

Workshop Theme (*bold/italicize* main theme and underline other relevant themes)

OC/EM (Ocean Crust/Earth's Mantle)

Project Title: Deep crustal architecture of a dying backarc spreading segment at Godzilla Megamullion

Affiliated proposal? Not Yet **(in fact, it has been deactivated)**

Contact Person and Principal Supporters

Contact: Y.Ohara (Hydrographic & Oceanographic Dept. Japan)
Supporters: J.E. Snow (Univ. Houston), H.J.B. Dick (WHOI), K. Michibayashi (Shizuoka Univ.), Y. Harigane (Geological Survey of Japan)

Scientific Objectives and Global Impact

Objectives: To obtain the first 3D view of a backarc basin lithosphere at Godzilla Megamullion

Global impact: A significant fraction of the ocean floor is created in backarc basins. The opportunity to explore the formation of the backarc basin lower crust and upper mantle is, therefore, an important contribution to the overall geology of the ocean basins. At the same time, much of our understanding of all ocean crust comes from ophiolites, most of which are thought to have at least some arc/backarc component. A better understanding of the construction of backarc basin crust and its relationship to the upper mantle will thus greatly aid in the interpretation of the results of ophiolite analog studies and their relevance to the creation of the oceanic crust.

Site Coordinates	Approximate Water Depth (m)	Approximate Penetration Depth	
		Sediment (m)	Basement (m)
To be determined			

Rationale for Deep Drilling

Currently, we are planning to propose multiple bit-to-destruction holes on the Godzilla Megamullion. Since the Godzilla Megamullion is the world's largest oceanic core complex, multiple coring (i.e., off-set drilling) along the Godzilla detachment fault will maximize the opportunity to achieve the objectives.

Technical Challenges (if already known)

Although there are the areas with ~2500 m water depth, the water depth of most parts of the Godzilla Megamullion varies from 4000 m to 6000 m. So, the deep-water depth is one of the technical challenges.

Potential for Discovery and Societal Relevance

We will see the first 3D view of a backarc basin lithosphere. In addition, this proposal will accomplish several related goals of M2M proposal, i.e., understanding the nature of MOHO, and will prepare the way for drilling a future total penetration hole elsewhere, giving a preview of the mineralogy, structures, hydrology and drilling conditions to be encountered at the lower levels of the oceanic crust. Furthermore, the Godzilla site will become the 4^{th} reference site of ocean lithosphere, succeeding to Hess Deep, Atlantis Bank, and Atlantis Massif.

Chikyu +10 Workshop: Drilling Project Idea

Workshop Theme (*bold/italicize* main theme and underline other relevant themes)

***SS (Sediment Secrets)*: High Resolution Climate Archives**

Project Title: Understanding Past Warm Climate Dynamics by Drilling the Bohai, Yellow Sea, and East China Sea

Affiliated proposal? Not Yet

Contact Person and Principal Supporters

Min-Te CHEN (National Taiwan Ocean University, Taiwan); Xuefa SHI (First Institute of Oceanography, SOA, China)

Scientific Objectives and Global Impact

Understanding the climate dynamics of past warm climate periods is essential in unraveling why and how the present warm climate has been persisted for ~10,000 years. Reconstructing the full spectrum of warm climate dynamics is required, in particular, to predict how the Earth's climate will evolve naturally with unprecedented anthropogenic influences by the increased greenhouse gases. Recent analysis on past interglacials in the past 1 My shows complex interactions among solar insolation, atmospheric pCO_2, and southern ocean ventilation. However, Most of the interglacial analysis relied on marine oxygen isotopes, which inherit inalienable effects from temperature and salinity. Searching for more robust estimates for past sea level would provide newly independent data to consolidate the rationales of such data/model analysis for past interglacials. The marine sediments preserved in western Pacific marginal seas (e.g. East China Sea, Yellow Sea, Bohai Sea) provide such natural archives for reconstructing and understanding past warm climate (interglacials). Marine transgressions caused by glacio-eustatics during past warm climate in the past 2-3 Myr help deposit high sedimentation rate mud sediments. The mud drifts contains multiple paleoclimatic proxies, and under the best, newly advanced age constraint methods (geomagnetisms, biostratigraphy, and radiogenic dating), will be able to use as high-resolution marine climate records of orbital, millennial/centennial to multi-decadal time scale. New IODP riser drilling down to few hundred meters into the mud sediments, where natural oil and gas are also possibly formed, will help obtain highly recovered, new marine sea-level and climate records from the areas. The mud sediment records from the western Pacific marginal seas are proposed here to drill and could be used to evaluate what roles, for example, the Kuroshio, PDO, and ENSO had been played in interacting or impacting the warm global climate since early Quaternary.

Site Coordinates	Approximate Water Depth (m)	Approximate Penetration Depth	
		Sediment (m)	Basement (m)
1. 38°N 120°E 2. 34°N 124°E	500-1000m	400m	unknown

Rationale for Deep Drilling
To recover sediment sequences deposited since ~2Ma during which global ice volume has been varied quasi-periodically, and with the drilling, to reconstruct past sea level changes by drilling a depth transect of cores along 500-1000m water depth, and by analyzing proxies of sedimentological, micropaleontological, and geochemical/physical properties. Precise measurements on paleomagnetic secular variations on the cores are required.
Technical Challenges (if already known)
Prevent potential gas and oil blowouts; stiff coarser sediments interbedded with soft silty mud layers.
Potential for Discovery and Societal Relevance
Provide more precise, independent estimates for past global ice volume changes by sea level reconstruction. The reconstruction will advance our understanding on what fundamental processes have been responsible for varied intensity and duration of past interglacials (for example, why MIS 7 was short and MIS13 has been prolonged but relatively cool; why Mid-Brunhes?). The sea level data will be compared with modeling to gain further insights on the controlling processes of the interglacials, increasing dialogues and cooperation between paleo-data observers and paleoclimate modelers. The core analysis needs closer cooperation with paleomagnetic scientists for maintaining highest quality of paleomagnetic age models. The analysis of past interglacisl will provide clues on why our present interglacial has been persisted for more than 10,000 years and how it will continue to evolve in the future with the anthropogenic interferences by input of fossil fuel greenhouse gases.

Chikyu +10 Workshop: Drilling Project Idea

Workshop Theme (*bold/italicize* main theme and <u>underline</u> other relevant themes)
AF (Active Faults), ***OC/EM (Ocean Crust/Earth's Mantle)***, CF (Continent Formation), SS (Sediment Secrets), DL (Deep Life), HYD (Hydrothermal Systems)
Project Title Potential temperature of mantle plumes as sensed by mineral chemistry in primitive lavas from LIPs
Affiliated proposal? Yes (number) ***Not Yet***
Contact Person and Principal Supporters
A/Prof Greg Yaxley, Research School of Earth Sciences, The Australian National University, Canberra ACT 0200 (E: greg.yaxley@anu.edu.au)
Scientific Objectives and Global Impact

The current paradigm for formation of LIPs such as the OJP involves mantle thermal anomalies in the form of hot mantle plumes upwelling from the core-mantle boundary. Plumes may have temperature excesses (relative to ambient mantle adiabat) of ≈200 °C or more. Alternative models involve extensive partial melting of refertilised mantle domains, which may include recycled components (eclogite, pyroxenite) and/or volatile components, at temperatures closer to the ambient adiabat, possibly involving upwelling of partially molten diapirs (Green et al., 2001; Yaxley, 2000; Yaxley et al., 1998). However, the plume hypothesis is not universally accepted; a minimum requirement to invoke it is evidence of high temperatures in the erupted products. The aim of this proposal is to test the "mantle plume" hypothesis by determining the temperatures of magmas parental to those constituting the OJP. High temperatures in lavas should be recorded by olivine phenocryst and quenched glass compositions.

The OJP is a major LIP in the southwest Pacific, which has been barely sampled by ocean drilling. The near-surface zone of this massive, 30 km thick section of oceanic crust has been drilled but is strongly altered and samples do not preserve the primary lava mineralogy or compositions. Deeper drilling using Chickyu may recover fresh, olivine-phyric material, which could be used to estimate reliable parental melt compositions. These can then be combined with data from experimental petrology and thermodynamics to determine melting pressures and temperatures in the mantle. By analogy with other LIPs such as continental flood basalt provinces and based on high pressure peridotite melting experiments, picritic lavas should be present in the volcanic sequence, particularly if magma-genesis occurred at the very high temperatures implied by the mantle plume hypothesis. Volatile contents of lavas are also important as they will suppress lavas' liquidus temperatures and this could be determined by FTIR or ion-probe on fresh glasses erupted at depth and quenched under high water pressure, or on melt inclusions trapped in primitive phenocryst phases (olivine, Cr-spinel) (Kamenetsky, 1996; Yaxley et al., 2004). Geochemistry of the estimated parental melts (major and trace elements, radiogenic isotopes) will constrain the nature of the source lithologies. Fe K-edge XANES (synchrotron) techniques (Berry et al., 2003) can also be applied to primitive glasses recovered to determine $Fe^{3+}/\sum Fe$ of quenched melts. This will enable calculation of oxygen fugacity of magmas, but knowledge of lava Fe^{3+} content is also critical in using primitive olivine compositions to precisely determine parental melt compositions. Oxygen fugacity is critical in understanding the potential speciation and role of fluids that may have been involved in magma genesis in the magmas' source regions and which may have out-gassed during eruption.

Site Coordinates	Approximate Water Depth (m)	Approximate Penetration Depth	
		Sediment (m)	Basement (m)
Ontong Java Plateau, near the margins of the area of thickened oceanic crust	?	?	?

Rationale for Deep Drilling

To drill through material which is altered by seawater interaction and hopefully recover fresh, olivine-phyric and glass-bearing lavas.

Technical Challenges (if already known)

Potential for Discovery and Societal Relevance

If fresh and primitive material is recovered there is a very significant potential for constraining potential temperatures of LIP producing mantle plumes and the lithological and chemical nature of the source region. This is a critical component in our understanding of mantle dynamic and evolution, as well as development of oceanic lithosphere.

References

Berry, A.J., O'Neill, H.S.C., Jayasuriya, K.D., Campbell, S.J., Foran, G.J., 2003. XANES calibrations for the oxidation state of iron in a silicate glass. Am Mineral 88, 967-977.

Green, D.H., Falloon, T.J., Eggins, S.M., Yaxley, G.M., 2001. Primary magmas and mantle temperatures. Eur J Mineral 13, 437-451.

Kamenetsky, V., 1996. Methodology for the study of melt inclusions in Cr-spinel, and implications for parental melts of MORB from FAMOUS area. Earth Planet Sc Lett 142, 479-486.

Yaxley, G.M., 2000. Experimental study of the phase and melting relations of homogeneous basalt plus peridotite mixtures and implications for the petrogenesis of flood basalts. Contrib Mineral Petr 139, 326-338.

Yaxley, G.M., Green, D.H., Kamenetsky, V., 1998. Carbonatite metasomatism in the southeastern Australian lithosphere. J Petrol 39, 1917-1930.

Yaxley, G.M., Kamenetsky, V.S., Kamenetsky, M., Norman, M.D., Francis, D., 2004. Origins of compositional heterogeneity in olivine-hosted melt inclusions from the Baffin Island picrites. Contrib Mineral Petr 148, 426-442.

Chikyu +10 Workshop: Drilling Project Idea

Workshop Theme (*bold/italicize* main theme and underline other relevant themes)

AF (Active Faults), ***OC/EM (Ocean Crust/Earth's Mantle)***, CF (Continent Formation), SS (Sediment Secrets), DL (Deep Life), HYD (Hydrothermal Systems)

Project Title **M2M: Moho to the Mantle**

Affiliated proposal? Yes (1)

Contact Person and Principal Supporters

Katsuyoshi Michibayashi.
Susumu Umino, Benoît Ildefonse, Peter B. Kelemen, Shuichi Kodaira, Tomoaki Morishita, Damon A.H. Teagle

Scientific Objectives and Global Impact

For the first time, the MoHole to the Mantle (M2M) project will sample upper mantle peridotites that in the near geological past resided in the convecting mantle, and recently (~20 to 100 Myrs) underwent partial melting at a fast-spreading mid-ocean ridge. This will be achieved by drilling through intact fast-spread oceanic crust and ~500 m into the mantle lithosphere. This first in-situ sampling of fresh upper mantle rocks will provide hitherto unattainable information on the chemical and isotopic composition (including fluid mobile components K, U, C, S, H_2O, CO_2, noble gases), physico-chemical conditions (e.g., fO_2, fS), seismic velocities and other physical properties, paleomagnetic and rock magnetic properties, deformation and rheology, and the scales of chemical, magnetic, and physical heterogeneity of the uppermost mantle. This information is essential to understand the formation and evolution of Earth, its internal heat budget, planetary differentiation and reservoir mixing by mantle convection, mantle melting, and melt focusing and transport at mid-ocean ridges.

Site Coordinates	Approximate Water Depth (m)	Approximate Penetration Depth	
		Sediment (m)	Basement (m)
Case1:Cocos Plate 6.7-8.7°N 89.5-91.9°W	3400-3650	250-300	>6000
Case2:Off southern/Baja California 20-33°N 120-127°W	Mostly 4000-4500	80-130	>6000
Case3: NE Hawaiian Arch 22.9-23.9°N 154.5-155.8°W	4050-4500	~200	>6000

Rationale for Deep Drilling

Fast spreading ocean crust is targeted because it exhibits relatively uniform bathymetry and seismic structure, and is representative of the great majority of crust recycled back into the mantle by subduction during the past 200 Myrs. The M2M project echoes long-term goals of Earth scientists since the late 1950's, to understand the oceanic lithosphere. To date, the elusive frontier at the Moho, and the enormous mantle domain beneath, have been symbolic, unattainable goals. However, with the riser-drilling vessel Chikyu, the aspirations of generations of Earth scientists to drill completely through the oceanic crust and into the upper mantle, ~6 km below seafloor, have moved into the realm of technical feasibility. The ultradeep hole (MoHole) will reach a zone which has been more inaccessible and less well known than the surface of the Moon, to address first-order questions about the composition and structure of the Earth's convecting mantle, the geological nature of the Mohorovičić Discontinuity (Moho), the formation and evolution of oceanic crust, and the deep limits of life. The M2M proposal provides the scientific justification for drilling a >6000 m borehole to the mantle. This rationale has been developed by six workshops since 2006 and integrated into the proposal, which summarizes the current state of the art and vision for engineering, technology, and operations necessary to achieve the objective. M2M directly addresses Challenges 6, 8, 9 and 10 of the 2013-2023 IODP Science Plan. Drilling the first MoHole will be a challenging enterprise requiring space-mission-levels of detailed planning and engineering. The depth of the required borehole is far beyond depths reached so far in ocean crust using conventional non-riser drilling. Industry commonly drills deeper beneath the seafloor, but the required water depth, the hardness of the formations encountered, and the temperature at the MoHole exceeds current industry thresholds. However, new technology exemplified by ongoing development of the Chikyu ultra-deep drilling vessel is arguably at the point where a framework for the operations can be constructed. A site for mantle drilling has yet to be selected; three potential target regions await additional site surveys.

Technical Challenges (if already known)

The M2M proposal provides the scientific justification for drilling a >6000 m borehole to the mantle. This rationale has been developed by six workshops since 2006 and integrated into the proposal, which summarizes the current state of the art and vision for engineering, technology, and operations necessary to achieve the objective. M2M directly addresses Challenges 6, 8, 9 and 10 of the 2013-2023 IODP Science Plan. Drilling the first MoHole will be a challenging enterprise requiring space-mission-levels of detailed planning and engineering. The depth of the required borehole is far beyond depths reached so far in ocean crust using conventional non-riser drilling. Industry commonly drills deeper beneath the seafloor, but the required water depth, the hardness of the formations encountered, and the temperature at the MoHole exceeds current industry thresholds. However, new technology exemplified by ongoing development of the Chikyu ultra-deep drilling vessel is arguably at the point where a framework for the operations can be constructed. A site for mantle drilling has yet to be selected; three potential target regions await additional site surveys.

Potential for Discovery and Societal Relevance

Drilling into the mantle will be the most ambitious undertaking ever achieved on Earth by the geoscience community, comparable in both scope and impact to the Moon and Mars missions, and must engage the full spectrum of scientific expertise. Observations of pristine upper mantle will transform our understanding of the evolution of our planet and challenge the fundamental paradigms that are the foundations of Earth Science.

Chikyu +10 Workshop: Drilling Project Idea

Workshop Theme (*bold/italicize* main theme and <u>underline</u> other relevant themes)
AF (Active Faults), ***OC/EM (Ocean Crust/Earth's Mantle)***, CF (Continent Formation), SS (Sediment Secrets), DL (Deep Life), HYD (Hydrothermal Systems)
Project Title: SloMo: Nature of the Lower Crust and Moho at Slower-spreading Ridges
Affiliated proposal? Yes (number) 800 MDP Not Yet
Contact Person and Principal Supporters
Henry Dick, James Natland, Shoji Arai, Paul Robinson, Christopher MacLeod, Maurice Tivey
Scientific Objectives and Global Impact

I. *Test the hypothesis that the Moho beneath Atlantis Bank is a serpentinization front.*
II. *Recover the igneous lower crust and the crust-mantle transition at an average melt flux for slow and ultraslow-spreading ridges.*
From this we seek to understand:

- The igneous stratigraphy of the lower crust
- How much mantle material is incorporated into the lower crust.
- How melt is transported through and emplaced into the lower crust
- How the lower crust and shallow mantle shapes the composition of mid-ocean ridge basalt, the most abundant magma on Earth?
- The primary modes of accretion of the lower crust.
- Lateral heterogeneity of the lower crust at magmatic time scales.
- The distribution of strain in the lower crust and shallow mantle in the shallow lithosphere during asymmetric seafloor spreading.
- The nature of magnetic anomaly transitions in the lower crust.
- The role of the lower crust and shallow mantle in the global carbon cycle.
- Life in the lower crust and hydrated mantle.

This drilling will:
Provide an important step towards a full penetration in the Pacific by providing critical needed experience in deep drilling in lower crustal and mantle rock.
Create a laboratory for hole-to-hole and ship-to-hole experiments for in-situ determination of the seismic character of lower crust and mantle rock at a seismically appropriate scale.

Site Coordinates	**Approximate Water Depth (m)**	**Approximate Penetration Depth**	
		Sediment (m)	**Basement (m)**
32°42.75'S 57°17.11'E	700-m	0	3,000

Rationale for Deep Drilling
Two phase project beginning with two JOIDES Resolution Legs to drill to 3-km, hopefully penetrating the crust-mantle boundary, which is believed to lie above the Moho at 5.5 km. Phase II will use the Chikyu to either deepen the Resolution Hole, or to drill down to 3-km and then core forward through the Moho at 5.5 km ~500 m into the underlying mantle to confirm the nature of Moho and recover fresh pristine mantle for analysis from the Indian Ocean to complement that drilled during M2M in the Pacific.
Technical Challenges (if already known)
Phase I essentially none, likely will require casing in the upper 100-300 m. Development of fluid sampling and biological sampling would be very useful. Hole design. Phase II will require a hard-rock re-entry ability for riser drilling, but will not require a blow out preventer.
Potential for Discovery and Societal Relevance
Will demonstrate the ability and technical challenges of drilling deep into lower ocean crust. Likely discover a new planetary biosphere lying beneath the ocean crust if Moho is a serpentinization front. Will document the extent to which lower crust and mantle represent a carbon reservoir. By coring the key crust-mantle transition document the role of the lower crust and shallow mantle in shaping the composition of mid-ocean ridge basalt, the most common magma type on Earth.

Chikyu +10 Workshop: Drilling Project Idea

Workshop Theme (*bold/italicize* main theme and underline other relevant themes)			
AF (Active Faults), ***OC/EM (Ocean Crust/Earth's Mantle)***, CF (Continent Formation), SS (Sediment Secrets), DL (Deep Life), HYD (Hydrothermal Systems)			
Project Title: Full Penetration of Slow Spread Ocean Crust			
Affiliated proposal? Yes (number) Not Yet **X**			
Contact Person and Principal Supporters			
Henry Dick, Woods Hole Oceanographic Institution			
Scientific Objectives and Global Impact			
To recover the full mature fully magmatic slow spread ocean crust section. Slow spreading ocean ridges constitute 60% of the global ridge system. Preliminary drilling during DSDP, ODP, and IODP has demonstrated that slow and fast spread ocean crust are dramatically different, both in terms of crustal architecture and hydrothermal cycles. Thus understanding the nature of the global geochemical cycle cannot be achieved without a fully representative section of slow spread magmatic crust. To recover the crust-mantle transition at a slow spread ocean ridge to provide another reference site for crustal accretion after M2M and SloMo representing Atlantic Crust. To document the state of alteration, carbon and biogeochemistry and limits to life in a fully mature (not a section of lower crust and mantle unroofed in a core complex) section of the lower crust and mantle at slow spreading rates, but one with the full dike and volcanic sections intact in older crust.			
Site Coordinates	**Approximate Water Depth (m)**	**Approximate Penetration Depth**	
		Sediment (m)	**Basement (m)**
Azores Rise	1500-3000 m	100-400 m	4-7 km
Rationale for Deep Drilling			
Only possible way to do this.			
Technical Challenges (if already known)			
After drilling a full penetration in the Pacific – Piece of cake. Possible to do with present riser system on Chikyu.			
Potential for Discovery and Societal Relevance			
Required to understand the global geochemical cycle, carbon reservoirs, and limits to life. Slow spreading ridges, unlike the tiny Pacific systems, host enormous hydrothermal sulphide deposits that have potential economic significance.			

Chikyu +10 Workshop: Drilling Project Idea

Workshop Theme (*bold/italicize* main theme and <u>underline</u> other relevant themes)
AF (Active Faults), OC/EM (Ocean Crust/Earth's Mantle), CF (Continent Formation), SS (Sediment Secrets), ***DL (Deep Life), HYD (Hydrothermal Systems)***

Project Titles:

1. **The Challenger Deep sediment coring (Kawagucci and Nunoura)**
2. **Nature of gas hydrate during the Earth's evolution (Tomaru et al.)**

I find both projects, listed above, to be highly compelling, based on lessons learned from IODP EXP 337, my experience in the deep terrestrial subsurface and on Ken Nealson's comment regarding the limits of life, survival in the deep subsurface; that low populations of bacteria (10^3 to 10^4 bacteria/cm^3) are not contributing much to the geochemistry of these systems, i.e., they're not very active.

Preliminary sediment coring for IODP EXP 337 demonstrated the presence of 10^8 to 10^9 bacteria/cm^3 sediment, associated with/near methane clathrates located several hundred metres below the ocean floor. These extremely high bacterial populations, comparable to highly productive terrestrial soils, were significantly greater than the low bacterial numbers of the deeper (coal-associated) biosphere found ca. 2.5 km below the ocean floor.

The bacterial populations above the clathrate zone, i.e., across ca. 100 m of sediment was 10^8-10^9 bacteria/cm^3, is at least 4 orders of magnitude greater than the highest populations of the deeper biosphere ca. 10^3 to 10^4 bacteria/cm^3. Using a conservative ratio of these two populations, the 100 m of active biosphere, i.e., a biological 'hot spot' is equivalent to 1000 km of the low biomass (deeper) 'sediment'.

Performing a proportionate depth comparison, using the 'general' population decline in marine sediment populations, which go from 10^8 bacteria/cm^3 at the sediment surface (0.1 m), to 10^7 bacteria/cm^3 at 10 m, to 10^6 bacteria/cm^3 at 1000 m depth, the "biological hotspot" identified by IODP 337 is still equivalent to 10 km of 'average' marine sediment biomass.

The biosphere excels at leveraging redox gradients in support of life, e.g., the 1. serpentinization driven energy and 2. gas hydrate, systems listed above. Understanding significant biosphere contributions to Earth system processes should focus on these "hot spots" of biological activity, in particular where they extend below the sea floor.

Affiliated proposal? Yes (number) Not Yet ☐

I am not currently affiliated with either of these proposals.

Contact Person
Gordon Southam, Professor & Vale-UQ Chair in Geomicrobiology
School of Earth Sciences, The University of Queensland
Participant on IODP EXP 331 – The deep hot biosphere.

Scientific Objectives and Global Impact

Focusing on dynamic redox gradients.

1. This serpentinisation system offers an ideal opportunity to examine the ability of the geosphere to support the biosphere and for the examination of subsequent feedback processes, in particular, the role of the biosphere in promoting mineral carbonation reactions. The output of 4-6°C circumneutral pH fluids driven by a 300°C hydrothermal system at the Challenger Deep sediment coring site demonstrates that serpentinisation (a highly alkaline reaction) must be happening at some depth below the seafloor, making this an ideal natural 'bioreactor' affecting carbon cycling on Earth.
2. Understanding the stability of gas hydrates below the seafloor, and the important relationship(s) between clathrates and the biosphere, similar to EXP 337, is critical to improve our understanding of the future health of our ocean ecosystems and on our future climate stability.

Site Coordinates	Approximate Water Depth (m)	Approximate Penetration Depth	
		Sediment (m)	Basement (m)
Project leads will provide this information.			

Rationale for Deep Drilling

Required for access to these key ecosystems:

1. The Challenger Deep project is at 5622 m from sea surface
2. Unspecified continental shelves, ca. 1 km from sea surface.

Gas associations (CH_4 and H_2) in both projects would benefit from Chikyu's riser drilling capability (as long as contamination can be worked out) so that these gasses can be monitored during drilling.

Limitations of ~~Technical Challenges (if already known)~~ low biomass environments

Bacterial populations of 10^3 to $10^4/cm^3$ will not drive geochemistry or mineralogy.

Potential for Discovery and Societal Relevance

General considerations for integrating geology and biology. The Scanning Electron Microscope (SEM) on Chikyu represents an under-utilized research capability for integrating the relationship between the geosphere and the biosphere. The limitation surrounds the need for a qualified electron microscopist-geomicrobiologist to be added to the science team of appropriate cruises, and critically, the acquisition if a critical point drier (ca. 1,000,000 Yen) for the microscopy suite to prepare biological materials for SEM.

Chikyu +10 Workshop: Drilling Project Idea

Workshop Theme (*bold/italicize* main theme and underline other relevant themes)

AF (Active Faults), ***OC/EM*** (Ocean Crust/Earth's Mantle), CF (Continent Formation), SS (Sediment Secrets), DL (Deep Life), HYD (Hydrothermal Systems)

Project Title: Oceanic Crust and Mantle Evolution From Ridge Through Trench

Affiliated proposal? Not Yet

Contact Person and Principal Supporters

J. P. Morgan, S.-I. Kodaira, I. Grevemeyer, L. Rüpke, C. Ranero, K. Johnson, P. Vannucchi

Scientific Objectives and Global Impact

Objective is to drill through the ocean crust in an area of active bend-fault serpentinization that is occurring as the Cocos Plate bends and subducts at the Middle American Trench. This is a unique site where known Bend-Fault Serpentinization lies beneath seafloor that is at ~3800m water depths.

Site Coordinates	Approximate Water Depth (m)	Approximate Penetration Depth	
		Sediment (m)	Basement (m)
86°45W, 9°50'N	3600	300	6500 (1km below Moho)

Rationale for Deep Drilling

Only way to return samples of what is potentially a major and largely unexplored geologic process — the serpentinization and associated carbonation reactions of seawater and cold ocean lithospheric mantle as the plate bends before entering a trench. Drilling is the only tool to get these materials, and explore the possibility of the existence of deep-life in what could the site of the origin of life on Earth.

Technical Challenges (if already known)

Drilling a Bend-Fault Zone, Deep Seafloor Drilling

Potential for Discovery and Societal Relevance

Potentially transformative science with implications for deep water and carbon cycles, chemical evolution of the mantle, origin of life, and location of what may be a new 'biorhelm' for deep life.

Chikyu +10 Workshop: Drilling Project Idea

Workshop Theme (*bold/italicize* main theme and underline other relevant themes)			
AF (Active Faults), OC/EM (Ocean Crust/Earth's Mantle), CF (Continent Formation), SS (Sediment Secrets), DL (Deep Life), ***HYD (Hydrothermal Systems)***			
Project Title: Abyssal hill drilling hosting active hydrothermal site, Indian Ocean			
Affiliated proposal? Yes (744-Pre, 780-Pre) Not Yet			
Contact Person and Principal Supporters			
Hidenori Kumagai; Kentaro Nakamura, Ken Takai			
Scientific Objectives and Global Impact			
To evaluate spatial scale of heterogeneous, hybrid uppermost lithosphere consisting of mafic and ultramafic lithologies and their multi-stage water-rock reaction by drilling down to approx. 1-2km below seafloor. It could provide the knowledge on physical properties of hard rocks in rather young lithosphere, which is required prior to M2M full penetration of oceanic crust; if not, it may raise some problems on hole instabilities and/or penetrations because such near ridge hydrothermal alteration even in deeper part of oceanic crust should change strength and stickiness of the formation. Even "the origin of life" is still hard to formulate its mission, however, to illuminate it as one of the eventual goal of our scientific community is essential to be recognized our activity by much broader, non-scientist citizens as like as solar system explorations.			
Site Coordinates	**Approximate Water Depth (m)**	**Approximate Penetration Depth**	
		Sediment (m)	**Basement (m)**
25.30°S, 70.15°E	~2400-2700	~2	~2000
Rationale for Deep Drilling			
Water rock interaction in rather deep environment, estimated as down to 1300mbsf, is largely controls fluid chemistries of hydrothermal vents in Kairei hydrothermal field. In addition, for efficient utilize of riser-specific tools, e.g. gas monitoring, requires >600m penetration in typical.			
Technical Challenges (if already known)			
Start drilling on less sedimented volcanic deposits, typically ~2m or less. Distant from the land/island utilizing as supply port. Less contaminated, pressurized in-situ sampling devices should be developed.			
Potential for Discovery and Societal Relevance			
Detailed composition of *in-situ* sampled recharging fluid for hydrothermal circulation, which . To be recognized the activities of scientific drilling community by much broader, non-scientist citizens as like as solar system explorations.			

Chikyu +10 Workshop: Drilling Project Idea

Workshop Theme (*bold/italicize* main theme and underline other relevant themes)			
AF (Active Faults), ***OC/EM*** (Ocean Crust/Earth's Mantle), CF (Continent Formation), SS (Sediment Secrets), DL (Deep Life), HYD (Hydrothermal Systems)			
Project Title: Life cycle of Oceanic Lithosphere: Roles of Ridge and Bend-Fault Processes			
Affiliated proposal? Not Yet			
Contact Person and Principal Supporters			
J. P. Morgan, B. Ildefonse, …(to be combined with existing CRISP riser-drilling proposals)			
Scientific Objectives and Global Impact			
Objective is to coordinate the drilling of a 'transect' constraining the processes of ocean crustal genesis at a mid-ocean ridge (EPR) and ocean crust modification during bend-faulting as the lithosphere bends and subducts at the Middle American Trench. This transect would be chosen to extend to include seismogenesis and forearc modification as the lithosphere subducts along the megathrust underlying a forearc (the existing CRISP riser-drilling project). The location of this Life Cycle Drill Transect is chosen to co-incide with a unique region where known Bend-Fault Serpentinization lies beneath seafloor that is at ~3500-3800m water depths.			
Site Coordinates	**Approximate Water Depth (m)**	**Approximate Penetration Depth**	
		Sediment (m)	**Basement (m)**
86°-89°W, 9°50'N	~3600-4000m	300	6500 (1km below Moho)
Rationale for Deep Drilling			
Combines objectives of M2M, Bend-fault serpentinization, and pre-existing CRISP seismogenesis project into a single scientifically coherent program that allows an additional scientific synergy between the objectives of the M2M and Bend-fault serpentinization programs, as well as a logistical synergy in terms of a combined site-survey and a stabler operations program to support riser-drilling at CRISP, M2M and BFS. The M2M and BFS subobjectives are the only way to return 'pristine' sub-Moho mantle samples and partially serpentinized mantle samples affected by bend-fault serpentinization processes. Drilling is the only tool to get these materials, and also the only tool to explore the possibility of the existence of deep-life in the SBF geologic setting that could the site of the origin of life on Earth.			

Technical Challenges (if already known)
Deep Oceanic Crustal Drilling, Drilling a Bend-Fault Zone, Deep Seafloor Drilling
Potential for Discovery and Societal Relevance
Potentially transformative science with implications for deep water and carbon cycles, chemical evolution of the mantle, origin of life, and location of what may be a new 'biorhelm' for deep life.

Chikyu +10 Workshop: Drilling Project Idea

Workshop Theme (*bold/italicize* main theme and underline other relevant themes)

AF (Active Faults), ***OC/EM (Ocean Crust/Earth's Mantle)***, CF (Continent Formation), SS (Sediment Secrets), DL (Deep Life), HYD (Hydrothermal Systems)

Project Title **Deep Drilling into Large Igneous Provinces**

Ontong Java Plateau, Shatsky Rise, Mid-Pacific Mountains, Hess Rise

Affiliated proposal? Yes (number) Not Yet

Contact Person and Principal Supporters

Clive Neal, Takashi Sano, Maria Luisa Tejada, Takeshi Hanyu, Masao Nakanishi, Seiichi Miura, Xixi Zhao, Daisuke Suetsugu, Kenji Shimizu, Akira Ishikawa, Junichiro Kuroda

Scientific Objectives and Global Impact

- Constrain the duration of LIP magmatic events
- Understand the environmental impact of LIP formation
- Evaluate the formation and evolution mechanisms of LIPs

*Site Coordinates	Approximate Water Depth (m)	Approximate Penetration Depth	
		Sediment (m)	Basement (m)
OJP (near Site 1183; 2°S, 157°E) Shatsky Rise (near Site U1346; 38°N, 163°E) Mid-Pac Mts (near Site 463; 21°N, 175°E) Hess Rise (near Site 465; 34°N, 179°E) Magellan Rise (near Site 167; 7°N, 177°W)	OJP (2400m) SR (3000 m) MPM(2400m) HR (2200m) MR(3200m)	OJP(700-1000m) SR (500-800m) MPM (800-900m) HR (400-500m) MR (1000-1100m)	OJP(3,000m) SR (3,000m) MPM (3,000m) HR (3,000m) MR (3,000m)

Rationale for Deep Drilling

Recovery of continuous pelagic sedimentary section down to the oldest available (e.g., syn-LIP sediments from Magellan)
Recovery of LIP basement rocks below depths previously drilled or sampled by fieldwork to evaluate source and magnetic heterogeneity.
Ontong Java Plateau can provide legacy data for constraining mid-Cretaceous magnetic pole to better constrain paleogeographic models and tectonic history of the Pacific basin.
Deep drilling allows more cooling units to be recovered thus allowing magnetic paleointensity and paleosecular variation at the onset of the long Cretaceous normal to be constrained.

Technical Challenges (if already known)

Water depth >3000m, except for OJP and MPM, which can be drilled with existing riser capabilities

Potential for Discovery and Societal Relevance
1) Origin and evolution of Pacific LIPs. 2) Constrain the duration of LIP volcanic events. 3) Constrain the volatile flux during LIP volcanic events. 4) Understand LIP contributions to the Cretaceous greenhouse and oceanic anoxic events. This requires both syn LIP sediments and deep sections into LIP basement to be recovered. Drilling of one or more of these LIP targets could be done at an early stage in the next decade and would provide invaluable experience in riser hard rock drilling that could then be used in achieving a long term goal in the new Science Plan, namely drilling through oceanic crust into the upper mantle (e.g., M2M).

* We supply a number of potential sites to allow flexibility of LIP drilling within CDEX operations. All have site survey data available, but at varying degrees of fidelity.

This drilling project idea combines all the ideas presented in the following white papers.

Neal [WP129] Exploring the solar system through scientific ocean drilling
Neal [WP047] Formation and environmental impacts of oceanic large igneous provinces
Sano [WP008] Deep drilling on Cretaceous oceanic plateaus in the Western Pacific
Tejada [WP032] Probing deeper into Pacific oceanic plateaus
Zhao [WP002] Deep drilling into Ontong Java Plateau basement using Chikyu's riser drilling system
Nakanishi [WP055] Exploring the deep crust of Mesozoic Pacific oceanic plateaus
Hanyu [WP058] Hotspot volcanism and oceanic plateaus; Search for the missing link
Miura [WP060] Drilling on Pacific oceanic plateaus for their origin and evolution
Kuroda [WP025] High-recovery drilling through the Cretaceous guyot limestones-Decoding high-resolution marine environmental changes in the greenhouse world

Chikyu +10 Workshop: Drilling Project Idea

Workshop Theme (***bold/italicize*** **main theme and** <u>underline</u> **other relevant themes**)

AF (Active Faults), ***OC/EM (Ocean Crust/Earth's Mantle)***, <u>CF (Continent Formation)</u>, <u>SS (Sediment Secrets)</u>, DL (Deep Life), HYD (Hydrothermal Systems)

Project Title

Canada Basin, Arctic Ocean, Stratigraphic and Basement Testing

Affiliated proposal? Yes (number) **Not Yet**

Contact Person and Principal Supporters

Deborah Hutchinson (USGS)
David Mosher (GSC)
Sam Mukasa (UNH)

Scientific Objectives and Global Impact

Because of its remoteness and now disappearing ice cover, the deep-water Canada Basin of the Arctic Ocean is one of the major ocean basins on Earth with no significant sampling of either the sediments or basement. The three sites proposed here are intended to provide sediment, synrift, and basement penetrations that will constrain the rifting, basement, and Late Cretaceous to Recent basin history. Although the sediments are thick, the locations are chosen along a sediment starved margin of the Basin. The oldest sediments (Early Cretaceous and older in age) are too deeply buried to be sampled. Two of the three proposed sites are east and north of Northwind Ridge in locations where it may be possible to sample inferred peridotite or basalt basement. The third hole may sample continental or transitional crust of the Mendeleev Plain northwest of the Chukchi Borderland. Better understanding and dating of the Canada Basin will allow plate models of the Earth to accurately represent Mesozoic and Cenozoic evolution in this part of the Arctic.

Site Coordinates	Approximate Water Depth (m)	Approximate Penetration Depth	
		Sediment (m)	Basement (m)
78.019 -151.237	3800	1500	~500
80.456 -154.082	3800	1000	~700
80.393 -166.446	3000	1500	~400

Rationale for Deep Drilling

Basement lithologies and ages are critical components for understanding the history and evolution of the Canada Basin. The proposed locations are in a sediment starved part of the basin where basement is deep, but accessible. Results will help resolve between many very different and conflicting hypotheses for the opening of the Canada Basin. The area where the three sites are proposed is where the existence of possible serpentinite material is best constrained by geophysical data.

Technical Challenges (if already known)

Not known at the present time.

Potential for Discovery and Societal Relevance

This part of Earth is a frontier region where any sampling data is likely to provide surprises and unexpected results. Because the location of the sites is proximal to the High Arctic Large Igneous Province, evidence of fossil hydrothermal systems and mineral resources may be one of the unexpected results of drilling. In addition to the IODP drilling on the Lomonosov Ridge, these holes will contribute to understanding whether the Early Cenozoic Arctic was an isolated fresh water body, as recently proposed by Hegewald (2012 Dissertation, AWI).

Chikyu +10 Workshop: Drilling Project Idea

Workshop Theme (*bold/italicize* main theme and underline other relevant themes)
AF (Active Faults), ***OC/EM (Ocean Crust/Earth's Mantle)***, CF (Continent Formation), SS (Sediment Secrets), DL (Deep Life), HYD (Hydrothermal Systems)
Project Title
Alpha-Mendeleev Large Igneous Province (LIP) – Exploring the Arctic Ocean Basin
Affiliated proposal? Yes (number) **Not Yet**
Contact Person and Principal Supporters
Samuel B. Mukasa (University of New Hampshire, USA) Larry Mayer (University of New Hampshire) Wilfried Jokat (Alfred Wagner Institute, Bremerhaven, Germany)
Scientific Objectives and Global Impact
Large Igneous Provinces (LIPs) remain enigmatic because of their enormous size and the difficulty in sampling them properly. The drilling done into them so far has often been likened to pricking the elephant and then describing the animal. Yet their potential impact on thermal evolution of the planet, environmental degradation, climate change, and mass extinctions (leading to modulation of the evolution of life itself) are enormous. It remains controversial whether LIPs are always formed within just one or two million years, or at least in some cases may represent protracted periods of magmatism lasting tens of millions of years. The Alpha-Mendeleev large igneous province in the West Arctic Basin provides an opportunity to test how rapidly LIPs develop. Besides drilling into the Alpha-Mndeleev Ridge itself, the adjacent Canada Basin has a sediment record that is likely to contain volcaniclastics and volcanic ash that document development of the LIP. Ice has kept the Arctic Ocean off limits for scientific drilling, except for one IODP leg to the Lomonosov Ridge some year ago. This will cease to be a problem as ice cover continues to recede and is projected to be completely gone by 2025. Already, the Mendeleev Ridge and Canada Basin are ice free during large portions the Northern Hemisphere summer. Sampling and finally dating volcanism that built the Alpha-Mendeleev Ridge will allow better understanding of Earth's Mesozoic and Cenozoic evolution in this part of the Arctic.

Site Coordinates	Approximate Water Depth (m)	Approximate Penetration Depth	
		Sediment (m)	Basement (m)
80.019 -180.000	1650	1000	4000
85.000 -180.082	1650	1000	4000

Rationale for Deep Drilling
Basement lithologies and ages are critical components for understanding the history and evolution of the Alpha-Mndeleev Ridge system. The proposed locations are on top of the Mendeleev Ridge, which is already quite accessible because of receding ice. With an area of about 7.5 x 10^5 km^2, the Alpha-Mendeleev LIP is one of the largest magmatic provinces on the planet in the past 100 million years. Results will help resolve between many very different and conflicting hypotheses for formation of the Alpha-Mendeleev LIP.
Technical Challenges (if already known)
Not known at the present time.
Potential for Discovery and Societal Relevance
This part of Earth is a frontier region where any sampling data is likely to provide surprises and unexpected results. In addition to the IODP drilling on the Lomonosov Ridge, and a few samples dredged from Alpha Ridge and Northwind Ridge by Healy cruises in 2008 and 2012, these holes will contribute to understanding whether LIPs are emplaced more or less instantaneously, and are unequivocally linked to deep-seated mantle plumes.

Chikyu +10 Workshop: Drilling Project Idea

Workshop Theme (*bold/italicize* main theme and underline other relevant themes)

AF (Active Faults), OC/EM (Ocean Crust/Earth's Mantle), CF (Continent Formation), SS (Sediment Secrets), DL (Deep Life), ***HYD (Hydrothermal Systems)***

Project Title

Deep drilling at PACMANUS: building on the results of ODP Leg 193 to unravel the anatomy of a felsic-hosted hydrothermal system

Affiliated proposal? Not Yet

Contact Person and Principal Supporters

Chris Yeats, CSIRO, Australia
Wolfgang Bach, Univ. Bremen, Germany

Scientific Objectives and Global Impact

Porphyry, epithermal and volcanic hosted massive sulfide (VHMS) mineral systems in ancient arcs and back arcs are globally significant sources of copper, zinc, lead, silver and gold. Human demand for these metals continues to grow and the minerals industry is struggling to find new resources. as the easily found, near-surface deposits have already been discovered across most areas of the globe. Mineral explorers require a better understanding of the factors that lead to the formation of economic ore deposits in order to have the confidence to undertake costly, high technical risk exploration in deeply buried terranes. In particular, the importance of magmatic systems as a source of metals and mineralizing fluids in near-surface and exhalative VHMS mineralization is not well understood, although there is general agreement that exsolved magmatic fluids play an important role in the formation of high grade (high metal content), large tonnage, so called "world class" deposits, such as the giant Kidd Creek deposit in Canada. Modern active arc- and back arc-hosted metal rich hydrothermal systems (so-called 'black smokers') provide a unique and unparalleled opportunity to study the formation of these economically important mineral systems as they accumulate, allowing direct observation of the physical and chemical processes that lead to mineralization, as well as the roles of magmatic fluids and seawater in the source, transport and deposition of metals.

Ocean Drilling Program Leg 193, which drilled the PACMANUS site on Pual Ridge in the Eastern Manus Basin in 2001, remains one of the ODP/Integrated ODP's two forays to a felsic-volcanic hosted seafloor hydrothermal system. The other, IODP Leg 331 to the Okinawa Trough, had a strong biological focus.

Leg 193 drilled three discrete hydrothermal sites (2 high temperature sulfide chimney fields and a low temperature diffuse venting site), to a maximum depth of 380mbsf. Despite the technical challenges of drilling in a highly heterogeneous hard rock sequence, which resulted in very poor overall core recovery (~10% ans <1% in key stockwork intervals), Leg 193 was highly successful scientifically, providing important insights into the volcanic stratigraphy, subsurface alteration and hydrology, the role of seawater and deeply-sourced fluids in the system, and the subsurface biosphere. Key results of the expedition include:

- Intense and pervasive, clay dominated alteration (illite-chlorite and advanced argillic), forming highly porous rocks beneath a 10-40 m dacite cap. Anhydrite-dominated veins are present throughout the system, indicating widespread penetration of seawater into fractures.

- Scarcity of subsurface mineralisation, apart from widespread disseminated pyrite, and a pyritic stockwork below the Roman Ruins chimney field.
- Pual Ridge is a sequence of relatively thin flows. No intrusive rocks were intersected by drilling
- Microbes flourish and were cultivated at temperatures up to 117°C.
- A borehole temperature of 313°C was recorded 5 days after drilling at 360mbsf. Extrapolating this thermal gradient implies that the intrusive heat source for the hydrothermal system is only 1.5-2 km below seafloor.

Extrapolating the thermal gradient defined by the temperature measurement above implies that the intrusive heat source for the hydrothermal system is only 1.5-2 km below seafloor. Thus a relatively shallow water (~1650mbsl), 2000m depth riser hole could be drilled into the high temperature reaction zone and the chilled margins of the intrusion, providing for the first time important data on high temperature alteration, the deep source of fluids, volatiles and metals, and the degree of deep penetration of seawater in an active ore forming system. This hole would also allow the underlying deep volcanic architecture of Pual Ridge to be investigated and contrasted with the sheet flow morphology of the upper portions of the sequence.

Site Coordinates	Approximate Water Depth (m)	Approximate Penetration Depth	
		Sediment (m)	Basement (m)
3°44.8’S 151°40.1’E	1650m	0m	2000m

Rationale for Deep Drilling

Riser drilling will allow improved recovery (both through continuous flow of cuttings and carefully selected cored intervals) and the possibility of analyzing drilling mud gas, providing direct evidence of the volatile phases present in these mineral systems.

Deep drilling will allow, for the first time, the high temperature reaction zone to be intersected in an active hydrothermal system. This region is key to understanding the sources of metals and fundamental physico-chemical processes that control the fluid compositions, metal budgets, depositional mechanisms and ultimately the economic value of these important sources of mineral resources. Deep drilling will also facilitate investigation of the linkages between the near-surface (VHMS and epithermal) and deeper (porphyry) environments, which is a key question for economic geology researchers.

Technical Challenges (if already known)

High temperature
Acidic fluids
Variably altered (hard to soft), highly fractured volcanic sequence

Potential for Discovery and Societal Relevance
The globe's increasing need for new mineral resources requires a step change in the understanding of ore forming processes, to enable mineral explorers to explore successfully in deeply buried terranes. Modern active arc- and back arc-hosted metal rich hydrothermal systems such as PACMANUS provide a unique and unparalleled opportunity to study the formation of these economically important mineral systems as they accumulate, allowing direct observation of the physical and chemical processes that lead to mineralization, as well as the roles of magmatic fluids and seawater in the source, transport and deposition of metals. In addition to their value as "natural laboratories" for understanding the processes that lead to the formation of crucially important ancient ore deposits, metal-rich arc- and back arc-hosted hydrothermal systems are increasingly seen as important economic resources in their own right. It is also generally thought that these inhospitable, highly acidic, sulfur-rich environments are analogous to the conditions present during the early history of the Earth. Documenting the microbial life associated with hydrothermal vents may therefore hold the key to understanding the origin of life on this planet.

Chikyu +10 Workshop: Drilling Project Idea

Workshop Theme (*bold/italicize* main theme and underline other relevant themes)
AF (Active Faults), OC/EM (Ocean Crust/Earth's Mantle), CF (Continent Formation), SS (Sediment Secrets), DL (Deep Life), ***HYD (Hydrothermal Systems)***
Project Title
SuSu Knolls: Fluid fluxes and role of magmatic volatiles in an actively forming copper-gold rich felsic hosted porphyry-epithermal-VHMS system
Affiliated proposal? Not Yet
Contact Person and Principal Supporters
Chris Yeats, CSIRO, Australia Wolfgang Bach, Univ. Bremen, Germany
Scientific Objectives and Global Impact
Porphyry, epithermal and volcanic hosted massive sulfide (VHMS) mineral systems in ancient arcs and back arcs are globally significant sources of copper, zinc, lead, silver and gold. Human demand for these metals continues to grow and the minerals industry is struggling to find new resources. as the easily found, near-surface deposits have already been discovered across most areas of the globe. Mineral explorers require a better understanding of the factors that lead to the formation of economic ore deposits in order to have the confidence to undertake costly, high technical risk exploration in deeply buried terranes. In particular, the importance of magmatic systems as a source of metals and mineralizing fluids in near-surface and exhalative VHMS mineralization is not well understood, although there is general agreement that exsolved magmatic fluids play an important role in the formation of high grade (high metal content), large tonnage, so called "world class" deposits, such as the giant Kidd Creek deposit in Canada. Modern active arc- and back arc-hosted metal rich hydrothermal systems (so-called 'black smokers') provide a unique and unparalleled opportunity to study the formation of these economically important mineral systems as they accumulate, allowing direct observation of the physical and chemical processes that lead to mineralization, as well as the roles of magmatic fluids and seawater in the source, transport and deposition of metals. The SuSu Knolls area hosts a hydrothermally active, significant tonnage. high grade copper-gold rich massive sulfide deposit (Solwara 1 - indicated and inferred resource of 2.2Mt @ 7.2% Cu, 6.2 g/t Au, 31 g/t Ag and 0.6% Zn; Nautilus minerals) at a water depth of 1500m, on the crest of Suzette, a dormant eroded dacitic volcano. 3km to the southeast at North Su volcano, with a crestal depth of 1150m, hydrothermal activity is much more diverse; ranging from high temperature (300-325^{0}C), supercritical, moderate- to low-pH (2.8-3.5) black sulfidic fluids associated with copper-rich sulfide chimneys near the crest, to lower temperature (48-215^{0}C), very acidic (pH 0.87-1.8) milky-white fluids and associated advanced argillic alteration and native sulfur from the flanks. The lower pH fluids are CH_4 and H_2S poor, with salinity identical to that of seawater, and are interpreted to represent a mix of heated seawater and magmatic volatiles. In contrast, the fluids associated with the chimneys have higher H_2S abundances (5.3 to 7.7 μmol/l) and very high CH_4 concentrations (91 to 566 μmol/l). Similar fluids recovered from the Suzette vent fields also contain high

concentrations of CH_4 (90 to 503 μmol/l). Elevated CH_4 concentrations in fluids from the SuSu Knolls area are interpreted to reflect entrainment of CH_4 generated by thermal alteration of the organic-rich sediments that underlie the SuSu volcanoes, similar to the processes involved in the Okinawa Trough.

Using an ROV-mounted drilling rig, Nautilus minerals have carried out extensive exploratory drilling, to a maximum depth of ~40mbsf at Suzette. However the hydrothermal system that underlies the massive sulfide remains unexplored. Nautilus' drilling indicates that fluid overpressure is an important mechanism for metal deposition in the Solwara 1 deposit and the temperatures recorded for fluids from black smokers at SuSu imply that phase separation is likely to be occurring in the immediate subsurface. The wide diversity of hydrothermal activity at SuSu Knolls provides a unique opportunity to investigate the critical factors leading to ore formation in the submarine environment. including fluid recharge and discharge, fluid flux and the role of magmatic fluids as a source of volatiles and metals. Specific scientific objectives include:

1. Quantify the manner in which fluids, volatiles and metals derived from magmatic sources, the underlying sedimentary sequence, and from leaching of wallrocks by circulated seawater, respectively, have combined within the hydrothermal system. This would be approached by applying geochemical and isotopic modeling to the vertical and lateral variations in hydrothermal alteration styles and sulfide mineral occurrences established by the drilling.

2. Evaluate the mechanisms of subsurface mineral precipitation, including comparison of exhalative and subhalative mineralizing processes, the link between near surface (VHMS-epithermal) and deeper (porphyry) mineralization, assessing the consequences of fluid phase separation, and seeking explanations for the elevated contents of copper, gold and silver, and relatively low concentrations of zinc, in massive sulfide chimneys at North Su and Suzette and massive sulfide at Suzette.

3. Delineate probable fluid pathways within the system and establish a hydrologic model by measuring and interpreting variations in physical properties and fracture patterns of fresh and altered bedrocks.

4. Evaluate the volcanic architecture of Suzette and North Su and the relative timing of major eruptive and mineralizing events. Test the hypothesis that inflation of the volcanic edifice by lava domes or shallow intrusions is the predominant process in this submarine felsic volcanic environment.

5. Develop a petrogenetic model for SuSu igneous rocks and seek evidence pertaining to the nature of the possible underlying source for magmatic components in the hydrothermal fluids.

6. Develop an integrated understanding of coupling between volcanological, structural, and hydrothermal phenomena in the SuSu system to provide a

new basis for interpreting ancient ore environments.

7. Establish the nature, extent, and habitat controls of microbial activity within the SuSu hydrothermal system and interpret the differences encountered in diversity and biomass in terms of nutrient supplies and environmental habitats in the context of the geochemical and hydrologic understanding of the total hydrothermal system. Hydrothermal venting at SuSu ranges from highly acidic, sulfur-rich, clearly magmatically derived fluids, to metal-bearing hydrothermal fluids, providing an opportunity to study the subsea biosphere in a range of extreme biogeochemical environments.

Site Coordinates	Approximate Water Depth (m)	Approximate Penetration Depth	
		Sediment (m)	Basement (m)
3°47.4'S 152°5.7'E 3°48.0'S 152°6.0'E	1550m 1150m	<5m 0m	800m 1200m

Rationale for Deep Drilling

Riser drilling will allow improved recovery (both through continuous flow of cuttings and carefully selected cored intervals) and the possibility of analyzing drilling mud gas, providing direct evidence of the volatile phases present in these mineral systems.

Deep drilling will allow, for the first time, the high temperature reaction zone to be intersected in an active hydrothermal system. This region is key to understanding the sources of metals and fundamental physico-chemical processes that control the fluid compositions, metal budgets, depositional mechanisms and ultimately the economic value of these important sources of mineral resources. It will also allow penetration beyond the neovolcanic edifice at SuSu and examine the penetration of the hydrothermal system into the underlying organc-rich sedimentary sequence to investigate the input of this material into the system (eg: CH_4). Deep drilling will also facilitate investigation of the linkages between the near-surface (VHMS and epithermal) and deeper (porphyry) environments, which is a key question for economic geology researchers.

Technical Challenges (if already known)

High temperature
Acidic fluids
Variably altered (hard to soft), highly fractured volcanic sequence
Potential volcanic gas reservoirs at North Su

Potential for Discovery and Societal Relevance

The globe's increasing need for new mineral resources requires a step change in the understanding of ore forming processes, to enable mineral explorers to explore successfully in deeply buried terranes. Modern active arc- and back arc-hosted metal rich hydrothermal systems such as SuSu Knolls provide a unique and unparalleled opportunity to study the formation of these economically important mineral systems as they accumulate, allowing direct observation of the physical and chemical processes that lead to mineralization, as well as the roles of magmatic fluids and seawater in the source, transport and deposition of metals.

In addition to their value as "natural laboratories" for understanding the processes that lead to the formation of crucially important ancient ore deposits, metal-rich arc- and back arc-hosted hydrothermal systems are increasingly seen as important economic resources in their own right. It is also generally thought that these inhospitable, highly acidic, sulfur-rich environments are analogous to the conditions present during the early history of the Earth. Documenting the microbial life associated with hydrothermal vents may therefore hold the key to understanding the origin of life on this planet.

Chikyu +10 Workshop: Drilling Project Idea

Workshop Theme (*bold/italicize* main theme and underline other relevant themes)

AF (Active Faults), <u>OC/EM</u> (Ocean Crust/Earth's Mantle), <u>CF</u> (Continent Formation), ***SS (Sediment Secrets)***, DL (Deep Life), HYD (Hydrothermal Systems)

Project Title

Scientific drilling by Chikyu to unravel the opening history of the South China Sea and its implications for Southeast Asian tectonics, climates, and deep mantle processes since the Late Mesozoic

Affiliated proposal? Yes (number) Not Yet **X**

Contact Person and Principal Supporters

Xixi Zhao and Chun-Feng Li

Scientific Objectives and Global Impact

Mesozoic continent-ocean interactions and tectonic transitions leading to continental margin break-up and seafloor spreading

Site Coordinates	Approximate Water Depth (m)	Approximate Penetration Depth	
		Sediment (m)	Basement (m)
SW subbasin	~3000m	1000	300

Rationale for Deep Drilling

To recover thick syn-rift sediments and significant basement penetration

Technical Challenges (if already known)

Disputed waters

Potential for Discovery and Societal Relevance

Chikyu +10 Workshop: Drilling Project Idea

Workshop Theme (*bold/italicize* main theme and underline other relevant themes)

AF (Active Faults), OC/EM (Ocean Crust/Earth's Mantle), HYD (Hydrothermal Systems)

Project Title Ocean Transform Fault Drilling and Water Injection: Active Experiment to Trigger Earthquakes

Affiliated proposal? Not Yet

Contact Person and Principal Supporters

Jim Mori mori@eqh.dpri.kyoto-u.ac.jp

Scientific Objectives and Global Impact

New proposal to trigger small and moderate size earthquakes on a mid-ocean transform fault using water injections in a borehole.

At many locations around the world small seismic events are being induced by fluid injections. At these places there are efforts trying *not* to cause larger earthquakes, but it is not known what are the conditions needed to inhibit or cause a larger event.

Using water injections, it is probably relatively easy to trigger small earthquakes in a natural fault zone. In addition, if we can actually cause and a moderate-size earthquake (M5-6) to occur, we have a unique opportunity to study key seismological questions.

1. What is the level of stress needed to initiate an earthquake ?
2. Are there differences in the initiation of small and large earthquakes ?
   (Can we predict a large earthquake ?)
3. What conditions are necessary to trigger a moderate size earthquake

Site Coordinates	Approximate Water Depth (m)	Approximate Penetration Depth	
		Sediment (m)	Basement (m)
Possible sites on Gofar or Discovery Fracture Zones	< 2500 m		~2000-3000 m

Rationale for Deep Drilling

Boreholes can reach the shallow seismogenic zones of transform faults (2 to 3 km). Use the riser for controlled water pressurization in the borehole to induce earthquakes. Pumping pressures of 0.001 MPa (about 0.1 psi) to higher values, possibly 1 MPa (140 psi). 1 MPa is in the range of stress drops for earthquakes.

Technical Challenges (if already known)
Monitoring of fluid pressures and seismic activity (borehole seismometers, OBS) are needed. Safety and pubic perception issues need to be carefully considered.
Potential for Discovery and Societal Relevance
There has been much recent public attention on damaging earthquakes that have been induced by fluid injections, such as 2011 Okahoma (M5.7) and 2006 Basil, Switzerland (M3.4). Also, possible hazards from 'fracking' have received much publicity. The conditions and mechanisms for triggering moderate (but damaging) earthquakes are not understood.

Chikyu +10 Workshop: Drilling Project Idea

Workshop Theme (*bold/italicize* main theme and underline other relevant themes)

AF (Active Faults), OC/EM (Ocean Crust/Earth's Mantle), CF (Continent Formation),
SS (Sediment Secrets), DL (Deep Life), HYD (Hydrothermal Systems)

Project Title Campbell Plateau, Paleogene paleoclimate

Affiliated proposal? Yes (number) Not Yet √

Contact Person and Principal Supporters

Chris Hollis, Greg Browne (GNS Science, NZ)

Scientific Objectives and Global Impact

Drill Paleogene sediment on the Campbell Plateau, NE of DSDP277 to determine the paleoclimatic signature of the Paleogene and the transition into the Neogene. This period marks the opening of the circum-Antarctic oceanographic currents a period of time poorly constrained by other drilling or outcrop studies. Understanding how the circum-Antarctic currents developed and evolve through the Neogene are important considerations for global climate change models, especially the transition from a greenhouse to an ice-house world. Additional outcomes will include (if the Cretaceous is drilled), an understanding of the breakup sequence as Antarctica and Zealandia began to drift away from one another. If basement is drilled, data would provide a constraint as to the link between eastern Zealandia and where it matches up with comparable geology in Antarctica.

Site Coordinates	Approximate Water Depth (m)	Approximate Penetration Depth	
		Sediment (m)	Basement (m)
53.5S; 166.5E	1200 m	>500 m	?

Rationale for Deep Drilling

- Period of time poorly constrained by other drilling or available outcrop
- Paleoclimate change during the Paleogene
- Tectonic breakup sequence if Cretaceous drilled
- Understanding of the onset of glaciation in Antarctica and the transition from a greenhouse world in the Eocene to an Ice house world from the Oligocene

Technical Challenges (if already known)
• Difficult sea conditions at most times of the year. High seas and strong winds are common
Potential for Discovery and Societal Relevance
• High potential for discovery as any data will be new to science • Providing constraints to global circulation models during the Paleogene • Understanding the development and modification of the circum Antarctic current from inception in the Eocene-Oligocene to present-day • Understanding of the onset of glaciation in Antarctica and changes during the Neogene from a site intermediate in terms of latitude from the proximal drilling sites in Antarctic (ANDRILL and IODP Wilkesland Expedition) and studies in New Zealand

Chikyu +10 Workshop: Drilling Project Idea

Workshop Theme (*bold/italicize* main theme and <u>underline</u> other relevant themes)			
AF (Active Faults), OC/EM (Ocean Crust/Earth's Mantle), <u>CF (Continent Formation)</u>, ***SS (Sediment Secrets)***, DL (Deep Life), HYD (Hydrothermal Systems)			
Project Title Challenger Plateau, continental rift succession			
Affiliated proposal? Yes (number) Not Yet			
Contact Person and Principal Supporters			
Kyle Bland, Greg Browne, Chris Hollis (GNS Science)			
Scientific Objectives and Global Impact			
To understand the development of the Cretaceous rift margin succession formed during the breakup of eastern Gondwana and the formation of theTasman Sea. New open-file 2D seismic acquisition in the area have indicated a considerable amount of Cretaceous sediment on the northern flank of the Challenger Plateau, that could have potential as source rock and reservoir facies. Comparable rocks are well-known from the productive Gippsland Basin, a mirror image succession on the Australian portion of the contemporaneous Gondwana margin. Previous DSDP holes include 592 (to the NW) and 593 (to the SW).			
Site Coordinates	**Approximate Water Depth (m)**	**Approximate Penetration Depth**	
		Sediment (m)	**Basement (m)**
37.5 S; 171.0 E	1500 m	4000 m	5000 m
Rationale for Deep Drilling			
• Modern 2D seismic profiles have been acquired over parts of this area • Mirror image of the eastern Australian margin (Gippsland Basin) • Understanding the hydrocarbon potential of mid and Late Cretaceous rift sediments. • No wells have penetrated to these depths in this area, so all the geological understanding is today based on seismic records.			
Technical Challenges (if already known)			

Potential for Discovery and Societal Relevance
- Sediments in this area are poorly understood, with no drilling in the area. Any data would provide new scientific material   - The area lies downdip of the productive Taranaki Basin to the SE, so drilling in this area would add considerably to our understanding of the paleogeographic setting at this time, and the tectonic evolution during Cretaceous breakup

Chikyu +10 Workshop: Drilling Project Idea

Workshop Theme (***bold/italicize*** main theme and <u>underline</u> other relevant themes)			
AF (Active Faults), OC/EM (Ocean Crust/Earth's Mantle), <u>CF (Continent Formation)</u>, ***SS (Sediment Secrets)***, DL (Deep Life), HYD (Hydrothermal Systems)			
Project Title Neogene and Paleogene undeformed sediments in an active convergent margin			
Affiliated proposal? Yes (number)		Not Yet √	
Contact Person and Principal Supporters			
Greg Browne, Kyle Bland, Chris Hollis (GNS Science)			
Scientific Objectives and Global Impact			
Drill a thick succession of Neogene to Paleogene sediments within the Pegasus Basin, eastern New Zealand. These sediments are relatively undeformed, yet are part of a Neogene convergent margin. They piggy back on a convergent margin succession active during the Cretaceous. Virtually nothing is known about these sediments. They have the potential to be oil and/or gas bearing. Onshore age equivalents occur in places.			
Site Coordinates	**Approximate Water Depth (m)**	**Approximate Penetration Depth**	
		Sediment (m)	**Basement (m)**
42.5S; 177.5E	2200 m	4000 m	5000 m
Rationale for Deep Drilling			
Open file, 2D seismic data has recently been collected from the area. It shows a thick (>3 km thick) Neogene and Paleogene basin and a drill site on the southern Chatham Rise portion of the basin would be chosen to optimize drilling depth to stratigraphy considerations. Unconformities would be tied to global sea level and tectonic controls.			
Technical Challenges (if already known)			
Depth to be drilled is considerable - >3 seconds so a location that optimizes scientific results with drilling practicality will be chosen.			

Potential for Discovery and Societal Relevance
Because virtually nothing is known of this area, results will considerably advance scientific understanding. That this area is potentially oil and/or gas bearing has potential for direct relevance.

Chikyu +10 Workshop: Drilling Project Idea

Workshop Theme (*bold/italicize* main theme and underline other relevant themes)

AF (Active Faults), OC/EM (Ocean Crust/Earth's Mantle), CF (Continent Formation),
SS (Sediment Secrets), DL (Deep Life), HYD (Hydrothermal Systems)

Project Title

Studies on paleomagnetism and cosmogenic nuclide using sediment cores in the West Caroline Basin: Possible connection among the geomagnetic field, Earth's orbit, and climate

Affiliated proposal? Yes (number) Not Yet

Contact Person and Principal Supporters

Toshitsugu Yamazaki, Yusuke Yokoyama, Toshiya Kanamatsu, Yusuke Suganuma, Yuhji Yamamoto

Scientific Objectives and Global Impact

The first objective is to prove or disprove the possibility of orbital modulation of the geomagnetic field. If this is true, it has fundamental implications for the geomagnetism because it means that an energy source of the geodynamo resides outside the Earth's core. The second objective is to extend the record of geomagnetic field intensity variations beyond ~2 Ma. Such record enables to solve important issues of the geomagnetism including possibility of polarity bias and relation between intensity and polarity length.

Site Coordinates	Approximate Water Depth (m)	Approximate Penetration Depth	
		Sediment (m)	Basement (m)
1°N, 138°E 3°N, 141°E	4300m 2500m	200m 200m	

Rationale for Deep Drilling

Technical Challenges (if already known)

Potential for Discovery and Societal Relevance

Understanding the possible connection between geomagnetic field and climate will be useful for predicting Earth's environments in the future.

Chikyu +10 Workshop: Drilling Project Idea

Workshop Theme (*bold/italicize* main theme and underline other relevant themes)

AF (Active Faults), OC/EM (Ocean Crust/Earth's Mantle), CF (Continent Formation), SS (Sediment Secrets), **DL (Deep Life)**, HYD (Hydrothermal Systems)

Project Title Origin of the deep biosphere

Affiliated proposal? Yes (number) **Not Yet**

Contact Person and Principal Supporters

Jan W. de Leeuw

Scientific Objectives and Global Impact Just an idea, nothing more

Presently we don't have a clue regarding the origin of the deep biosphere; Were the original "primitive" microbes (Archaea and/or Bacteria) living deep in the water column and/or sediments and/or crust and did they ultimately find their way up to the surface or did they originally occupy the surface of the planet and went down via subduction or otherwise? In both cases there was enough time for evolutionary adaptation to their continuously changing habitats.
We may approach this "chicken-egg" type problem by drilling three holes in a subducting plate located just before subduction, in the subduction zone at ca. 70-80 C and at ca 120 C. By metagenomic analyses of the microbial populations in the three cores we may get an idea about the evolution of the deep biosphere.
To some extent this idea is touched in the white paper by Morgan and Vannucchi (Chikyu+10 white papers book, p.221-222).
This project should not generate a stand-alone expedition but should be combined with an expedition already drilling a subduction zone. An "APL" mode project but likely to consume much more time than a regular APL.

Site Coordinates	Approximate Water Depth (m)	Approximate Penetration Depth	
		Sediment (m)	Basement (m)
Any future expedition targeting the subduction zone	Depending on already planned expedition	Depending on already planned expedition	Depending on already planned expedition

Rationale for Deep Drilling

Deep riser drilling is the only way to obtain the required samples

Technical Challenges (if already known)
Avoiding contamination as much as possible
Potential for Discovery and Societal Relevance
Interesting scientific discoveries will be made, no direct social relevance expected.

Chikyu +10 Workshop: Drilling Project Idea

Workshop Theme (*bold/italicize* main theme and underline other relevant themes)

AF (Active Faults), OC/EM (Ocean Crust/Earth's Mantle), CF (Continent Formation), SS (Sediment Secrets), DL (Deep Life), ***HYD (Hydrothermal Systems)***

Project Title: Brothers volcano: gateway to the sub-arc mantle

Affiliated proposal? ***Yes*** (number) IODP Pre-proposal Not Yet

Contact Person and Principal Supporters

Cornel E.J. de Ronde (GNS Science, New Zealand)
Ken Takai (JAMSTEC, Japan)
Junichiro Ishibashi (University of Kyushu, Japan)
Wolfgang Bach (Bremen University, Germany)

Scientific Objectives and Global Impact

Our primary scientific objective is to discover the fundamental, underlying processes that drive differences between hydrothermal systems in arc volcanoes from those in spreading environments, such as back-arc basins and mid-ocean ridges.

Site Coordinates	Approximate Water Depth (m)	Approximate Penetration Depth	
		Sediment (m)	Basement (m)
-34.86S/179.06E	1850	10s of m	600-800 m

Rationale for Deep Drilling

1. Characterizing the sub-volcano, magma chamber-derived volatile phase to test model-based predictions that this is either a single-phase gas, or two-phase brine-vapor.
2. Exploring the sub-seafloor distribution of base and precious metals and metalloids, and the reactions that have taken place along pathways to the seafloor.
3. Quantifying the mechanisms and extent of fluid-rock interaction, and consequences for mass transfer of sulfur and carbon metals and metalloid species, into the ocean
4. Assessing the diversity and extent of microbial life in an extreme, metal-toxic and acidic volcanic environment.

Technical Challenges (if already known)

- Up to 302°C fluid venting in active part of vent field
- Fluids with pH down to 2.0 in some parts of the system

Potential for Discovery and Societal Relevance

- First attempt to quantify the transfer of metals from arc magmas to the seafloor
- Provide insight into the formation of Cu-Au deposits that are crucial for society in its need for these metals in a modern world
- Potential for great discovery of subseafloor microbial communities in what is a very extreme (hot, gassy and acidic) environment

Chikyu +10 Workshop: Drilling Project Idea

Workshop Theme (***bold/italicize*** main theme and <u>underline</u> other relevant themes)
AF (***Active Faults***), OC/EM (<u>Ocean Crust/Earth's Mantle</u>), CF (<u>Continent Formation</u>), SS (Sediment Secrets), DL (<u>Deep Life</u>), HYD (Hydrothermal Systems)
Project Title Costa Rica Seismogenesis Project (CRISP)
Affiliated proposal? 537B Full
Contact Person and Principal Supporters
C. R. Ranero, C. Marone, S. Bilek., U. Barckhausen, P. Charvis, J-Y Collot, H. DeShon, G. Di Toro, T. Dixon, L. Dorman, E. Flueh, S. Galeotti, I. Grevemeyer, R. Harris, S. Husen, M. Kastner, M. Kinoshita, S. Kuramoto, T. Matsumoto, K. McIntosh, J. Morgan, J. Morris, C. Mueller, S. Neben, C. Reichert, D. Scholl, S. Saito, S. Schwartz, V. Spiess, E. Suess, P. Vannucchi, H. Villinger, S. Vinciguerra, R. von Huene, W. Wallmann.
Scientific Objectives and Global Impact
CRISP is designed to investigate the processes leading to seismogenesis at erosional convergent margins. At least 50% of the world's subduction zones are erosional. Erosional convergent margins have a subduction channel containing material removed from the overriding plate mixed with sediment from the incoming plate. The nature and physical properties of this material are currently unconstrained. Similarly, the volume, distribution and chemistry of fluids at erosional plate boundaries are poorly known. Drilling will for the first time sample eroded material and fluids in the subduction channel and investigate plate boundary fault mechanisms during tectonic erosion. CRISP will provide the core material for detailed laboratory experiments designed to isolate the processes and physical conditions that control the onset of seismogenesis. The Four Major Goals of CRISP are: **1)** Quantify effective stress and plate boundary migration via focused investigation of fluid pressure gradient and fluid advection across the erosional plate boundary. **2)** Determine the structure and fault mechanics of an erosional convergent margin . **3)** Constrain how fluid-rock interaction affect seismogenesis by studying fluid chemistry and residence time, basement alteration, diagenesis, and low grade metamorphism. **4)** Obtain physical properties of a 3-D volume that spans the seismogenic zone.

Site Coordinates	Approximate Water Depth (m)	Approximate Penetration Depth	
		Sediment (m)	Basement (m)
8.74098833 N 84.11349167 W	550	1500	3500

Rationale for Deep Drilling
Drilling an erosional plate boundary near the nucleation area of a Mw6.4 EQ.

Technical Challenges (if already known)
- Fluid overpressure - Basement rock
Potential for Discovery and Societal Relevance
The project will seek to obtain the information necessary to understand fault constitutive laws. This understanding will permit to evaluate fault behavior and how it affects earthquake rupture dynamics and tsunami generation.

Chikyu +10 Workshop: Drilling Project Idea

Workshop Theme (*bold/italicize* main theme and <u>underline</u> other relevant themes)
AF (Active Faults), OC/EM (Ocean Crust/Earth's Mantle), CF (Continent Formation), SS (Sediment Secrets), DL (Deep Life), HYD (Hydrothermal Systems)
Project Title Products of submarine explosive volcanic eruptions
Affiliated proposal? Yes (number) **Not Yet**
Contact Person and Principal Supporters
Martin Jutzeler Fukashi Maeno James White Rebecca Carey
Scientific Objectives and Global Impact
Submarine volcanoes have been intentionally avoided to drill by the Joides Resolution, because it is difficult to achieve high core recovery from them, though some small basaltic guyots were cored. Entirely submarine volcanoes of silicic composition have been mostly studied from uplifted outcrops, but alteration (diagenesis, hydrothermal alteration) and tectonic damage (faults, other deformation) obscure some textures and disrupt lateral continuity of the beds, while limits to exposure prevent confident whole-eruption or whole-volcano reconstructions. Recent ROV sampling and dredging gives information on only the uppermost deposits. Many submarine silicic volcanoes were discovered in the last decade, and are known to erupt violently, and to be accompanied on occasion by tsunamis and subaerial plumes that threaten local and distant coastal populations. A better understanding of the deposit distribution around submarine volcanoes would be the first step in the comprehension of the eruption and sedimentation processes of pyroclasts under water, as well as allowing a better preparedness for their associated hazards. Ocean drilling around and radially from selected entirely submarine volcanoes would be ideal to reveal the 3-dimensional distribution of volcanic beds, and their relationship to each other, from proximal to distal facies.

Site Coordinates	**Approximate Water Depth (m)**	**Approximate Penetration Depth**	
		Sediment (m)	**Basement (m)**
Unknown yet			

Rationale for Deep Drilling
No deep drilling needed, but specialized coring heads from Chikyu may be extremely useful in mixed lithologies (e.g. lava flows vs. pyroclastic sediments).

Technical Challenges (if already known)
Mixed lithologies. High temperature gradient for near-vent facies.
Potential for Discovery and Societal Relevance
Tsunami mitigation; safety for navigation in submarine arc environments; better understanding of our planet; origin/presence of life associated with hydrothermal systems.

Chikyu +10 Workshop: Drilling Project Idea

Workshop Theme (*bold/italicize* main theme and <u>underline</u> other relevant themes)

AF (Active Faults), OC/EM (Ocean Crust/Earth's Mantle), CF (Continent Formation), ***SS (Sediment Secrets),*** DL (Deep Life), HYD (Hydrothermal Systems)

Project Title: ***Tethys Ocean in situ (TOIS)***

Affiliated proposal? Yes (number) ***Not Yet***

Contact Person and Principal Supporters

Erba E.

Scientific Objectives and Global Impact

The Cretaceous-Jurassic archive in the eastern Tethys Ocean (Ionian Basin, Eastern Mediterranean) will provide information from a so far unsampled area in between the Tethys-Atlantic and Indo.Pacific Oceans. The section will include all major Oceanic Anoxic Events (OAEs) and other climate-environmental perturbations of Jurassic and Cretaceous age as well as marine biosphere responses and evolutionary changes. Scientific objectives comprise:

- long-term warming and cooling including pre- and post- mid Cretaceous Greenhouse conditions. Late Jurassic cooling and possible minor "ice-house".
- Short-term climatic extremes (hyperthermals and cooling interludes) during times of global warming and highCO_2.the Mesozoic.
- Earth system functioning under low and high levels of CO_2.
- ocean's response to chemical perturbations during OAEs as well as before and after OAEs. Spatial and vertical extent of oceanic anoxia.
- ocean acidification during intervals of elevated CO_2. History of CCD.
- Links between ocean chemistry and (extreme) internal and external forcings.
- oceanic ecosystem response to LIPs.
- Calcareous and siliceous plankton evolution and paleobiodiversity.

Site Coordinates	Approximate Water Depth (m)	Approximate Penetration Depth	
		Sediment (m)	Basement (m)
Ionian Basin – Eastern Mediterranean	~4000 m	~6000 m	

Rationale for Deep Drilling

The Ionian Abyssal Plain of the Eastern Mediterranean might be the oldest in situ ocean fragment of the world, with ocean crust of Late Triassic age. *Chikyu* is the only scientific platform capable of recoverying such a thick Mesozoic section.
The location is key to fill the gap between the Tethys-Atlantic Ocean and the Indo-Pacific Ocean.

Technical Challenges (if already known)

Implementation to $\geq$4000 m water depth AND penetration to ~ 6000 m.

Potential for Discovery and Societal Relevance

Greenhouse world, Ecosystem functioning in highCO_2 worlds.

Chikyu +10 Workshop: Drilling Project Idea

Workshop Theme (*bold/italicize* main theme and underline other relevant themes)
AF (Active Faults), OC/EM (Ocean Crust/Earth's Mantle), CF (Continent Formation), ***SS (Sediment Secrets)***, DL (Deep Life), HYD (Hydrothermal Systems)
Project Title **Constraining the Mesozoic break-up of east Gondwana: drilling the Capel and Faust Basins, Lord Howe Rise, eastern Australia**
Affiliated proposal? Not Yet
Contact Person and Principal Supporters
Dr Andrew D. Heap, Geoscience Australia Email: Andrew.Heap@ga.gov.au Principal Supporter: Geoscience Australia
Scientific Objectives and Global Impact

The Lord Howe Rise region is one of the world's largest remaining offshore frontiers for scientific research and resource exploration outside the polar regions. The submerged continental landmass covers an area of over 1,500,000 km^2 and its geological history is poorly known, despite the fact that the region holds the key to global-scale plate tectonic events and environmental change during the Mesozoic and Cenozoic of Eastern Gondwana.

The principal objective is to undertake deep stratigraphic drilling into the pre-Late Cretaceous succession in the Capel and Faust basins on the Lord Howe Rise which will provide essential information to unlock the geological history and break-up of eastern Gondwana.

The lack of deep stratigraphic drilling is a major roadblock to furthering our knowledge of this major tectonic event. It will refine our understanding of crustal evolution during the major Cretaceous–Cenozoic plate tectonic re-organisation of the western Pacific.

Realising this objective will also provide the first direct evidence for the development of large, offshore asymmetric continental rifting and opening of marginal ocean basin in eastern Australia, as well as the associated magmatic history and environmental changes arising from continental breakup, microcontinent submergence, and ocean basin formation.

This has the potential to provide insights into the geologic drivers and biospheric effects of the Cretaceous and Cenozoic 'Super-Greenhouse' conditions. It will also identify any potential petroleum system elements, i.e. source, reservoir and seal rocks, providing baseline information for petroleum prospectivity assessments.

Site Coordinates	Approximate Water Depth (m)	Approximate Penetration Depth	
		Sediment (m)	Basement (m)
TBC	1500-2500		

		2500-3500	N/A

Rationale for Deep Drilling

Createaceous section, inferred from high quality 2D seismic is inferred to be between 2.5-3.0 km bsf, although this has yet to be tested. Water depths over primary core sites are between 1.5-2.5 km.

Coring will be restricted to priority/select sections – particularly the Cretaceous section to better understand break-up, palaeo-environments, climate signatures, and potential for petroleum source rocks.

This deep drilling leg complements and extends information that will be obtained by the proposal by Sutherland et al. submitted to IODP in April 2013 to use the Joides Resolution to drill shallow (<500 m) sub-surface holes to better constrain the nature and timing of the Cenozoic section over a latitudinal gradient of the Lord Howe Rise.

Technical Challenges (if already known)

Riser drilling required due to possible occurrence of hydrocarbons. Highly ranked drilling sites will be necessarily off-structure so as to minimize potential of encountering hydrocarbons.

Remote location: Lord Howe Island is closest port for mobilization, and it has helicopter facilities.

Occurrence of tropical cyclones. These are rare at this latitude.

Austral summer drilling campaign preferred to minimize potential with winter storms and East Coast low pressure systems.

Potential for Discovery and Societal Relevance

Deep stratigraphic drilling on the Lord Howe Rise will finally constrain the nature and timing of the Mesozoic break-up of Eastern Gondwana and its effects on regional and global tectonics, ocean basin formation and microcontinent formation.

Discovery of expected late- to mid-Cretaceous petroleum source rocks and confirmation of functioning petroleum systems will support regional and global energy security.

Chikyu +10 Workshop: Drilling Project Idea

Workshop Theme (*bold/italicize* main theme and underline other relevant themes)

AF (Active Faults), OC/EM (Ocean Crust/Earth's Mantle), CF (Continent Formation), ***SS (Sediment Secrets)***, DL (Deep Life), HYD (Hydrothermal Systems)

Project Title

Salt and sub-salt sedimentary environments of the Mediterranean (GOLD DREAM)

Affiliated proposal? Yes (partially former MDP 798)

Contact Person and Principal Supporters

Marina Rabineau, Angelo Camerlenghi, Hugh Daigle, Junichiro Kuroda, Francisco Jimenez

Scientific Objectives and Global Impact

- Explore the impact of salt bodies on surrounding sediments (fluid, diagenesis, geochemistry, geomechanics)
- Understand the unique event of the sea level drop in the Mediterranean (Messinian Salinity Crisis - MSC) and its impact on global climate, biogeochemistry and geo-dynamics
- Explore the salt-related deep biosphere
- Recover the sedimentary history of the Neogene rifting in the Western Mediterranean and the oldest Tethian basins in the worlddocuemnt* (Ionian Sea deep Mesozoic sequence)
  * see separated document Tethian Ocean In Situ (TOIS)

Site Coordinates	Approximate Water Depth (m)	Approximate Penetration Depth	
		Sediment (m)	Basement (m)
W-Med: N41º45.92 E 05º00.10 Other sites not yet identified (to be identified during the DREAM workshop)	• W-Med: 2300 m • From 1000 to 2500 m. • Some sites can be located more conveniently in water depth between 2500 and 4000 m • 4000 m needed for the Ionian Site	• 6 km in two Sites to basement • 2-3 km in other sites	To reach oceanic basement in two sites.

Rationale for Deep Drilling

- The Messinian Salinity Crisis can be solved only through the drilling of the deep Mediterranean basins.
- Sub salt environments can be studied only with deep riser drilling
- The Eastern Mediterranean hosts the deepest and oldest sedimentary cover of the globe: Thetis Ocean (Jurassic, possibly Triassic).

• Interest of petroleum companies in subsalt environments • Intense exploration activity in the Mediterranean
Technical Challenges (if already known)
• Ultra deep water depth, salt drilling (salt deformation in hole), subsalt drilling (compaction disequilibrium, overpressure) • Drilling through salt • Riser drilling in water depth of 4 km (Ionian Sea in the Eastern Mediterranean)
Potential for Discovery and Societal Relevance
• Solve one to the longest living geological controversy emerged from early stage scientific drilling: the Messinian Salinity Crisis of the Mediterranean Sea • Possible discovery of resources below the Messinian Salts • Cretaceous greenhouse world • Deep biosphere related to salt deposits

Chikyu +10 Workshop: Drilling Project Idea

Workshop Theme (*bold/italicize* main theme and underline other relevant themes)

AF (Active Faults), OC/EM (Ocean Crust/Earth's Mantle), CF (Continent Formation), SS (Sediment Secrets), DL (Deep Life), HYD (Hydrothermal Systems)

Project Title

Kanto Asperity Project

Affiliated proposal? Yes (number) 707 (umbrella), 770 (monitoring), 782 (ultradeep) Not Yet One or two more daughter proposal(s)

Contact Person and Principal Supporters

Reiji Kobayashi, Toshinori Sato, Yuzuru Yamamoto, Saneatsu Saito

Scientific Objectives and Global Impact

Scientific Objectives

Objective 1: To understand why the three different types of events occur laterally, at similar depths in the Sagami Trough (i.e., under the same P–T conditions).

Objective 2: To establish realistic earthquake-generation models using data obtained at each step of the generation cycle of natural earthquakes.

Global Impact

Understanding diversities of slip events along the Sagami trough, through the achievement of the two objectives, can be related to understanding those along all subduction zones and is important to assess geohazards.

Site Coordinates	Approximate Water Depth (m)	Approximate Penetration Depth	
		Sediment (m)	Basement (m)
For 770 (monitoring)			
34.714983, 140.497846	2000	300	100
34.714983, 140.497846	1645	600	100
35.040507, 140.809153	1225	500	100
35.340191, 141.109503	565	600	100
34.596611, 140.765538	3460	300	100
34.954181, 140.887397	1840	800	100
For 782 (ultradeep)			
34.46143, 140.32372	1880	6900	50
35.09214, 139.26155	900	6500	0

Rationale for Deep Drilling

To intersect plate boundaries in the source region of two different types of slip events; the Boso slow slip region and the Taisho Kanto earthquake.

Technical Challenges (if already known)

For 782 (ultradeep drilling), extensive logging (Vp, Vs and anisotropy), in situ experiment, such as pore pressure, hydraulic properties and stress tensor, VSPs, and oriented cores are necessary for the initial values for geodetic and seismic monitoring.

Potential for Discovery and Societal Relevance

The southern Kanto region (Tokyo Metropolitan Area) of southeastern Japan is an important and densely populated economic center that has been subjected to repeated great (M~8.0) earthquakes. An understanding of the physical properties of the plate boundaries that underlie this region and the establishment of a realistic earthquake-generation model are of critical importance in mitigating the danger posed by earthquake hazards.

Our monitoring program proposes that, in final stage, a seafloor cable network will be deployed and then the observatories will be connected to the cable. Electrical power will then be supplied by the cable for real-time transmission of the data to on-land stations. Real-time monitoring can contribute to societal relevance as well as to science.

Through the 2011 Tohoku earthquake and the J-FAST, we realized that plate boundary at shallow depth plays an important role in subduction process including giant earthquake generation. The Kanto Asperity Project will discuss drilling the shallow part of the plate boundary along the Sagami trough. It is important to assess tsunami hazard.

Chikyu +10 Workshop: Drilling Project Idea

Workshop Theme (*bold/italicize* main theme and underline other relevant themes)

AF (Active Faults), OC/EM (Ocean Crust/Earth's Mantle), CF (Continent Formation),
SS (Sediment Secrets), DL (Deep Life), HYD (Hydrothermal Systems)

Project Title

Extending the Remarkable Ultra-High-Resolution Global Climate Record in Santa Barbara Basin Back to ~1.5 Ma

Affiliated proposal? Yes (705-full2) Not Yet

Contact Person and Principal Supporters

contact Richard Behl (Richard.Behl@csulb.edu) or Craig Nicholson (nicholson@msi.ucsb.edu);
additional Proponents: James Kennett, Ingrid Hendy, Tessa Hill, Dorothy Pak, Ryuji Tada, Christopher Sorlien, Kenneth Verosub, Irina Delusina, Maria Prokopenko & Peter Eichhubl

Scientific Objectives and Global Impact

Santa Barbara Basin has the potential to become the world's premier global climate reference site, providing ultra-high-resolution paleoclimatic records equivalent to the Greenland ice cores but extending back much further in time (to ~1.5 Ma) if drilled by the *Chikyu*. The primary objective is to assemble complete, well-dated, ultra-high-resolution records from a known mid-latitude global reference site back to >1.2 Ma for comprehensive paleoclimatic and paleoceanographic studies of Earth system history. Based on previous ODP drilling (Site 893) and seafloor sampling, Santa Barbara Basin can provide a high fidelity, continuous record back to >1.2 Ma at millennial to centennial to sub-decadal time scales. This would allow unprecedented resolution and evaluation of abrupt global climate change, climate variability and the evolution of the global climate system during the late Quaternary, including detailed insight into the major mid-Pleistocene climate transition, as well as detailed baseline information to calibrate, test and develop new models for global climate change.

Site Coordinates	Approximate Water Depth (m)	Approximate Penetration Depth	
		Sediment (m)	Basement (m)
SBC-01A, SBC-01B 34°17'N 120°02'W	580 m	1500 m	
SBC-03A, SBC-03B 34°15'N 119°47'W	185 m	900 m	

Rationale for Deep Drilling

The sole obstacle to deeper drilling in Santa Barbara Basin is a perceived safety issue with riserless drilling, even though the basin was safely drilled using a riserless ship in 1992 to 200 m (ODP Site 893) and with industry riser drilling to depths of 4 km in the early 1980's. Riser drilling with the *Chikyu* can provide both added safety and access to older basin sediments (>1 Ma) present at considerable depth (>1000 m) owing to the unusually high and constant basin sedimentation rates (>1 m/kyr). The *Chikyu* can also provide deeper coring capability with HPC and higher quality core recovery below HPC refusal needed for such high-resolution paleoclimate studies.

Technical Challenges (if already known)

There are two primary challenges: 1) acquiring high-quality cores below HPC penetration. This may require additional drilling in shallower water (SBC-03) where less-deeply-buried, less compacted older basin sediments have been uplifted to near seafloor depths and were previously drilled safely with a riser ship; and 2) an oxygen-free, nitrogen core storage container (or individual core storage D-tubes) onboard the *Chikyu* to prevent oxidation and core deterioration during long-term core storage.

Potential for Discovery and Societal Relevance
The potential for important scientific discovery by coring Santa Barbara Basin is very high owing to the quality and high-fidelity nature of its continuous, undisturbed, laminated sediments and preserved microfossils. Understanding the causes of late Quaternary climate behavior represents one of the fundamental challenges in the Earth sciences. Santa Barbara Basin already provides one of the highest-resolution paleoclimatic archives of the latest Quaternary being studied from the world's oceans, and—to date—the highest resolution marine record in the world for the penultimate deglaciation (Termination II at ~130 ka). Recent sampling of older basin sediments uplifted to near seafloor depths has verified that this sensitivity to global climate change and the quality and resolution of the basin record extends back to ~750 ka and possibly to ~1.4 Ma. Investigation of these older basin records has already resulted in the discovery of several new patterns of global climate behavior, including an unusual stadial-interstadial climate oscillation with near ~1200-yr cyclicity at ~735 ka that had never before been observed or modeled owing to the previous lack of climate information with sufficient age and resolution until these older Santa Barbara Basin sediments were sampled. In addition, because of its unique location on the California continental margin, Santa Barbara Basin has the unique advantage that sediment rates are not only high (>1 m/kyr), but remarkably constant over time spans of >1 Myr, and these sediments can provide both a surface-water and rare intermediate-water record, a sub-polar and sub-tropical record, and a marine record with important components of terrestrial environmental and biotic change all in the same core. This record also reflects broad-scale changes involving changing strengths of the oxygen minimum zone around the North Pacific and its relationship to upper intermediate water variations. The net result and the fundamental relevance to society is a world premier global climate reference site that can support unprecedented, detailed paleoclimatic, paleoceanographic and paleo-environmental studies of abrupt climate change, climate variability, and the major mid-Pleistocene climate transition, while providing fundamental insights into the processes and feedback mechanisms driving these unusual patterns in the global climate system. Understanding the causes of late-Quaternary climate instability, including abrupt warming episodes is crucial given societal concerns about present day anthropogenic climate change. The proposed coring in Santa Barbara Basin will enable the testing of a whole suite of important questions and related hypotheses to help improve our understanding of the causes of such late-Quaternary climate behavior, including such important past episodes of abrupt climate change.

Chikyu +10 Workshop: Drilling Project Idea

Workshop Theme (*bold/italicize* main theme and underline other relevant themes)			
DL (Deep Life), HYD (Hydrothermal Systems)			
The temperature limit of life: probing the biotic/abiotic interface in subseafloor sediments at Nankai Trough			
Affiliated proposal? Not Yet			
Contact Person and Principal Supporters			
Kai-Uwe Hinrichs, Wolfgang Bach, Verena Heuer, Fumio Inagaki, Heath J. Mills, et al. khinrichs@uni-bremen.de, MARUM, Bremen			
Scientific Objectives and Global Impact			
Redrill selected sites first drilled during Leg 190, Nankai Trough; Sites 1173 and 1174 penetrated sedimentary rocks to temperatures of about 100 and 140°C, respectively. Increasing H2 concentrations downhole (; source of hydrogen uncertain. High heat flow area, hydrothermal inputs from crust. Sufficiently high quality data exists already, which will allow building a strong, focused proposal for research project with high probability of success (see attached Figure from Parkes et al., 2007, Org. Geochem., 38, 845-852). Investigative approaches in microbiology and biogeochemistry have advanced dramatically in the last 13 years and would now make this a perfect location for a short microbiology leg that addresses one of the long-standing key questions in IODP. The operation could be accomplished as an "extended APL" aimed at penetrating the sediments and into basement in a matter of weeks. • **Constraining the T-limit of life in the sediment-hosted subseafloor** • **Study the relationship of abiotic chemical reactions at high T and biology** • **Physically and chemically characterize horizons where life becomes extinct** • secondary objective: study multiple sulfate-methane transition zones at depth, e.g. Site 1173 at 50°C			
Site Coordinates	**Approximate Water Depth (m)**	**Approximate Penetration Depth**	
		Sediment (m)	**Basement (m)**
Redrill ODP Sites 1173 and 1174, Nankai Trough		1173, 725-750 m 1174, 1.1 km	
Rationale for Deep Drilling			
Sites that can be accessed by shallow drilling, e.g., Guaymas Basin, Okinawa Trough, have too high geothermal gradients and additionally are too dynamic in terms of fluid flow; this situation results in sterilization of broad depth intervals and strongly complicates the detection of the "biotic/abiotic interface"			
Technical Challenges (if already known)			
Non-riser drilling, deploy PCS, potentially penetrate into shallow basaltic basement at Site 1173 below 725 mbsf			

Potential for Discovery and Societal Relevance
Constraining the lower limit of life is one of the most fundamental questions pursued by the deep life community and beyond. This location provides an excellent opportunity to determine the temperature limit in a highly energy-limited subseafloor microbial ecosystem and characterize the zones where life goes extinct. The discoveries will be of interest to geoscientists, life scientists and astrobiologists.

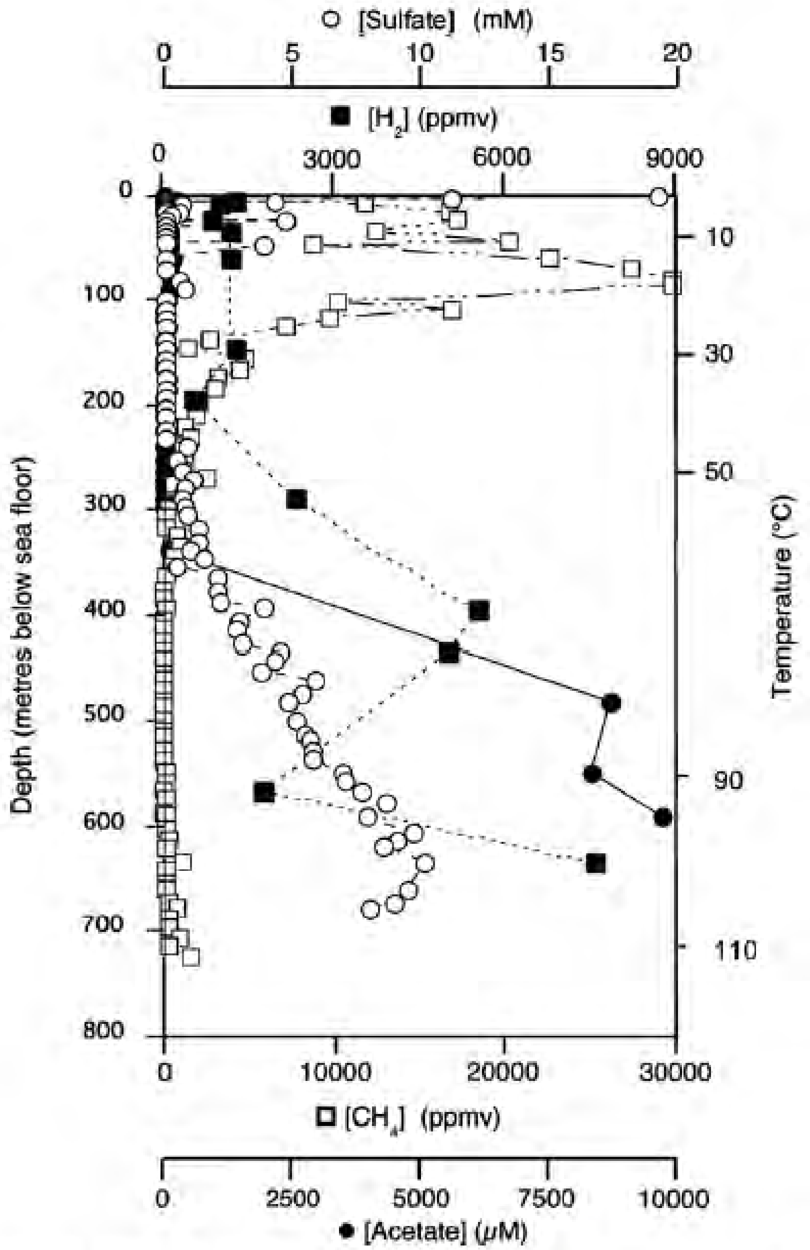


Fig. 3. Increase in bacterial metabolites with temperature in Nankai Trough (ODP Leg 190, Site 1173) deep, hot sediments. Sulfate, CH_4 and temperature (Moore et al., 2001), H_2 (Spivak, personal communication and unpublished data), acetate (this publication).

Chikyu +10 Workshop: Drilling Project Idea

Workshop Theme (*bold/italicize* main theme and <u>underline</u> other relevant themes)

AF (Active Faults), ***OC/EM (Ocean Crust/Earth's Mantle)***, CF (Continent Formation), SS (Sediment Secrets), DL (Deep Life), HYD (Hydrothermal Systems)

Project Title: Testing the Ophiolite Model by Scientific Drilling with Chikyu

Affiliated proposal? Yes (805 MDP) M2M Not Yet

Contact Person and Principal Supporters

J. Koepke >> for M2M: Susumu Umino, Benoît Ildefonse, Peter B. Kelemen, Shuichi Kodaira, Katsuyoshi Michibayashi, Tomoaki Moroshita, Damon A.H. Teagle, and the MoHole proponents

Scientific Objectives and Global Impact

Test whether our model of the deep fast-spread oceanic crust based on field observation in the Oman ophiolite does correspond to the real in-situ crust formed in the Pacific ocean. In detail: Test the presence or absence

(1) of layered gabbro in the lower part of the crust
(2) of foliated gabbro in the upper part of the crust
(3) of a Moho transitions zone
(4) of intrusive crustal wehrlites, gabbronorites, large plagiogranites

These goals can be achieved as a sub-project with the M2M drilling project, and the work can be done en-route to the mantle by coring specific intervals in the whole gabbroic section.

Site Coordinates	Approximate Water Depth (m)	Approximate Penetration Depth	
		Sediment (m)	Basement (m)*
32°25'N; 125°45'W	4000-4500	250-300	6000
6.7-8.7°N; 89.5-91.9°W	3400-3650	250-300	5500
22.9-23.9°N; 154.5-155.8°W	4050-4500	150	5500-6000
Data from the M2M proposal!!			* crustal thickness

Rationale for Deep Drilling

For testing, drilled samples of deep gabbros are absolutely necessary. There is no alternative way to test.

Technical Challenges (if already known)

About 4000 m Riser is necessary.

Potential for Discovery and Societal Relevance

-

Chikyu +10 Workshop: Drilling Project Idea

Workshop Theme (*bold/italicize* main theme and underline other relevant themes)

AF (Active Faults), ***OC/EM (Ocean Crust/Earth's Mantle)***, CF (Continent Formation), SS (Sediment Secrets), DL (Deep Life), HYD (Hydrothermal Systems)

Project Title **Ultra-Deep drilling into the Tohoku Outer Rise**

Affiliated proposal? Not Yet

Contact Person and Principal Supporters

Tomoaki Morishita, Katsuyoshi Michibayashi, Shuichi Kodaira, Biswajit Ghosh

Scientific Objectives and Global Impact

This proposal is aiming to drill into the Tohoku Outer Rise as the deepest as possible (up to 4,000 m) at ultra deep water depth (6,000 m from the sea surface). Since the outer rise is bending just before the subduction, numerous faults are expected to be created. In fact, trenchward-dipping multichannel seismic reflections are imaged probably due to infiltration of water along the faults. The major objective is to recover the materials of the outer rise of the subducting Pacific plate in order to understand the igneous stratigraphy of the oceanic plate and its modification due to faulting coupled with water percolation at the outer rise. These lines of information should be useful to understand the nature of the interface of the seismic zone and global water and carbon cycles through the subduction zone. The hole should be used for the monitoring of geophysical signals to mitigate the damage of seismic activities.

Site Coordinates	Approximate Water Depth (m)	Approximate Penetration Depth	
		Sediment (m)	Basement (m)
	6,000 m		> 4,000 m

Rationale for Deep Drilling

Many large interplate earthquakes frequently occur at the Japan Trench convergent margin, where is the one of the highest population density areas in the world. Intermediate- and deep-focus earthquakes might be linked to metamorphic dehydration reactions in the subducting plate, meaning that intermediated- and deep-focused earthquakes were caused by the reactivation of pre-existing faults in the oceanic plate before subduction. If we do not know the materials of the deeper part of the subducting oceanic plate, we are not able to understand completely where and how the earthquake will be occurred at convergent margins. In the other aspect, the hydration of the oceanic plate is a key to understand the water and carbon cycled in the Earth.

Technical Challenges (if already known)

The outer rise drilling should be a technically challenging drilling proposal because we need to drill > 4,000 m from Seafloor at ultra-deep water depth (> 6,000 m).

Potential for Discovery and Societal Relevance

We expect to know how much water (& carbon) is incorporated into the subducting oceanic lithoshepre, which must be crucial to quantitatively discuss water and carbon cycling in the earth. Our material data should be used for the understanding of origin of the earthquake at subduction zone and will be, therefore, used for mitigation of the natural disasters related to the subducting plate.

Chikyu +10 Workshop: Drilling Project Idea

Workshop Theme (*bold/italicize* main theme and underline other relevant themes)

AF (Active Faults), ***OC/EM (Ocean Crust/Earth's Mantle)***, CF (Continent Formation), SS (Sediment Secrets), DL (Deep Life), HYD (Hydrothermal Systems)

Project Title: Drilling into the mantle beneath ultra-slow spreading ridges

Affiliated proposal? Yes (number) **Not Yet**

Contact Person and Principal Supporters

Alexandra Yang Yang, alexandrayyang@gmail.com, Guangzhou Institute of Geochemistry, Chinese Academy of Sciences

Scientific Objectives and Global Impact

1. To confine the driving forces of seafloor spreading by studying the fault systems of the avolcanic ridge segment (tectonic-dominated spreading) of ultra-slow spreading ridges.
2. To know the structure of mid-ocean ridges. It is impossible at present to drill directly into the MOR of faster-spreading ridges because of the magma supply. But it can work under ultra-slow spreading ridges.
3. To study possible magma transportation paths in the oceanic lithosphere, especially in the lithospheric mantle beneath ultra-slow spreading ridges because mantle melting beneath such ridges is believed to stop at the lithosphere-asthenosphere boundary.

Site Coordinates	Approximate Water Depth (m)	Approximate Penetration Depth	
		Sediment (m)	Basement (m)
MOR of avolcanic ridge segments of ultra-slow spreading ridges (12°25' E, -52°20'N Southwest Indian Ridge for example)	4000-5000	N.A.	2000~3000

Rationale for Deep Drilling

By drilling into the mantle of ultra-slow spreading ridges, not only could it make M2M much easier considering much thinner crustal thickness, but it also can give us a direct view about the composition and structure of this unique oceanic lithosphere beneath ultra-slow spreading ridges.

One point must keep in mind that the lithosphere of EPR represents the usual oceanic lithosphere **only at present**. So other ridge systems could share more interests except for EPR as we do **NOT** know about the seafloor spreading before Mesozoic and therefore definitely **NOT** know about the exact compositions of the seafloor that subducted into the mantle which may cause the heterogeneity we identify today. Therefore, different ridges systems deserve much more attention!

Technical Challenges (if already known)

Potential for Discovery and Societal Relevance

1. Driving forces of seafloor spreading.
2. 2. Structure of lithosphere of ultra-slow spreading ridges.
3. 3. Achieving the goal of M2M with an easier solution.

Chikyu +10 Workshop: Drilling Project Idea

Workshop Theme (*bold/italicize* main theme and underline other relevant themes)

AF (Active Faults), OC/EM (Ocean Crust/Earth's Mantle), CF (Continent Formation), SS (Sediment Secrets), DL (Deep Life), HYD (Hydrothermal Systems)

Project Title:

FLOWS: Impact of fluid circulation in old oceanic lithosphere on the seismicity of transform-type plate boundaries

Affiliated proposal? Not Yet

Contact Person and Principal Supporters

Pierre Henry (henry@cerege.fr), Christian Hensen, Marianne Nuzzo, Eulalia Gracia, Pedro Terrinha

Scientific Objectives and Global Impact

Demonstrate the occurrence of fluid circulation in old oceanic crust in response to strike-slip deformation, and its consequences (on geochemistry, geophysics, fault strength and seismicity, mud volcanism). Understand the influence of the sedimentary cover, and interactions between fluid flow systems in the oceanic crust and in the sediment. Determine stress state within an intra-oceanic deformation zone. Targets are tentatively proposed in seismically active segments of the Gibraltar-Azores Fracture Zone in two areas with contrasting sedimentary cover thicknesses. (1) serpentinite body (presumably intrusive) and fault zone in the Gloria reactivated transform; (2) source layer for mud volcanism influenced by flow in the underlying oceanic crust, within a transpressive zone in the Horseshoe Abyssal Pain.

Global impact from better understanding the interplay of mantle alteration by fluids, seismicity and lithosphere strength.

Site Coordinates	Approximate Water Depth (m)	Approximate Penetration Depth	
		Sediment (m)	Basement (m)
N37°, W021°20' N35°45', W010°20'	4000-4500 m 4500 m	500-1000 m 1000-2000 m	500-1000 m

Rationale for Deep Drilling

Characterization of in situ conditions (temperature), compositions and reactions in active system. In situ fluid and microbiological sampling.
Sampling of active fault and deformation zones in oceanic crust.
Installation of borehole instrumentation (fluid pressure) in the context of an EMSO European Multidisciplinary Sea Observatory site.

Technical Challenges (if already known)

Deep water, drilling conditions (fault zones, formation altered by fluid)

Potential for Discovery and Societal Relevance

New types of low-T hydrothermal systems
Earthquake hazards

Chikyu +10 Workshop: Drilling Project Idea

Workshop Theme (*bold/italicize* main theme and underline other relevant themes)

AF (Active Faults), OC/EM (Ocean Crust/Earth's Mantle), CF (Continent Formation), SS (Sediment Secrets), DL (Deep Life), ***HYD (Hydrothermal Systems)***

Project Title

Unprecedented volcanic catastrophe revealed by drilling the Kikai caldera

Affiliated proposal? Yes (number) Not Yet

Contact Person and Principal Supporters

F. Maeno (Univ. Tokyo), K. Tani (JAMSTEC), M. Jutzler (Univ. Otago), R. Carey (Univ. Tasmania), J. Kuroda (JAMSTEC), T. Shimano (Tokoha Univ.), C. Busby (Univ. California), J. Ishibashi (Kyushu Univ.)

Scientific Objectives and Global Impact

We propose drilling the Kikai caldera, Japan, to tackle the following key questions on submarine caldera. 1. What is dynamics and evolution of gigantic caldera-forming eruptions in submarine condition and consequent hazards? 2. What are impacts of ash and volatile release by the eruption that may cause a long-lasting global hazard? 3. What are recurrence history and future eruptive potential? 4. What hydrothermal system and resources are developed in the collapsed caldera? 5. What is the origin of a large silicic magmatic system and the evolution of arc crust that generates and stores a huge amount of silicic magma?

Site Coordinates	Approximate Water Depth (m)	Approximate Penetration Depth	
		Sediment (m)	Basement (m)
Potential sites			
N30°43' E130°23' (Inside caldera)	500	~600 (?) (not known)	~100
N30°53 E130°25' (Outside caldera)	300	~300 (?) (not known) need to be site-surveyed	~100

Rationale for Deep Drilling

To obtain the entire sequence of (welded and/or non-welded) ignimbrite sheets, ashfall layers, intra-caldera fill deposits and intrusive lavas inside and outside caldera. Non-disturbed, loosely packed pyroclastic deposits and hydrothermal system need to be drilled and recovered.

Technical Challenges (if already known)

Sampling non-disturbed, loosely packed pyroclasts may be a technical challenge. Also drilling at high temperature condition (~300 °C) is expected. The drilling depth depends on a temperature gradient inside caldera.

Potential for Discovery and Societal Relevance

Exploring a large silicic magmatic system is economically important, in terms of tapping new resources like mineral deposits and geothermal energy. Scientific results are expected to contribute development of human activity.

Detection and reconstruction of the past caldera-forming events will be crucial to find predicted patterns and consequent hazards. Various scales of impacts (pyroclastic flows, ash fall, tsunamis, etc.) from the eruption should be highlighted in order to raise interest and educational outreach of the public. Based on renewed knowledge, we should prepare mitigation and evacuation plans for a future event.

Chikyu +10 Workshop: Drilling Project Idea

Workshop Theme (*bold/italicize* main theme and <u>underline</u> other relevant themes)
AF (Active Faults), OC/EM (Ocean Crust/Earth's Mantle), CF (Continent Formation), SS (Sediment Secrets), DL (Deep Life), HYD (Hydrothermal Systems)
Project Title Monitoring state of stress in the earthquake fault system in the Nankai Trough by networked active deep borehole observatories
Affiliated proposal? Yes (number) Not Yet
Contact Person and Principal Supporters
Eiichiro Araki, Shuichi Kodaira, Koshun Yamaoka, Demian Saffer, and Masataka Kinoshita
Scientific Objectives and Global Impact
Establish a networked borehole observatories monitoring pore-p, temperature, strain, and seismic in the vicinity of the seismogenic plate boundary to measure physical property of the seismogenic plate boundary and evolution of the property during the seismic cycle of a large earthquake (Tonankai Earthquake). Temporal change in the pore-fluid or stress in the area is evaluated also by repeated (and eventually continuous) seismic measurements by controlled seismic source and seismic receivers installed in the boreholes. These observations (pore-p, temperature, strain, seismic wave characteristics) are jointly analyzed to compare deeper interface with seismogenic slip characteristic and shallower interface with episodic slow slip known as VLF earthquakes. This observation experiment with networked borehole instruments actively scanning the media at depth will develop our ability to visualize how subducting plate is evolving in time.

Site Coordinates	**Approximate Water Depth (m)**	**Approximate Penetration Depth**	
		Sediment (m)	**Basement (m)**
C0002	2000	1000	5000
C0010	2600	700	0
C0006	3900	800	0

Rationale for Deep Drilling
Seismic array installed in the vicinity of the seismogenic plate interface at depth is needed to receive seismic waves influenced by the structure at the interface without near surface disturbances. Pore-fluid pressure at the interface may not be observed in the seafloor or shallow depths.
Technical Challenges (if already known)
High temperature (~180degC) and high pressure (2km water and 6-7km formation) environment necessitates special care in the design of observation system. Controlled seismic source that can be operated for years continuously in a seafloor borehole is to be developed.
Potential for Discovery and Societal Relevance
Measurement of temporal change of the stress in and around the seismogenic plate interface may reveal contribution of fluid in triggering earthquakes. The proposed sites are located in the Tonankai earthquake which caused severe impacts to human life both by strong motion and Tsunami in the history.

Chikyu +10 Workshop: Drilling Project Idea

Workshop Theme (*bold/italicize* main theme and underline other relevant themes)

AF (Active Faults), OC/EM (Ocean Crust/Earth's Mantle), ***CF (Continent Formation)***, SS (Sediment Secrets), DL (Deep Life), HYD (Hydrothermal Systems)

Project Title (Project IBM) Continental Crust formation at intra-oceanic arc: Ultra-deep drilling to the middle crust of the Izu-Bonin-Mariana arc

Affiliated proposal? Yes (698-Full3)

Contact Person and Principal Supporters

Yoshihiko Tamura (Team Leader, Project IBM Research Team, IFREE, JAMSTEC)
tamuray@jamstec.go.jp

Workshop report (2012) entitled "Ultra-deep drilling into arc crust: genesis of continental crust in volcanic arcs" is below.
http://www.jamstec.go.jp/ud2012/

Scientific Objectives and Global Impact

The over-arching science objective for ultra deep drilling into the middle crust of the IBM arc is to understand how juvenile arc crust forms and differentiates. This objective directly supports the International Ocean Discovery Program Theme 4: Earth Connections: Deep Processes and their Impact on Earth's Surface environment, specifically Challenge 11: How do subduction zones initiate, cycle volatiles, and generate continental crust?

Site Coordinates	Approximate Water Depth (m)	Approximate Penetration Depth	
		Sediment (m)	Basement (m)
IBM-4	1798 m	800	4700

Rationale for Deep Drilling

The proposed drilling of intact upper to middle oceanic arc crust - without the structural complications accompanying collision - to penetrate an entire crustal-scale volcanic-plutonic connection has never been done before. Consequently ultradeep drilling in the Izu forearc can be expected to result in a quantum advance in our understanding of the solid Earth system.

Technical Challenges (if already known)

Ultra-deep drilling into hard rocks

Potential for Discovery and Societal Relevance

This research program promises to transform our understanding of the solid Earth at the same time that it will lead to advances in techniques and strategies that must be met if we are to successfully meet the challenges of other deep crustal drilling projects such as Project Moho. Moreover, the acknowledged temperature limit to microbial life at ~120°C will be encountered at the depth of 3.5 km bsf, which is the boundary between upper and middle crust. What will the biosphere consist of as we drill down to and across this inferred temperature limit?

Chikyu +10 Workshop: Drilling Project Idea

Workshop Theme (*bold/italicize* main theme and underline other relevant themes)

AF (Active Faults), ***OC/EM (Ocean Crust/Earth's Mantle)***, CF (Continent Formation), SS (Sediment Secrets), DL (Deep Life), HYD (Hydrothermal Systems)

Project Title: Carbonation and Serpentinization of Oceanic Crust from Ridge to Subduction Zone: Volatile Budget in the Lithosphere and Recycling in the Mantle

Affiliated proposal? Yes (number) ***Not Yet***

Contact Person and Principal Supporters

Kevin Johnson, Jason Phipps Morgan, Tomo Morishita, Tetsuya Sakuyama

Scientific Objectives and Global Impact

Carbonation and serpentinization of oceanic mafic and ultramafic rocks are intimately related processes and are ubiquitous wherever seawater circulates through seafloor igneous rocks. These processes are sinks for CO_2 and H_2O as well as other volatile elements and the reactions also create chemical and thermal conditions conducive for metabolic activity in some microorganisms. Ultimately the altered oceanic crust is returned to the mantle at subduction zones and reintroduced into the convecting engine of plate tectonics. The main volatile species, CO_2, H_2O, and SO_2, involved in these processes have direct influence on life in virtually every ecosystem on Earth, and understanding these processes is critically important.

Site Coordinates	Approximate Water Depth (m)	Approximate Penetration Depth	
		Sediment (m)	Basement (m)
this work is needed at M2M, outer rise faulted blocks, LIPS, and many other locales.	Any		

Rationale for Deep Drilling

It is critically important to map out the depth limits of fluid penetration and the extent of chemical reactions that involve seawater CO_2 and H_2O.

Technical Challenges (if already known)

High temperatures, hole stability, sample recovery

Potential for Discovery and Societal Relevance

The potential for discovery and societal relevance is immense in terms of understanding fluxes of key volatile species, bio-activity related to these reactions, better understanding of fluid penetration in a variety of important tectonic environments, and potential sinks of key greenhouse gases.

Chikyu +10 Workshop: Drilling Project Idea

Workshop Theme (*bold/italicize* main theme and underline other relevant themes)
AF (Active Faults), OC/EM (Ocean Crust/Earth's Mantle), CF (Continent Formation), ***SS (Sediment Secrets)***, DL (Deep Life), HYD (Hydrothermal Systems)
Project Title
Drilling of mid-Cretaceous shallow marine limestone
Affiliated proposal? Not Yet
Contact Person and Principal Supporters
Junichiro Kuroda (kurodaj@jamstec.go.jp), Naohiko Ohkouchi, Elisabetta Erba, Millard F. Coffin, and Takashi Sano
Scientific Objectives and Global Impact
- Understanding how massive eruption associated with emplacement of Ontong Java Plateau (OJP) impacted the Earth's environments (atmosphere, ocean and marine ecosystem). - Investigation on the causal mechanisms of 'extremely shallow water' black shale deposited during the Oceanic Anoxic Event-1a (120 Ma). - Understanding formation of seamount (atoll) in the Mid-Pacific Mountains based on investigation on basement rocks.

Site Coordinates	**Approximate Water Depth (m)**	**Approximate Penetration Depth**	
		Sediment (m)	**Basement (m)**
Resolution Guyot 21°20'N, 174°19'E (at 866A)	Resolution Guyot 1,370 m (at 866A)	1,620 m	200 m

Rationale for Deep Drilling
Our first priority is coring through the 1,620 m carbonate rocks plus 200 m volcanic rocks. Therefore, deep drilling is not necessary.
Technical Challenges (if already known)
Although limestone succession has been recovered at several guyots by D/V JOIDES Resolution during the ODP Leg 143, recoveries of cores were mostly less than 25% in the limestone interval. We strongly believe that drilling capacities in Chikyu improve core recovery substantially, compared to the previous scientific drillings.
Potential for Discovery and Societal Relevance
Strong social relevance to understand how massive volcanic degassing caused climatic/environmental changes, as well as sealevel changes.

Chikyu +10 Workshop: Drilling Project Idea

Workshop Theme (*bold/italicize* main theme and underline other relevant themes)			
AF (Active Faults), OC/EM (Ocean Crust/Earth's Mantle), CF (Continent Formation), ***SS (Sediment Secrets)***, DL (Deep Life), HYD (Hydrothermal Systems)			
Project Title Mesozoic Global Environments			
Affiliated proposal? Yes (number) #61 and #79 (legacy) Not Yet √			
Contact Person and Principal Supporters			
Mike Coffin, Institute for Marine & Antarctic Studies, University of Tasmania mike.coffin@utas.edu.au James Channell, Elisabetta Erba, Hugh Jenkyns, Judith McKenzie, James Ogg, Michael Storey, Ellen Thomas			
Scientific Objectives and Global Impact			
Objectives: to understand 1) fundamental mechanisms that drive climate and oceanic variability on long timescales, 2) Mesozoic climate processes and mechanisms that sustained the greenhouse Earth, 3) event(s) or process(es) that terminated greenhouse climate patterns, 4) dominant frequencies of Milankovitch forcing during the greenhouse Earth, 5) operation of and variation in Mesozoic biogeochemical cycles, 6) effects of evolution, extinctions, and radiations on Mesozoic carbon cycles, 7) Mesozoic variations of carbon cycles and budgets between continental shelves and the open ocean, 8) CCD variability during the Mesozoic, 9) balance between oceanic and continental chemical fluxes in the Mesozoic, 10) Mesozoic history of oceanic oxygenation and black shales. **Global impact**: Continuous geologic/climatic records from Tethys will fill a major gap in the global array—the deep ocean. Most existing Mesozoic climatic/oceanic records are from the Atlantic. During the Mesozoic, however, the Atlantic Ocean was a relatively narrow seaway, and oceanographic conditions must have been quite different in the Tethyan-Pacific realm that dominated the aquatic world.			
Site Coordinates	**Approximate Water Depth (m)**	**Approximate Penetration Depth**	
		Sediment (m)	**Basement (m)**
tbd: 3°-4°N, 45°-50°E	~4000 - 5000	~2500	~200
Rationale for Deep Drilling			
High-resolution Mesozoic pelagic sections from Tethys are only accessible by deep drilling.			
Technical Challenges (if already known)			
A similar depth of penetration in sediment has been achieved by *Chikyu* in non-riser mode, but no igneous basement was penetrated. Riser drilling may or may not be necessary. JOIDES *Resolution* has never achieved such depth of sediment or igneous basement penetration. Piracy is a challenge, if not necessarily technical. *Chikyu* was protected by the Kenyan navy while drilling offshore Kenya in 2007, and recent and current seismic exploration and drilling offshore Kenya and Tanzania is protected by naval vessels.			
Potential for Discovery and Societal Relevance			
Enormous potential for discovery; understanding the greenhouse Earth better will provide society with insights into Anthropocene environmental changes.			

Chikyu +10 Workshop: Drilling Project Idea

Workshop Theme (*bold/italicize* main theme and underline other relevant themes)

AF (Active Faults), OC/EM (Ocean Crust/Earth's Mantle), CF (Continent Formation), SS (Sediment Secrets), DL (Deep Life), HYD (Hydrothermal Systems)

Project Title

Kanto Asperity Project KAP Program B
Geodetic and geophysical monitoring of slow-slip events in the southern Kanto region for revealing the processes of slow-slip events and establishment of earthquake generation models

Affiliated proposal? Yes (number) 770-Full3

Contact Person and Principal Supporters

Toshinori Sato, Chiba University, Japan
satot@earth.s.chiba-u.ac.jp tel:+81-43-290-2849 fax:+81-43-290-2859

Scientific Objectives and Global Impact

This project proposes shallow drilling (400-900m) at six sites and constructs an observation network covering the Boso slow slip events to obtain 2 to 3 cycles of the slip distribution during entire event cycles in 10-15 years. Using the data, we reveal the process of SSEs and establish realistic physical models of earthquake generation cycle. The established earthquake cycle models can apply to normal earthquakes. This means that we can forecast earthquakes physically.

Site Coordinates	Approximate Water Depth (m)	Approximate Penetration Depth	
6 sites		Sediment (m)	Basement (m)
140.50, 34.71	2000	300	100
140.66, 34.88	1645	600	100
140.81, 35.04	1225	500	100
141.11,35.34	565	600	100
140.77,34.60	3460	300	100
140.89,34.95	1840	800	100

Rationale for Deep Drilling

To obtain precise slip distributions, we need to use tilt meters in boreholes. Reliable tilt observations can be achieved in sedimentary section with Vp 2km/s. At off Boso, this section is about 400-900m bsf. Therefore, this project is riserless and can conduct in very short term.
The last Boso SSE occurred in 2011. Then the next Boso SSE will occur 2016-2017. So, we want construct at least one observatory before the next events.

Technical Challenges (if already known)

Our observatories can be connected to ocean bottom cable systems such as Cable Observatory System at Japan trench (under construction by NIED). If so, our observatories can be a part of monitoring network around Japan.

Potential for Discovery and Societal Relevance

Our observatories can detect large earthquakes such as 1677 Enpo earthquake (M8) which generated large tsunamis, and located south of 2011 Tohoku earthquake.

Chikyu +10 Workshop: Drilling Project Idea

Workshop Theme (*bold/italicize* main theme and underline other relevant themes)

AF (Active Faults), ***DL (Deep Life)***, HYD (Hydrothermal Systems)

Project Title: *Discovering signatures of deep soft matter through the mud-volcano observatory and DONET*

Affiliated proposal? Not Yet

Contact Person and Principal Supporters

Fumio Inagaki, Akira Ijiri, Eiichiro Araki, Yoshio Nishio, Yusuke Kubo (JAMSTEC), Achim Kopf, Kai-Uwe Hinrichs (Univ. Bremen), Juichiro Ashi (Univ. Tokyo), Jinwook Kim (Yonsei Univ.), and the JAMSTEC Chikyu Expedition 906 Scientists.

Scientific Objectives and Global Impact

Submarine mud-volcanoes are globally distributed in the plate accretionary margins, which are formed by the vertical intrusion of a lower density and deformable materials from the deep realm to the seafloor. In the Nankai accretionary wedge, there are ten or more mud-volcanoes associated with the fault structures of the Kumano basin.

In 2009 and 2012, the *Chikyu* explored one of the most active mud-volcanoes (i.e., no. 5) from the summit down to the depth of 200m, providing unique opportunities to study the geophysical, geochemical and microbiological characteristics of the deep mud-volcano subsurface. The *in-situ* temperature measurement indicated the gradient of 24ºC, corresponding the Bottom Simulating Reflector (BSR) within the mud-volcano at 590 m from the summit. The preliminary isotopic results of H_2O, CH_4 and Li have revealed that (1) porewater fluids are derived from the dehydration of clay minerals (e.g., smectite-illite reaction), (2) methane are derived from deep biogenic processes, and (3) high concentration of Li is derived from the high-temperature environment at least over 350ºC (see **Fig. 1**). Furthermore, exceptionally high concentrations of H_2 have been observed in the cored sediment, which is possibly derived from the fault-associated friction.

These our accumulating data from the Kumano mud-volcano no. 5 have consequently led a new scientific hypothesis: ***Are fluid and gas chemicals (and possibly the deep mud-volcano biosphere) transported through the diapiric channel sensitively responding to the deep seismogenic behaviors?***

To test this hypothesis, we would like to propose for the first time the long-term geophysical, geochemical, and microbiological observatory of deep mud-volcano subsurface in connection with the DONET (**Fig. 2**).

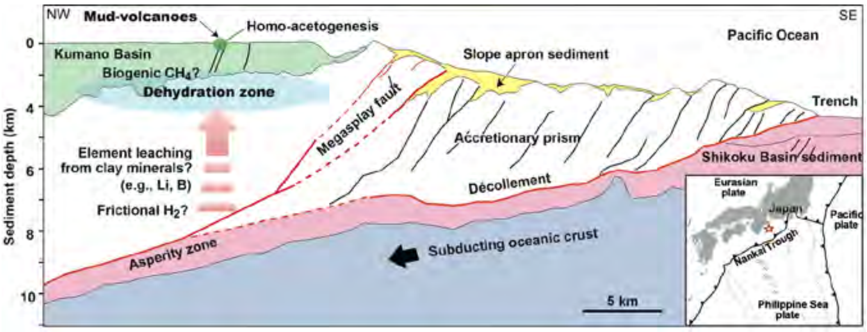


Fig. 1. A schematic figure of the Nankai accretionary wedge transect. (Ijiri et al., in prep.)

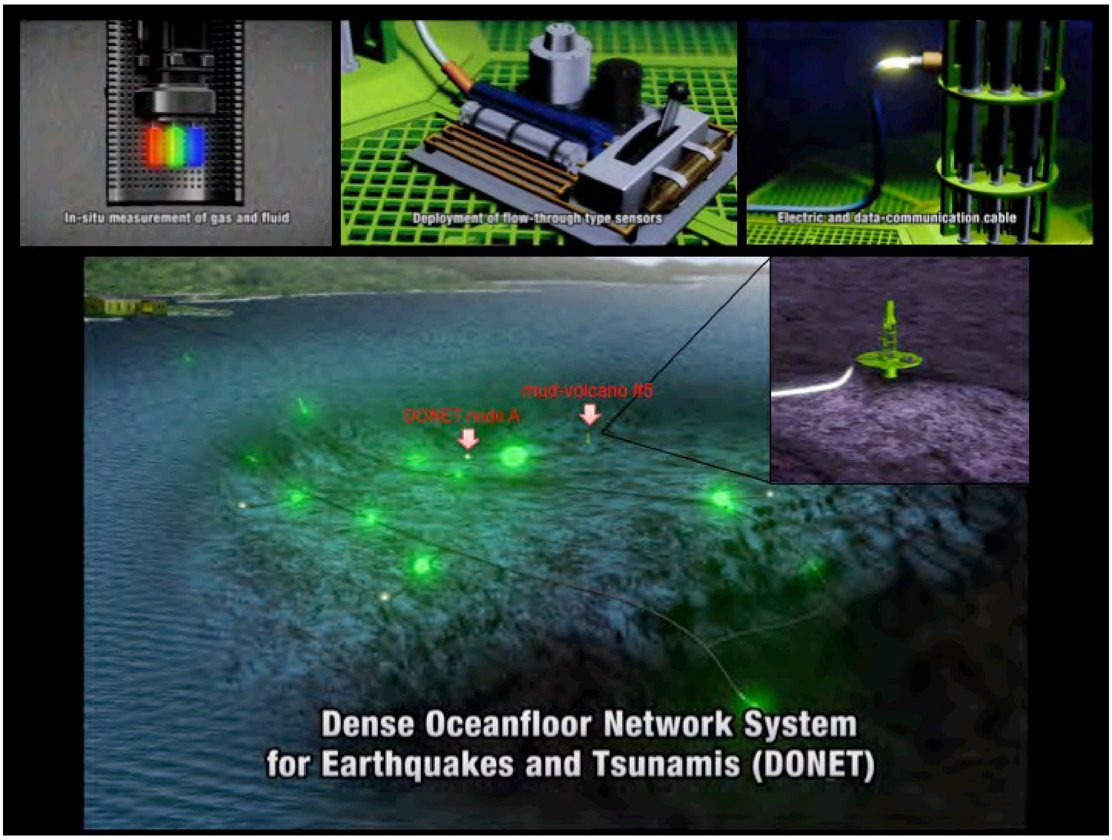


Fig. 2. The deep mud-volcano observatory and DONET.
The mud-volcano no. 5 is approximately 5km distant from the DONET node A.

Site Coordinates	Approximate Water Depth (m)	Approximate Penetration Depth	
		Sediment (m)	**Basement (m)**
33°67.581N, 136°56.8085E	1,986 m	650 m	-

Rationale for Deep Drilling

The proposed site is located in the most-well studied accretionary wedge that has been explored by the *Chikyu*. The feasibility to utilize the DONET system is high because of the close location to the node A (i.e., 5 km in distance), and the data will be able to compare any records from the seafloor and other borehole observatories (e.g., Site C0002). The *Chikyu* has ever drilled the mud-volcano no. 5 at Site C9004 and C9005 down to 200m in 2009 and 2012, and the operational data such as drilling parameters for the sticky mud are available at the CDEX.

Technical Challenges (if already known)

Feasibility of the proposed operation is high and the cruise duration will be relatively short, assuming less than a few weeks. The design of sensors and casing pipe is a key: because H_2 is supposed to be a crucial factor that may sensitively respond to the frictional reaction, the use of steel casing pipes is not adequate. Instead of steel, either CRFP or glass fiber casing is recommended (cf. Expedition 336). To prevent stacking the gas/fluid flow-through line by hydrate formation in, Teflon-coated line is probably better for the use. The borehole may

shrink, requiring quick drilling and the casing deployment. The Hybrid-PCS will be used for the gas analysis since H_2 and other hydrocarbons are critical factor for the subsequent analyses through the observatory. During the test operation in 2012, the Hybrid-PCS coring had been technically unsuccessful for the shallow soft mud formation, however will presumably be available for the deep consolidated mud in the deeper zone,. The 3.5m-PCS core needs to be transferred with keeping the pressure and temperature, for which the GeoTeck Pressure Core Analysis and Transfer system (PCAT, 3 connected 20ft containers with ice-shock hole) is only the system deployable for the *Chikyu* in terms of the size capacity, and hence only the *Chikyu* can do this project operation. The site will be visited by ROV to connect the cables with the DONET, which will need support from JAMSTEC.
Potential for Discovery and Societal Relevance
If our isotope data-driven hypothesis is correct, the data output from the mud-volcano observatory will be an enormous impact on the retrieval of (pre)seismic signatures in the Nankai accretionary wedge. The observed data will be significantly expanding our knowledge of the seismogenic zone in the Nankai accretionary wedge, as the behavior of "***soft mater***" (e.g., fluid flux, gas composition, redox, small elements such as H2, Li, etc.) that have never been explored through the observatory missions of scientific drilling. Comparing with other seafloor and borehole observatories that have already been equipped (i.e., DONET and C0002+, respectively), we will be able to obtain a high quality data set, of which societal relevance as well as its novelty is extremely high. The discoveries will be of great interest to geoscientists, life scientists and public people.

Chikyu +10 Workshop: Drilling Project Idea

Workshop Theme (*bold/italicize* main theme and underline other relevant themes)
SS (Sediment Secrets), ***DL (Deep Life)***, HYD (Hydrothermal Systems)
Project Title: ***The ultra-deep coalbed biosphere (Shimokita II): Exploration of the limits of life and deep carbon cycle associated with the 4km-deep coalbed methane.***
Affiliated proposal? Not Yet
Contact Person and Principal Supporters
Fumio Inagaki, Tatsuhiko Hoshino, Akira Ijiri, Yusuke Kubo, Yuki Morono (JAMSTEC), Kai-Uwe Hinrichs, Verena Heuer (Univ. Bremen), Yasuhiro Yamada (Kyoto Univ.), Takeshi Tsuji (Kyushu Univ.), Mark A. Lever (Aarhus Univ.), and Expedition 337 Scientists.
Scientific Objectives and Global Impact

The IODP Expedition 337 was the first microbiology-biogeochemistry dedicated riser-drilling in the offshore hydrocarbon system associated with deeply buried coalbeds. The limits of subseafloor life and the biosphere is one of the fundamental scientific questions that can only be addressed by the deep drilling. In addition, the deep carbon cycle associated with offshore hydrocarbon reservoirs is highly relevant to the global climate and biogeochemical carbon cycles as well as to the societal issues of energy resources and CO_2 sequestration; however, our scientific knowledge of these fundamentally significant questions is very limited because of the lack of drilling opportunity in such deep hydrocarbon reservoirs.

In 2012, Expedition 337 successfully drilled down to the extended world depth record of 2466 meters below the seafloor, providing an unprecedented opportunity to tackle these important questions. The depositional environment in the sedimentary sequence shows the transition from deep-sea to lagoon or wetlands, and the entirely exposed land deposit (e.g., soil) has not been observed –this is critical for studying the molecular and functional evolution of subseafloor microbial ecosystems associated with the environmental change. Our efforts on shore-based analysis of the 337 samples are still on going, revealing that we might have not still reached at the depth limit of life at 2.4km-depth and the diagenetic processes of the lignite coals stimulate the indigenous deep microbial population. The temperature at 2.4km-depth was measured at 60ºC, which is still within the habitable range of microbial life. The carbon and deuterium isotopic values of methane strongly indicate that methane is mediated by biological CO_2 reduction, meaning that we could not have reached at the end-member of thermogenic methane and other hydrocarbons.

Given these preliminary results from Expedition 337, we should consequently consider to have an opportunity to drill down to the 4.5km-deep coalbed by the *Chikyu* riser drilling, at which temperature *in-situ* is presumably close to the upper limit of life, and the terrigenous sediment hosts the thermogenic coalbed methane (CBM) and other end-member compositions. The predicted age in the proposed depth interval is Eocene to Cretaceous, providing useful references for the study of paleoclimate and formation history of the old continental margin.

<table>
<tr><th>Site Coordinates</th><th>Approximate Water Depth (m)</th><th colspan="2">Approximate Penetration Depth</th></tr>
<tr><td rowspan="2">IODP Site C0020 (JAMSTEC Site C9001) off Hachinohe, Japan</td><td rowspan="2">1900 m</td><th>Sediment (m)</th><th>Basement (m)</th></tr>
<tr><td>4500 m</td><td>-</td></tr>
</table>

Rationale for Deep Drilling

The 4.5km-deep hydrocarbon reservoir (i.e., coalbed methane) is only drillable with riser system, and the mud-gas geochemical monitoring as well as the non- (or less-)contaminated sampling of cores with its continuous PFT assay can only be performed by the science-dedicated drilling facilities on the *Chikyu*.

Technical Challenges (if already known)

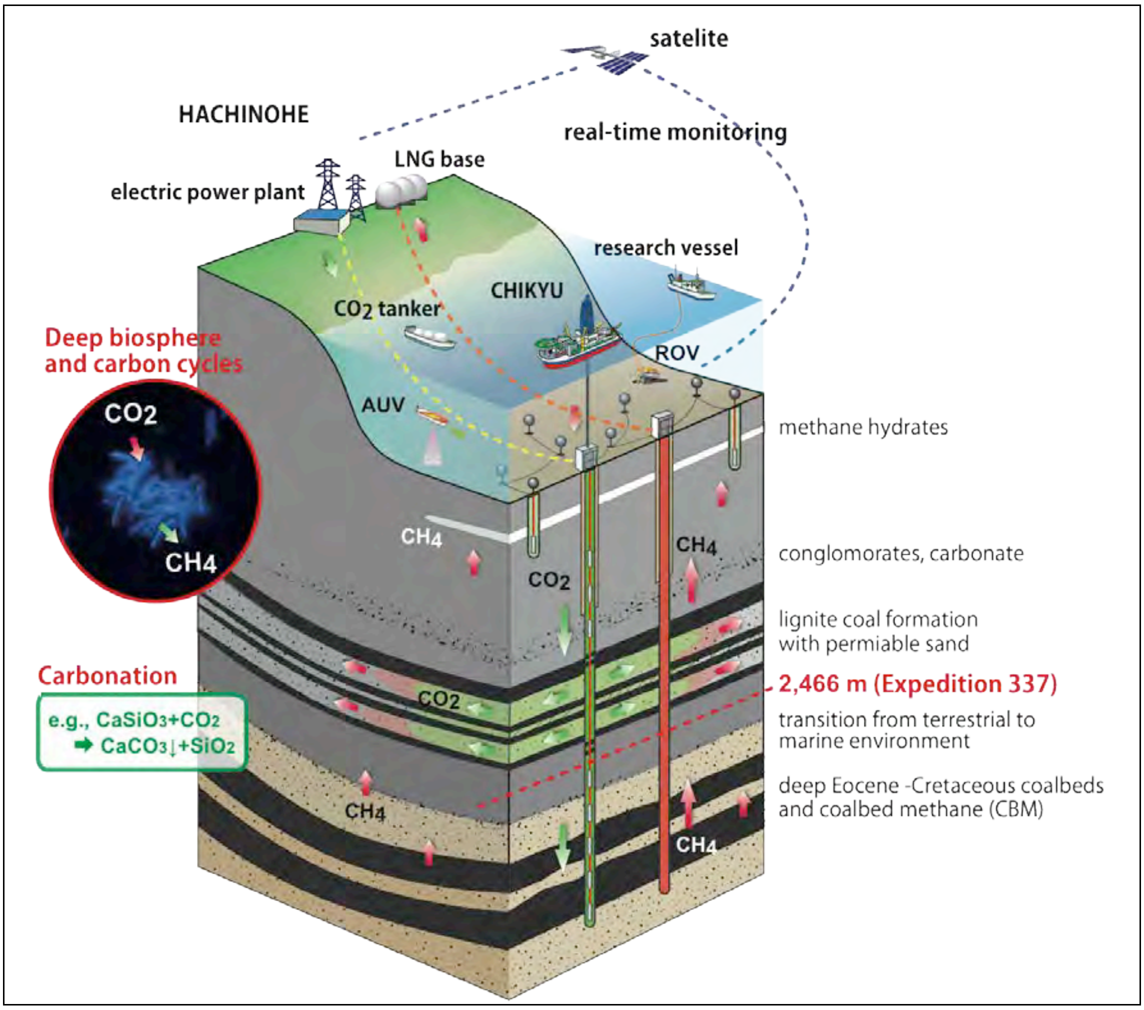
The riser borehole at Site C0020 Hole A (2,466 mbsf) has been suspended since Expedition 337; however, the feasibility of deeper riser drilling should be considered because the hole was not originally designed in 2006 for drilling such a great depth of high-pressure zone associated with CBM. If Hole C0020A has an operational risk, making another deep-riser hole nearby Hole A might be safe and feasible. In this case, having two riser boreholes will have tremendous merits as "*natural subseafloor laboratory*" for scientific and/or industrial purposes: e.g., CO_2 sequestration into 2km-coal/sand formation or 4km-CBM for its enhanced gas recovery (EGR) are only testable through multiple boreholes by controlling the pressure, and one can be used for the injection hole of CO_2 or other type of fluids, and other can be for the observatory (e.g., VSP and other real-time wireline logging at Hole A and CO_2-fluid injection at Hole B). This might be the case for the next step, but should design the borehole condition that reflects conceivable future projects in collaboration with the oil/gas industry.

The quality of circulation mud should be improved for the study of deep life and carbon. To minimize the contamination of core samples, the routine use of large diameter core is preferential.

The detailed wireline logging data (from Expedition 337) and 3D seismic images exist.

Potential for Discovery and Societal Relevance

The proposed expedition is the first scientific deep-riser drilling targeting on the host-rock of the globally distributed offshore hydrocarbon system. Discovery of the deepest microbial ecosystem, molecular and biogeochemical functions, and new views of the extent of the subseafloor biosphere, paleoclimante and formation history of the Eocene-Cretaceous continental margin, co-evolution of microbial ecosystem associated with forearc history, and the deep carbon and energy cycles can be expected (but not limited to). The results will be highly relevant to some societal issues such as energy and carbon, opening a new window to the innovative geobiological application in the deep coalbed biosphere as well as to the creation of sustainable systems relevant to the energy and carbon cycles.



satelite
HACHINOHE
real-time monitoring
LNG base
electric power plant
research vessel
CHIKYU
CO_2 tanker
Deep biosphere
and carbon cycles
ROV
CO_2
AUV
methane hydrates
CH_4
CH_4
CH_4
CO_2
conglomerates, carbonate
lignite coal formation
with permiable sand
Carbonation
2,466 m (Expedition 337)
CO_2
e.g., $CaSiO_3+CO_2$
➡ $CaCO_3\downarrow+SiO_2$
transition from terrestrial to
marine environment
deep Eocene -Cretaceous coalbeds
and coalbed methane (CBM)
CH_4
CH_4

Chikyu +10 Workshop: Drilling Project Idea

Send to <ws2013_info@jamstec.go.jp>

Workshop Theme (*bold/italicize* main theme and <u>underline</u> other relevant themes)

AF (Active Faults), OC/EM (Ocean Crust/Earth's Mantle), CF (Continent Formation), SS (Sediment Secrets), <u>DL (Deep Life)</u>, HYD (Hydrothermal Systems)

Project Title Unlocking the secrets of slow slip by drilling at the northern Hikurangi subduction margin, New Zealand: Riser drilling to intersect the plate interface

Affiliated proposal? Yes (number) 781B-Full

Contact Person and Principal Supporters

Laura Wallace, Yoshihiro Ito, Stuart Henrys, Harold Tobin, Shuichi Kodiara, Susan Schwartz, Miriam Kastner, Lisa McNeill, Kimi Mochizuki, Greg Moore, Arito Sakaguchi. Note: I have listed proponents who were present at the C+10 workshop. See proposal for full proponent list.

Scientific Objectives and Global Impact

Over the last decade, the discovery of episodic slow slip events (SSEs) at subduction margins around the globe has led to an explosion of new theories about fault rheology and slip behavior along subduction megathrusts. ***The northern Hikurangi margin is the only place on Earth where well-documented SSEs occur on a subduction interface within range of scientific drilling capabilities.*** Drilling, down-hole measurements, and sampling of the northern Hikurangi SSE source area provides a unique opportunity to definitively test hypotheses for the physical conditions and rock properties leading to SSE occurrence, and ultimately, to unlock the secrets of slow slip.

This proposal is for the deep, riser drilling component of a recently submitted Multi-phase Drilling Project (781-MDP) proposal for IODP drilling to discern the mechanisms of subduction zone slow slip events (SSEs) by drilling into the source area of SSEs at northern Hikurangi. The primary aims of the riser phase are to sample, log, and conduct downhole measurements in the hanging wall and across the plate interface where SSEs occur.

Here, we propose a single riser borehole intersecting the plate interface at 5-6 km bsf, to **collect samples, geophysical logs and make downhole measurements at the source of SSEs**. The riser borehole is designed to address two fundamental scientific objectives: (1) characterize the composition, mechanical properties, and structural characteristics of the megathrust in the slow slip source area; and (2) characterize hydrological properties, thermal regime, stress, and pore pressure state *above and within* the SSE source region. Together, these data will test a suite of hypotheses about the fundamental mechanics and behavior of slow slip events, and their relationship to great subduction earthquakes.

We also expect that comparison between cores and logs from deep, riser drilling of the subduction interfaces at both north Hikurangi and Nankai (the NanTroSEIZE project) will address the mystery of why some subduction zones rupture in Great earthquakes (e.g., Nankai), while others are dominated by aseismic creep (e.g., N. Hikurangi).

Site Coordinates	Approximate Water Depth (m)	Approximate Penetration Depth	
		Sediment (m)	Basement (m)
38º 43.637'S 178º 36.854E	994	6000	

Rationale for Deep Drilling
To address objectives we are targeting the slow slip event source area which is at 5-6 km below the seafloor. Riser drilling is required to reach the target.
Technical Challenges (if already known)
We don't anticipate significant technical challenges beyond those typically associated with riser drilling. Installation of long-term, deep borehole observatories will be challenging.
Potential for Discovery and Societal Relevance
The physical mechanisms producing episodic slow slip behavior are a huge topic of debate within the seismological community. Many theories have been put forth for the origin of these events, including elevated fluid pressures and conditionally stable frictional behavior. This project offers a unique opportunity to actually test these ideas and determine why slow slip occurs. Moreover, comparison of results from NanTroSEIZE, JFAST, and Hikurangi drilling has the potential for scientists to understand what makes a subduction zone lock-up and slip in great earthquakes (e.g., Nankai, Japan Trench), while others are dominated by aseismic creep and smaller earthquakes. Comparison of these sites could truly transform our understanding of seismic and tsunami hazard posed by subduction zones. Slow slip is also now known to play a role in the timing of great megathrust earthquakes, such as the Japan trench earthquake. Absolute pressure gauges on the seafloor offshore northern Japan detected a slow slip event in the month leading up to the Mw 9 earthquake. Stress changes due to that slow slip may have triggered the Mw 9 earthquake and resulting tsunami, making it even more imperative to understand slowly slipping areas as well as seismogenic areas. There is a direct societal relevance to monitoring subduction thrust processes on the northern Hikurangi margin, as that portion of the margin has had historical "tsunami" earthquakes that occurred just updip of the slow slip drilling target.

Chikyu +10 Workshop: Drilling Project Idea

Workshop Theme (*bold/italicize* main theme and <u>underline</u> other relevant themes)
AF (Active Faults), <u>OC/EM (Ocean Crust/Earth's Mantle)</u>, CF (Continent Formation), <u>SS (Sediment Secrets)</u>, <u>DL (Deep Life)</u>, HYD (Hydrothermal Systems)
Project Title: Earthquakes with Large Slip to the Japan Trench: Mechanisms and Geologic History
Affiliated proposal? Yes (number) **Not Yet**
Contact Person and Principal Supporters
<u>Shuichi Kodaira</u>, Jim Mori, Jim Sample, Jan Berhmann, Ryota Hino, Takehiro Hirose, Matt Ikari, Ken Ikehara, Tsuyoshi Ishikawa, Toshiya Kanamatsu, James Kirkpatrick, Sumito Morita, Yasuyuki Nakamura, Liz Screaton, Bunichiro Shibazaki, Michael Strasser, Ken Takai, Marta Torres, Virginia Toy, Kohtaro Ujiie, Paola Vannucchi, Gerold Wefer
Scientific Objectives and Global Impact

We propose an investigation of the record of great earthquakes in the Japan Trench, a setting where only three years ago we would not have considered such events possible. The occurrence of the 2011 M 9.0 Tohoku-oki earthquake triggered a paradigm shift in our understanding of slip behavior in shallow subduction zones. We are formulating new hypotheses that (i) subduction zones have mega-earthquake super-cycles not covered in instrumental and historical data, and (ii) the occurrence and spatial variation of earthquake slip-to-trench is governed by (a) the structure of the weak layer or (b) special physical properties of the slip layer or (c) the geometry of the incoming plate.

These hypotheses can be tested by a program of drilling transects parallel and perpendicular to the trench. Scientific questions to be addressed include: 1) How often does this fault zone slip in great earthquakes? 2) What is the nature of slip along strike related to this large earthquake? 3) What are the present post-seismic deformation rates and how are they related to the earthquake cycle? 4) What physical properties and deformation mechanisms govern strain energy accumulation and release at shallow depths? 5) What can b learned about the physics controlling rupture to the trench and shallow slip? 6) What are the current hydrologic conditions that characterize this active high-slip fault zone? 7) What can we infer about pre-earthquake pore pressures from denser sampling across faults?

The initial stages of the research can be accomplished by drilling three transects across the trench, one at the latitude of Site C0019, and one each to the north and south of this region to understand variations in megathrust behavior related to difference in input and material properties in the megathrust zone. Along each transect we propose to drill a site on the Pacific Plate east of the trench as a reference site, 1-3 sites along the trench axis, and 1-2 sites into the prism that would penetrate well into the lower plate.

At a minimum, coring would be required at key horizons. These include the upper 50-100 meters of trench fill to gather samples for spatial and temporal correlation of seismo-turbidites for a history of Japan Trench mega-earthquakes, the likely stratigraphic level of the megathrust in the incoming sedimentary section to characterize its physical properties, the frontal sedimentary prism above the plate boundary to characterize its structure, physical properties and hydrogeology of prism, and complete sampling across the décollement horizon.

Observatories should be established at one or more key sites to monitor post-seismic behavior of the megathrust zone.

The result of this research will bear importantly on other convergent margins where tsunamigenic great earthquakes have a high potential of occurrence. These include the Costa Rica and New Zealand margins, for which the Japan Trench is held as an important example of what could occur at other places in the Pacific Rim.

Site Coordinates	Approximate Water Depth (m)	Approximate Penetration Depth	
		Sediment (m)	Basement (m)
TBD, but in rectangular area defined roughly by 35N, 142E in the SW, and 41N, 145E in the NE.	7000 to 8000 m	Varies from 500-1000	≤ 100 m

Rationale for Deep Drilling

This historically unprecedented slip event is only accessible in the Japan Trench. Shallower water in not an option, since moving upslope to the west of proposed area requires a sediment penetration to reach the megathrust boundary that is too great. This project is proposed as a series of drill holes in deep water, which can be drilled in stages during separate expeditions as time becomes available of the Chikyu.

Technical Challenges (if already known)

Use of supporting technologies (e.g., underwater TV, ROVs) presents some difficulties at great water depths. However hole conditions were quite stable during drilling at Site C0019.

Potential for Discovery and Societal Relevance

Such a large slip has never been observed by geoscientists and has caused a re-evaluation of the paradigm of earthquake mechanisms and the potential for tsunami generation at convergent boundaries. The great earthquake has already happened. It resulted in severe economic damage and loss of life. Now we need to understand why and how often so much slip occurred at the trench, if we are to be able to model the potential for similar behavior at other plate boundaries around the Pacific Rim, and how deformation during these events is linked to structures in the incoming and downgoing plates and plate interface. In our one previous visit to the margin, we recovered only ~53 meters of core material, which did not include complete sampling of the megathrust boundary zone, and is not adequate to characterize this system.

Chikyu +10 Workshop: Drilling Project Idea

Workshop Theme (*bold/italicize* main theme and underline other relevant themes)
AF (Active Faults), OC/EM (Ocean Crust/Earth's Mantle), CF (Continent Formation), SS (Sediment Secrets), DL (Deep Life), HYD (Hydrothermal Systems)
Project Title **Shimokita Slump Mechanism**
Affiliated proposal? Not Yet
Contact Person and Principal Supporters
Sumito Morita (GSJ, AIST), Yasuhiro Yamada (Kyoto University), Michael Strasser (ETH Turich), Kiichiro Kawamura (Yamaguchi University)
Scientific Objectives and Global Impact

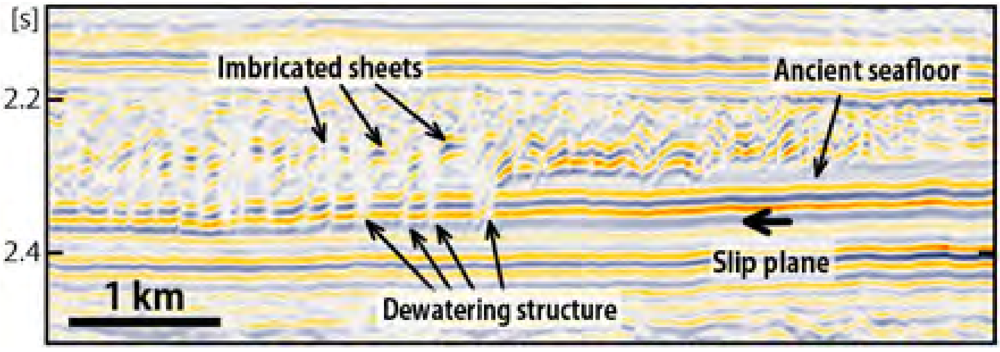
Submarine landslides are regarded as geohazard which sometimes cause or enhance tsunami, cut submarine cables and destroy architectures on the ocean floor. By analyzing recent high resolution 3D seismic dataset, a great number of huge submarine landslide deposits have been identified in Pliocene and shallower sequences in northern Sanriku-oki Basin off Shimokita Peninsula, NE Japan. The submarine landslide (slump) deposits are probably generated by layer-parallel slip on very gentle continental slopes of less than 1 degree in gradient. Therefore, the slump deposits generally avoided fatal collapse while slumping and are composing imbricated thrust sheets which peeling off the ancient surface layers. The horizons corresponding to slip planes of the slump deposits are characterized by low-amplitude having some thickness. The thickness decreases just below the slump sheets, accompanying dewatering structures which cut the slump sheets vertically. This infers that the excess fluid retained in the slip plane was drained by the dewatering.

The sedimentary basin is also known as having hydrocarbon potential. The slump deposits may have potential to maintain gassy formation fluid inside. Gas hydrate BSR occurs only within the slump deposits in the area and some gas chimneys occurs at the top of the roof of the slump deposits. This is the nature just like hydrocarbon reservoirs and is opposite to those of the slump deposits observed in GOM, offshore Brazil, and so on where the slump deposits work as seal.

For the aim of potential geohazard mitigation of this area, we propose a scientific drilling project whose primary target is the slump deposits to enhance our current knowledge on the pre and post failure mechanism of submarine landslides induced by layer-parallel slip. Our fundamental questions are what controls ground instability in such gentle continental slope, and what the initiation process of slip planes is like. As mentioned above, the slump deposits have very simple structure and the slip planes are so clear and easy to trace in the 3D seismic data. The concept of the scientific drilling is to collect definitive information by coring, borehole logging, sidewall operation and long term monitoring to build a suitable model of submarine landslide mechanism. To compare non-deformed (apparent before slumping) bed and deformed (apparent after slumping) bed in a specific formation using several drill sites is one idea of operation. To deploy a long term monitoring system in a shallow low-amplitude layer (a possible future slip plane) is another. To determine age of each slumping is another important issue to determine frequency of slumping periods and check correlation with climate change.

The Shimokita slump deposits are one of the best targets to answer key questions of submarine landslides. The outcomes from this scientific drilling should form the core information for the future marine geohazard mitigation.

Current status of the project is at the beginning of preparation of proposal. We are now investigating suitable locations of candidate sites using a set of high resolution 3D seismic data, and investigating what kinds of research operation should be applied to the project. *Chikyu* actually experienced a riser drilling penetrating some of the slump deposits in this area at Site C9001 on the shakedown cruise in 2006. Sediments were successfully cored in the slump deposits intervals with almost full recovery except for a slip plane portion of zero recovery.



Slump sheets show imbrication structure and dewatering which occur in slip surface cut the imbrication vertically, indicating drainage of excess fluid in the slip plane. Slip planes are clear and characterized by low amplitude reflection.

Site Coordinates	Approximate Water Depth (m)	Approximate Penetration Depth	
		Sediment (m)	**Basement (m)**
TBD (2 to several sites are needed)	800-1,500 [m]	<600 [m]	0 [m]

Rationale for Deep Drilling

Submarine slide research does not really require deep drilling, but the riser system of Chikyu provides fundamental infrastructures to recover cores from potential weak planes, that confirmed through coring of unconsolidated slump deposits at Exp. 902 (Shimokita shakedown cruise) and very soft sandstone layers at Exp. 337.

Technical Challenges (if already known)

Weak planes of submarine slides are generally shallow (<100m) and riser drilling for such shallow targets may be major technical challenges.

To clarify in-situ formation fluid condition is a very important issue and permeability will be a key parameter in this project. How to apply to them may be another technical challenge. To recover the sediments in the slip planes which

are very sweet spots to evaluate initiation process of slip planes is placed on one of the highest priority.
Potential for Discovery and Societal Relevance
Submarine slides have potential to cause / enhance tsunamis and this may the most significant concern by the society, in terms of the Earth-in-motion field of geosciences. The mechanisms and their dynamic processes to generate failures and their post-failure dynamics as well as their consequences are poorly constrained. Ocean drilling is the only one method to get to major discovery of submarine slide research.

Chikyu +10 Workshop: Drilling Project Idea

Workshop Theme (*bold/italicize* main theme and underline other relevant themes)			
AF (Active Faults), ***OC/EM (Ocean Crust/Earth's Mantle)***, CF (Continent Formation), SS (Sediment Secrets), DL (Deep Life), HYD (Hydrothermal Systems)			
Project Title			
Behavior and mass balance of the volatile components in the oceanic plate: sampling from outer rise			
Affiliated proposal? Not Yet			
Contact Person and Principal Supporters			
Tetsuya Sakuyama, Takeshi Hanyu, and Jun-Ichi Kimura (JAMSTEC)			
Scientific Objectives and Global Impact			
- To estimate downhole variation of volatile content (water, carbon, sulfur, etc.) in old oceanic crust at outer rise - To reveal seawater infiltration process through normal fault developed at outer rise - To constrain maximum amount of volatiles to be introduced by the oceanic lithosphere into the mantle - Contribution to estimate global cycle of carbon and other volatile elements - Contribution to study biological activities in deep crust (and mantle)			
Site Coordinates	**Approximate Water Depth (m)**	**Approximate Penetration Depth**	
		Sediment (m)	**Basement (m)**
NW Pacific 1. Offshore NE Japan (e.g., offshore JFAST drilling site C0019) 2. Near ODP Site 1149	5000-6000 m	~400 m at Site 1149	- 1500 m or more - ~6000 m to reach peridotite layer
Rationale for Deep Drilling			
Since recent seismological studies suggest that seawater infiltration reaches even peridotitic layer in the oceanic plate, more amount of volatiles is now expected to be introduced to the deeper oceanic plate than that by previous estimation. Thus, downhole variation of volatile contents in oceanic crust at outer rise is the essential information to estimate amount of volatiles to be introduced into the mantle.			
Technical Challenges (if already known)			
- Deep water depth - Fragility of rocks due to development of faults by bending at outer rise			
Potential for Discovery and Societal Relevance			
- Hydration and formation of carbonate minerals (>several % of carbonate in bulk crust) in deep oceanic crust have been suggested by seismic study on outer rise and petrological study on old oceanic crust before outer rise - Serpentinite formation (10-20% of serpentinization) in the uppermost peridotite in oceanic plate has been suggested by seismic study			

Chikyu +10 Workshop: Drilling Project Idea

Workshop Theme (*bold/italicize* main theme and underline other relevant themes)
AF (Active Faults), OC/EM (Ocean Crust/Earth's Mantle), CF (Continent Formation), SS (Sediment Secrets), DL (Deep Life), HYD (Hydrothermal Systems)
Project Title Seismo/Tsunamigenic Fault Activity Monitoring : The Frontline Formation along Japanese Coast
Affiliated proposal? Yes (number) Not Yet
Contact Person and Principal Supporters
Masa Kinoshita, Sanny Saito (with potential agreement from Earl Davis, Keir Backer, Shuichi Kodaira, Reiji Kobayashi, Eiichi Araki, Harold Tobin)
Scientific Objectives and Global Impact
As we encounter new observations, such as the large coseismic slip or slow-slip events at the *aseismic* part of the seismogenic fault zones, we think that the seismogenesis mechanism has to be reconsidered from a simple 'accretion vs. erosion' end-member model, or from a seismic vs. aseismic zone model. Obviously the key roles for seismogenesis, including above newly-found events, should require more knowledge on the state of effective stress as well as material along the subducting plate interface. During the Chikyu+10 workshop, quite a few white papers include installation of borehole observatories to monitor insitu strain accumulation or pore pressure at the fault zone. Among these, three white papers (CORK array across Nankai, off-Boso slow-slip monitoring, Tohoku array) target subduction zone around Japan. These sites should comprise a significant diversity on their seismogenic characteristics, which should be compared in a systematic way as much as possible. For example, each observatory site should include common measurement items with as much unified specifications as possible. Thus, I came up with an idea of suggesting a 'loose' linkage among these monitoring proposals along the Japan coast, making up a 'seismogenic or Tsunamigenic monitoring frontline'. It can also include collaboration with other observatories in, say, Costa Rica or New Zealand, but as a start I would propose tighter cooperation, on a international basis, among Japan-coast frontline observatories.

Site Coordinates	**Approximate Water Depth (m)**	**Approximate Penetration Depth**	
		Sediment (m)	**Basement (m)**
Sites proposed in the following white papers:			
Davis: Nankai	4000-4800m	500-1000m	0-100m
Tobin/Araki: Nankai	2000-4000m	1000-7000m	0
Kodaira/Lin: Tohoku	6000-7000m	500-1000m	0
Kobayashi: Boso	3000-4000m	500m	0

Rationale for Deep Drilling
One observatory for deep riser site (NanTroSEIZE C0002) is proposed by Araki et al., but it is not technically available for the next few (?) years. Other sites do not require riser.
Technical Challenges (if already known)
Same as stated in Davis et al.
Potential for Discovery and Societal Relevance
Standardized data should be of extreme value for understanding seismogenesis and potential tsunamigenesis, especially for more reliable assessment of Tsunamigenic potential along Nankai Trough, where we face a very high risk of next large earthquakes/tsunamis.

Chikyu +10 Workshop: Drilling Project Idea

Workshop Theme (*bold/italicize*main theme and underline other relevant themes)			
AF (Active Faults), OC/EM (Ocean Crust/Earth's Mantle), CF (Continent Formation), SS (Sediment Secrets), DL (Deep Life), HYD (Hydrothermal Systems)			
Project Title			
Modes and Temporal Variation of Great Earthquakes in the Western Nankai Trough			
Affiliated proposal? Yes (number) xNot Yet			
Contact Person and Principal Supporters			
Contact Person: Masao Iwai[1], Principal Supporters: C. Hans Nelson[2], Yasuhiro Yamada[3], Minoru Ikehara[1], Toshiya Fujiwara[4] Institution (s): 1.Kochi University (Japan), 2.InstitutoAndaluz de Ciencias de la Tierra, CSIC (Spain), 3.Kyoto University, 4.JAMSTEC			
Scientific Objectives and Global Impact			
To obtain continuous uppermost Quaternary section to assess the temporal history of historic and prehistoric Nankai Great Earthquakes during last 200-400kyrs for better understanding of tempo and mode of subduction earthquakes under different climatic conditions.			
Site Coordinates	**Approximate Water Depth (m)**	**Approximate Penetration Depth**	
		Sediment (m)	**Basement (m)**
【Site TB1】 32-53°13'N 134-35°51'E	1650m	205m	0m
【Site TB2 】 32-53°30'N 134-38°00'E	1670m	205m	0m
Rationale for Deep Drilling			
Seismogenic zone at proposed site is ~7-9 km. Late Quaternary section up to 260m in the Tosabae Basin will be a pilot hole prior to drill the seismogenic zone where a subducted seamount making an aspelity.			
Technical Challenges (if already known)			
1. Drilling nearby a cable of the Dense Oceanfloor Network system for Earthquake and Tsunami, DONET2. 2. Drilling in the Kuroshio Current			
Potential for Discovery and Societal Relevance			
It is important and essential for the risk assessment of low frequency/high impact subduction earthquake and tsunami hazardin the climatically unpredictable warming century. Also a deep drilling for a long paleoseismic record has a potential to detect possible superquakes, such as 2011 Tohoku earthquake.			

APPENDIX 5
White Papers

Table of Contents

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CHALLENGES IN MESOZOIC PALEOCEANOGRAPHY

Elisabetta Erba[1]

[1]Department of Earth Sciences, University of Milan, Milan, Italy

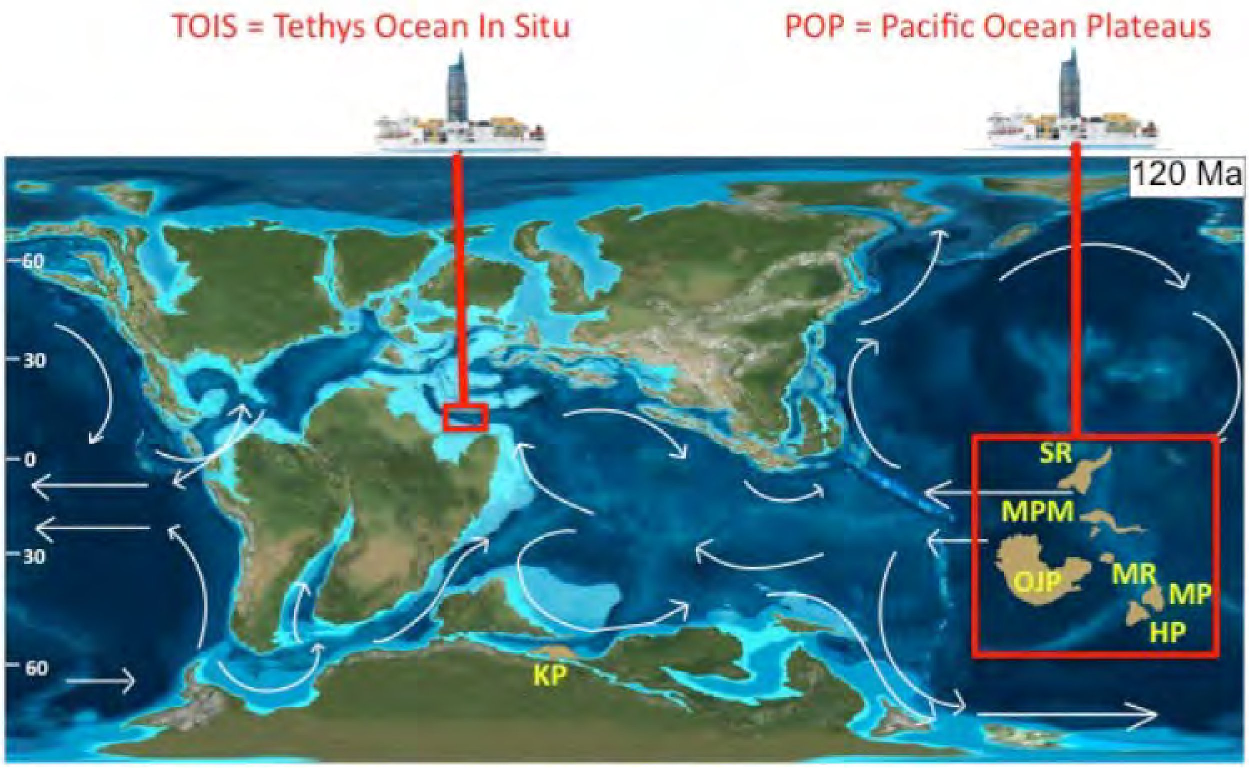
Keywords: paleoceanography, Mesozoic, oceanic anoxic events, ocean fertilization, ocean acidification, marine biosphere evolution.

The Cretaceous ocean was unusual in many aspects and provide opportunities to explore, quantify, and model processes that might impact our current ocean in the (near) future. A pressing issue for humankind is the understanding of the future state of the planet within the context of increasing carbon dioxide (CO2) and other greenhouse gas concentrations, climate change, and the adaptations or extinctions in the Earth's biosphere in response to Anthropocene perturbations. The ocean is the oldest and largest ecosystem on Earth, and biodiversity changes at one trophic level (primary producers) lead to a variety of responses at higher levels. To predict future effects of increasing atmCO2 and other greenhouse gases, global warming, sea level rise, ocean acidification, and eutrophication, short-term current changes require integration with long-term variations. Thus, the geologic record of past environmental perturbations is relevant for understanding current and future global changes, biotic responses, and how and at what rate pre-perturbation conditions are eventually restored.

Cretaceous examples of coupled excess CO2 (and other greenhouse gases) and extreme climates are also associated with global anoxia, making the recognition of individual causes and their role extremely challenging. Major information on Cretaceous oceans was obtained from the early stages of scientific ocean drilling (DSDP), and augmented subsequently (ODP), but significant geographic and stratigraphic limitations prevent a thorough understanding of the causes and consequences of environmental changes. Cretaceous sediment in the global ocean is largely under-sampled, despite its vast geographic extent. Moreover, Cretaceous pelagic sections from the Pacific and Indian oceans, characterized by alternating hard-soft (e.g., chert-chalk) layers, have been exceedingly difficult to core during DSDP, ODP, and IODP. It remains a major technical challenge to improve upon sparse core recovery in such section, and lack of such sections precludes systematic studies of the geological past and applications to our future.

An ad hoc Magellan Workshop will be held in April 2013 to foster new scientific (ocean and continental) drilling projects that will advance understanding of the Cretaceous world, and develop a long-term strategy of drilling targets. Some priority targets require *Chikyu*, a unique platform that has deep riser drilling capabilities to core (and recover) Cretaceous sedimentary sections.

This white paper focuses on major challenges in Mesosozic paleoceanography—Oceanic Anoxic Events, (super)greenhouse climates, marine biota and environment co-evolution—in the Pacific Ocean and the in situ Tethys. In the Pacific, *Chikyu* riser drilling will allow good recovery of Cretaceous and Upper Jurassic sedimentary sections from the Magellan Rise, Shatsky Rise, Ontong Java Plateau, Manihiki Plateau, Hikurangi Plateau, and Hess Rise, where chert and chert-chalk alternations have hampered core recovery. The POP (Pacific Ocean Plateaus) project comprises a number of sites located in water depths currently within *Chikyu*'s range (≤2500 m); other key sites in greater water depths (2500-4000 m) may be drilled when *Chikyu* gains such capabilities. Recent investigations suggest that the Ionian Abyssal Plain of the Eastern Mediterranean might be the oldest in situ ocean fragment of the world, with ocean crust of Late Triassic age. Here, the TOIS (Tethys Ocean In Situ) project proposes to sample a Cretaceous-Jurassic and Upper Triassic section uncontaminated by the Alpine orogeny and subsequent tectonics. The current water depth of the Ionian Abyssal Plain is ~4000 m, and the sedimentary section is estimated to be ~ 7000 m thick. Coring of Tethys in situ is thus an extremely ambitious target comparable to the Moho project.



Map at 120 Ma, modified http://www2.nau.edu/rcb7/globaltext2.html
OJP = Ontong Java Plateau; SR = Shatsky Rise; MPM = Mid-Pacific Mountains; MR = Magellan Rise; MP = Manihiki Plateau; HP = Hikurangi Plateau; KP = Kerguelen Plateau.

The deep riser-drilling vessel *Chikyu* is the only scientific platform capable of retrieving key data from the oceans and provides the scientific community with the opportunity to reach targets inaccessible by any other platform. Implementation of its technical capabilities in the next decade (greater water depths and deeper drilling) will be constitute milestones in scientific exploration of ocean and Earth history.

Chikyu+10 and ICDP: Partners in Scientific Drilling

Brian Horsfield

GFZ German Research Centre for Geosciences, Potsdam, Germany

Keywords: ICDP, strategic cooperation, scientific cooperation, technical exchange, 2013 Science Conference

Protecting society from natural disasters, sustaining economic growth with minimal impact on the environment, supplying an ever-growing world population with raw materials, energy, and potable water, and meeting the challenges posed by global change: these are fundamental challenges facing mankind in the 21st century.

The challenges are inextricably linked with the dynamics of planet Earth, not just at the solid Earth surface on which we live, but also with the chemical reactions, physical shifts and biological interactions taking place beneath our feet. Scientific drilling plays a key role in unravelling and unveiling these processes - from the dark and distant past to the recent present. ICDP is the global leader in that endeavour as far as the continents are concerned, and IODP is the global leader in the marine realm.

Though the two organisations operate in fundamentally different parts of System Earth, each with its own logistical and organisational challenges, it is clear that ICDP can play a key role in deep ocean riser drilling, and that ICDP can learn important lessons from Chikyu operations. This extends all the way from strategic cooperation in future science plans, through scientific cooperation to technical exchange programmes; in other words, the whole spectrum of activities.

Beginning with technical exchange programmes, the tools and methods developed for scientific drilling on land can be readily applied in riser drilling. ICDP courses on cuttings analysis are available for Chikyu scientists, and ICDP experienced scientists have been active on Chikyu cruises for both cuttings analysis and online gas analysis. As far as scientific cooperation is concerned, riser, non-riser and land drilling can and must in future be more fully combined where it makes sense to do so. The coastline basically separates our respective activities, but rather than enforcing a “coastal border” (or coastal barrier”) we need to provide all assistance possible to enable scientists to meet their objectives, by pooling ideas and resources. We have already started this. At the project level, there is the example of IODP/ECORD’s New Jersey Expedition being co-funded by ICDP. Some (pre-) proposals submitted to IODP have also been sent to ICDP (Chicxulub, Beaufort Sea, Ryukyu Islands Reefs), and while this development is a large step in the right direction, it has to be said that the respective review mechanisms are not ideally synchronised. Regarding upcoming new joint actions and targets, drilling targets on land are being addressed by the ocean community, the best current example being the Oman Ophiolite (new ICDP proposal) using the Joides Resolution as a moored offshore laboratory. Our joint publication *Scientific Drilling* is clearly a big success story that both organisations can feel proud of.

The strategic scientific goals of ICDP and Chikyu overlap to a great extent, and therefore the cooperation between the two organisations can be expected to increase. After all, we address the same societal concerns, as iterated in the first paragraph, both organisations being science driven. Two complementary advances regarding natural hazards are the Chikyu drilling of a subduction zone via a megasplay riser pilot in NanTroSeize, and the Rapid Response Drilling idea developed in ICDP. Similarly, the pooling of information from ocean drilling and the drilling of lake sediments is providing new insights into the drivers of Earth climate. And when it comes to natural resources, our complementary studies of gas hydrates are revealing not only how we may be able to produce natural biogenic and thermogenic gas as part of the world's energy-mix, but also how the ecosystems that live in and around them in deep water and permafrost settings develop and thrive.

In short we are at the beginning of a new era of collaborative scientific drilling, promising to radically improve our understanding of how the planet with all its component parts operates, all the way from shallow aquifers and recent sediments, down to the MOHO. We at ICDP are embracing this exciting challenge, and take this opportunity to make everyone aware of our 2013 Science Conference "Imaging the Past to Imagine the Future", taking place in Potsdam, 11-14 November 2013. Hope to see you there!

Why do we need more samples of oceanic peridotite and gabbro?

Craig E. Manning
Dept. of Earth and Space Sciences
University of California, Los Angeles

More than 50 years after it was proposed, an original goal of ocean drilling remains unattained: a single, complete drill hole through fast-spread crust, from ocean floor to Moho and beyond into the mantle lithosphere. The deepest existing holes approach but do not penetrate the dike-gabbro transition. Offset drilling strategies have led to samples of lower crustal and peridotite lithologies. But either spreading rates are slow or a plausible case can be made that exhumation to the shallow crustal depths attainable by drilling has caused deformation, alteration, and metamorphism that mask many of the most important chemical and physical records of the constructional and early cooling history of the crust. The absence of samples of in situ, fast-spread, lower oceanic crust and mantle from a single, crustal-scale hole means that we have better direct sampling of >4.0 Ga materials from our own planet and from the moon than we do from some six km beneath the ocean floor. Thus today, as the Curiosity rover is carries on its drilling program on Mars, we have not yet recovered a single piece of fresh, in situ oceanic peridotite from sub-Moho depths.

The gap in the sampling of fresh, intact components of the deeper oceanic lithosphere significantly limits our understanding of the origin and evolution of the most voluminous components of our planet's crust. These limitations have been articulated repeatedly in proposals to for ocean drilling to the mantle, including the most recent Mohole to the Mantle (M2M) project (www.mohole.org). But recent work highlights our lack of sampling and brings new urgency to the goal. I will discuss two examples.

Metamorphism, fluid-rock interaction, and heat transport in the lower crust. While we understand much about how hydrothermal activity contributes to crustal cooling above the dike-gabbro transition, our ability to link fluid flow, mineral alteration, heat transport from the lower crust remains poor because of sampling problems. Penetration of aqueous fluids into the crustal section occurs on a range of scales and structures. Large through-going fault and fracture zones occur on the hundred- to thousand-meter scale; at the outcrop scale fractures now represented as mineral-filled veins are meters to tens of meters in length and millimeters to centimeters in width; on the thin section scale, microveins and fluid inclusion arrays occur on micron to millimeter scales (e.g., Manning and MacLeod, 1996). Characterization of the role of these structures is essential for understanding the integrated geochemical, thermal, and temporal evolution of the lower crust. For example, the two main models for the construction of the lower crust at fast spreading centers are the gabbro-glacier model (Henstock et al., 1993; Phipps Morgan and Chen, 1993; Quick and Denlinger, 1993), and the sheeted-sill model (Kelemen et al., 1997). These models require distinctly different cooling history and rate. A detailed understanding metamorphic and hydrothermal evolution constrains the extent and rate of water-rock interaction and the pace of subsolidus cooling. Such studies therefore offer the potential to provide basic data with which to evaluate the leading models. Studies of highly disrupted but nominally fast-spread crust in the oceans (e.g., Hess Deep) and ophiolites (e.g., Oman) provide insights, but studies have returned conflicting results (Manning et al., 1996; 2000; Coogan et al., 2007; VanTongeren et al., 2008). It remains unclear which (if any) result is most applicable to in situ, fast-spread oceanic crust, and consequently the links between metamorphism, hydrothermal alteration, and heat transport are unclear. Crustal-scale drilling is required to resolve this problem.

The convecting mantle and the deep carbon cycle. A second example is the volatile content of fresh oceanic mantle rocks. Knowledge of the concentrations of volatile elements such as H, C, S, Cl, etc. in pristine mantle is essential for understanding whether the mantle is gaining or losing these components, and how this may have changed through Earth history. Of particular interest is the role of the mantle in the earth's deep carbon cycle. The Deep Carbon Observatory, a long-term effort aimed at better understanding carbon in the earth (dco.gl.ciw.edu), has stimulated new interest in this topic. The DCO targets four research topics – the chemistry and physics of carbon at extreme conditions, the reservoirs and fluxes of carbon into and out of the earth, deep life, and deep energy. All have significant overlap with the aims of ocean drilling in general, and a Mohole-type project in particular. Of special relevance is the carbon content of fresh oceanic peridotite that has recently been transferred from asthenosphere to lithosphere. Estimates of global volcanic degassing imply that less carbon is being returned to Earth's surface reservoirs than is being subducted, which implies that today there is a net loss of carbon to the interior (Dasgupta and Hirschmann, 2010). The absence of fresh oceanic peridotite samples currently requires estimation of carbon concentration to be made using geochemical proxies, such as Nb and La (e.g., Nb, La; Saal et al., 2002; Niu, 2004; Godard et al., 2008). Using 10 ppm CO_2 over 10 km depth in the uppermost mantle, then results from Niu (2004) and Saal et al (2002) imply that this reservoir would contain ~100 trillion tons of CO_2 globally. This is roughly the mass of CO_2 in today's ocean and atmosphere combined. If correct, more CO_2 is being subducted than is currently assumed (Dasgupta and Hirschmann, 2010); however, uncertainties are so great that the opposite may be true. We simply do not know how much CO_2 is actually present in the upper mantle beneath ocean crust, and we thus cannot quantify the net carbon transfers into and out of the deep Earth.

Concluding remarks. The twin strategies for studying the lower oceanic crust and upper mantle – working on ophiolites and offset drilling – have taught us much. However, the list of questions that they cannot answer is long, and growing longer. Our lack of systematic sampling of core retrieved from intact, in situ deep lithosphere of fast spread origin remains one of the most glaring holes in the sampling of our solar system.

References

Coogan, L. A., Manning, C. E., Wilson, R. N., and E.I.M.F., 2007. Oxygen isotope evidence for shortlived high-temperature fluid flow in the lower oceanic crust at fast-spreading ridges. Earth Planet. Sci. Lett. 260, 524-536.

Dasgupta, R. & Hirschmann, M. M., 2010, The deep carbon cycle and melting in Earth's interior. Earth Planet. Sci. Lett. 298, 1-13.

Godard, M., Lagabrielle, Y., Alard, O., Harvey, J., 2008. Geochemistry of the highly depleted peridotites drilled at ODP Sites 1272 and 1274 (Fifteen-Twenty Fracture Zone, Mid- Atlantic Ridge): Implications for mantle dynamics beneath a slow spreading ridge. Earth Planet. Sci. Lett. 267, 410- 425

Manning, C. E., and MacLeod, C. J., 1996. Fracture-controlled metamorphism of Hess Deep Gabbros, Site 894: Constraints on the root zones of mid-ocean ridge hydrothermal systems at fast spreading centers. In: Mével, C., Gillis, K. M., Allan, J. F., and Meyer, P. S., eds., Proceedings of the Ocean Drilling Program, Scientific Results, v. 147, College Station, TX (Ocean Drilling Program), 189-209.

Manning, C. E., Weston, P. E., and Mahon, K. I., 1996. Rapid high-temperature metamorphism of East Pacific Rise gabbros from Hess Deep. Earth Planet. Sci. Lett. 144, 123-132.

Manning, C. E., MacLeod, C., and Weston, P. E., 2000. Lower-crustal cracking front at fast-spreading ridges: evidence from the East Pacific Rise and the Oman ophiolite. In Dilek, Y., Moores, E., Elthon, D., and Nicolas, A., eds., Ophiolites and Ocean Crust: New Insights From Field Studies and Ocean Drilling Program, Geological Society of America Special Paper 349, 261-272.

Niu, Y.L., 2004. Bulk-rock major and trace element compositions of abyssal peridotites: Implications for mantle melting, melt extraction and post-melting processes beneath mid- ocean ridges. J. Petrol. 45, 2423-2458.

Saal, A.E., Hauri, E.H., Langmuir, C.H., Perfit, M.R., 2002. Vapour undersaturation in primitive midocean-ridge basalt and the volatile content of Earth's upper mantle. Nature 419, 451-455.

VanTongeren, J.A., Kelemen, P.B., Hanghoj, K., 2008. Cooling rates in the lower crust of the Oman ophiolite: Ca in olivine, revisited. Earth Planet. Sci. Lett. 267, 69-82.

Importance of Data Integration in the Challenging Deep Riser Operations

Moe K., Sanada Y., Aoike K., Kido Y., Sugihara T., Kaminishi T., Nakamura Y., Saito S.,

Key Words: Riser drilling, logging, mudlogging, cuttings/core-log-seismic integration

Riser Drilling Cycle

Unlike JOIDES Resolution's historic and successful expeditions, riser drilling cycle (figure) can be divided into four stages, pre-expedition planning, expedition execution, post-expedition reporting and review, and next expedition planning with considerable differences in each stage from riser-less drilling. Center for Deep Earth Exploration (CDEX), operator of the Chikyu, performs drill site surveys, drilling and expedition planning and coordination which include acquiring and managing data and samples taken from drilling/coring/downhole measurements and developing new technology. Understanding riser planning process will benefit to proponents for efficient planning of the project together with implementing organization.

Chikyu Timeline

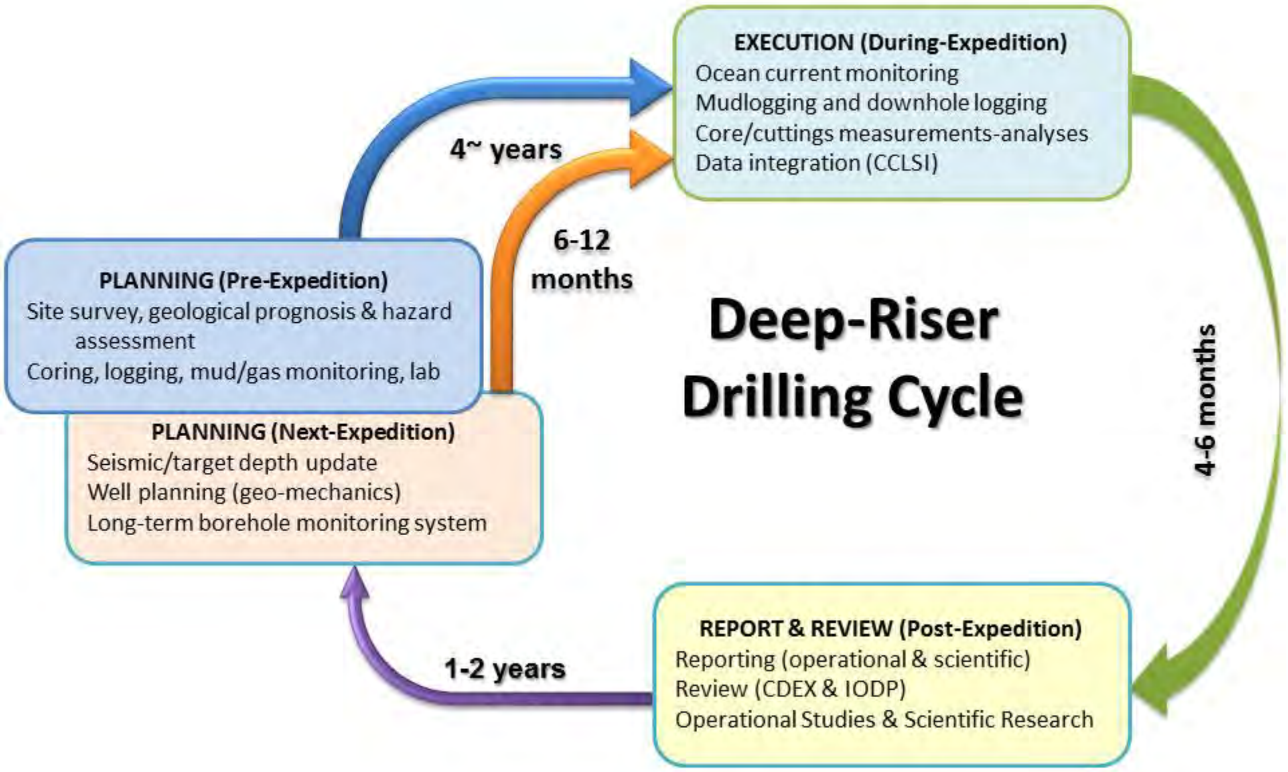
Before starting IODP mission in 2007 September, Chikyu went through two years of System Integration Tests (SIT) at domestic and international locations to train Chikyu team of people with various backgrounds except scientific drilling. During the shakedown period, riserless to riser drilling, coring, mudlogging and logging operations and laboratory measurements were carried, and specialists from IODP community were invited to guide, train and review the process of laboratory set up and measurements. Even official shakedown operations were over, staff from ship operator and CDEX kept learning numerous lessons from the challenging operations, advanced instruments under various deep water and geological challenges. During the course of NanTroSEIZE expeditions, Chikyu was able to test and refine operational techniques and structures, and able to pioneer the use of new tools and equipments not only in the lab area but also at the rigfloor in coring and logging operations. Those include first-ever and rarely-used logging tools, new coring systems and techniques, extensive use of X-ray Computed Tomography (XCT) on whole core sections and several laboratory instruments.

Chikyu Capabilities and Limits

With her mud circulation and blow-out-preventing (BOP) systems, riser drilling can operate in safer and better ways for challenging scientific targets. In addition, core quality and recovery improved, and wider choice of downhole logging tools expand data quality and quantity that were of science community's dream for long. However, riser operations cost much more than riser-less operations, and take longer time in preparations, such as multiple years to do geotechnical studies, hazard assessment, geological prognosis, procurement of instruments, and several days at well-site for running, connect and testing riser. Moreover, planning is complicated with larger contingency window, longer time needed for weather related evacuations, and importance of keeping single hole to the deep target.

Future Direction

In the last seven years, CDEX and IODP community learnt many valuable lessons from Chikyu expeditions related to strong current, difficult borehole conditions, and ultra-deep water environment. Chikyu team and scientists worked in various ways to integrate data under the operational challenges and budget/cost constraints. Efficient and safe operations and focusing on the measurements of primary targets instead of full coring became best way in riser expeditions. In this new course, cuttings analysis and Logging-while-drilling (LWD) becomes important as continuous data source, and high-quality wireline logging compliment to this type of new data integration. Then new style of team work onboard becomes critical to have efficient data processing, analysis and supporting science party. As Chikyu drilling progress to the deep challenging targets, cuttings/core-log-seismic integration (CCLSI) will be key to provide wellsite planning and to produce best scientific results both at well-site and post-expeditions.



EXPLORING THE SOLAR SYSTEM THROUGH SCIENTIFIC OCEAN DRILLING

Clive R. Neal.
Dept. of Civil & Env. Eng. & Earth Sciences, University of Notre Dame, Notre Dame, IN 46556, USA
(neal.1@nd.edu)

Scientific ocean drilling affords an opportunity to undertake planetary exploration through investigating the process that shape our planet and comparing the results with information obtained from spacecraft that have visited the other terrestrial planets. A number of nations beyond the USA and Russia have successfully launched and operated robotic spacecraft to destinations in our Solar System. For example, in the last decade successful missions to the Moon have been flown by the European Space Agency (SMART-1 orbiter), Japan (Kaguya orbiter), China (Chang'e 1 and Chang'e 2 orbiters with the Chang'e 3 lander/rover being launched later this year), and India (Chandrayaan-1 orbiter). All of these space faring nations are IODP member countries. Therefore, the next decade of ocean drilling has the opportunity to cement strong linkages to the planetary science community through a "comparative planetology" approach. Despite the Earth being unique among the terrestrial planets in having oceans of liquid water and plate tectonics, there are a number of features preserved in the crust and accessible by ocean drilling that can shed light on how other terrestrial planetary bodies evolved.

Fig. 1: Relative sizes of the inner planets and Earth's Moon.

Large Igneous Province (LIP)/Hotspot Magmatism: The inner planets of our solar system (Fig. 1) exhibit a variety of sizes, atmospheres, and evolutionary developments. The continual recycling of the Earth's surface by plate tectonics makes this planet unique in the Solar System. Volcanism on Venus, Mars, and the Moon (and possibly Mercury) occurred on one-plate planets, most commonly through hotspots. For example (Fig. 2), there are huge

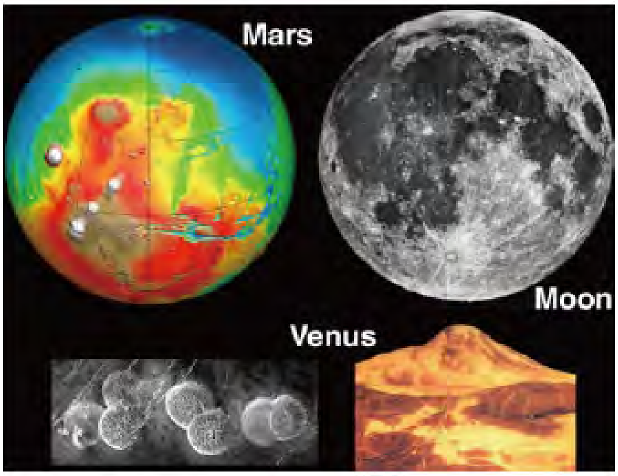


Fig. 2: Volcanism on Mars, Moon & Venus.

volcanoes on Mars that appear to have grown above a stationary hotspot as part of the Tharsis LIP; mare fill of impact basins on the Moon is unrelated to the impact event and are consistent with hotspot-type eruptions; the surface of Venus contains “pancake” volcanoes formed through a combination of hotspot volcanism and the extreme atmospheric pressure. Study of hotspot emplacement and LIP initiation mechanisms allows insights into magmatism within the other terrestrial planetary bodies and studying those in the oceans removes the complications caused by the physical and chemical presence of continental crust. Investigating plume vs. non-plume models for LIPs and seamounts through ocean drilling will allow investigation of the ultimate origin of these structures (i.e., plume vs. non-plume or a combination of both), which will give insights into the evolution of other terrestrial planets.

Impact Processes. The results of bolide impact on the terrestrial planets are seen on Mars, Mercury and the Moon because modification processes are extremely slow on these smaller planetary bodies. On Earth and Venus, with their respective tectonic activities and atmospheres mean that impact craters tend to be eroded and/or buried. Detailed investigation of terrestrial impact craters is needed to investigate what effect the nature of the impacted planet has on the cratering process. Craters of varying sizes have been preserved on the continental shelves in the oceans around the world. Examples include the Silverpit Crater in the North Sea (late Cretaceous, 20 km diameter), the Bedout High, Western Australia (end of Permian, 30 km diameter), and Chicxulub in the Yucatan Peninsula (end of Cretaceous, 180 km diameter) (Fig. 3). The latter two have been associated with the two most dramatic mass extinctions our planet has experienced. The study of such craters allows “two-way” comparative planetology in that we can use remotely sensed data of craters from the Moon (e.g., Schrödinger Basin) to better understand where to drill peak ring impact complexes. The material recovered from drilling will better inform us how peak ring basins formed, both on Earth and other planetary bodies.

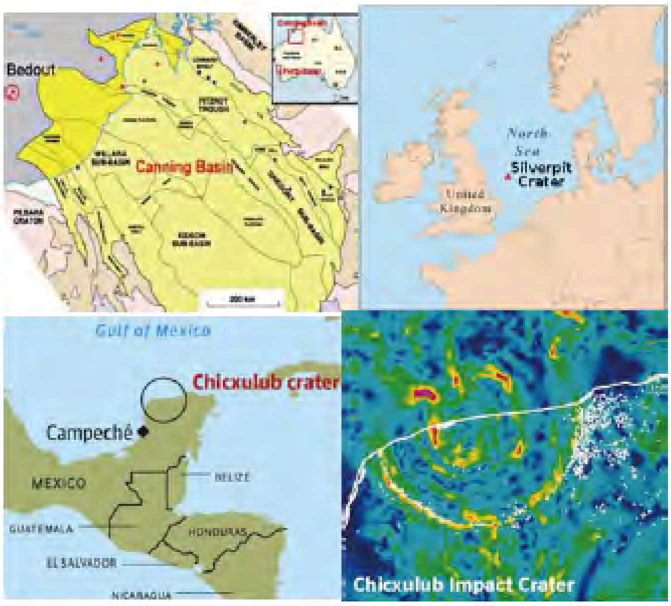


Fig. 3: Locations of Bedout, Silverpit, and Chicxulub impact craters

Origin and Survival of Life: The search for life on other planets has been focused on Mars since the discovery of the Martian meteorite ALH84001 and the confirmed presence of ice in the Martian regolith and clay mineral develop early in the history of the red planet. Two fundamental questions need to be addressed: 1) Did life develop on Mars and where? 2) If life did develop on Mars where could it be found present day? Ocean drilling can help address these questions through drilling at mid-ocean ridges (addressing question 1) and examination of the deep biosphere (addressing question 2). The understanding of how life survives in nutrient poor environments could be used by NASA to search for life on (in) Mars and beyond.

Reaching out to the growing planetary science community will help in broadening the appeal of scientific ocean drilling.

Microbial Expectations for the Marine Deep Subsurface

Kenneth H.Nealson

University of Southern California, U .S.A.

Key words: subseafloor, microbiology; limitation, energy, nitrogen

The Oceanic Deep Subsurface: Studies of the subsurface provide us with unique opportunities for experimenting with, and learning about life in a truly uncharacterized and unknown environment. Many parts of the deep subsurface are, in comparison to the shallow sediments, extremely challenging for life as we know it. While adaptation to extreme pressures and temperatures (at least those compatible with carbon-based life) is readily accomplished, adaptation to extreme nutrient limitation may be more difficult to contend with (*1-11*). Thus, as one proceeds downwards in the sediments, microbial life steadily becomes less abundant, and the properties of this life seem quite remarkable, with estimated average doubling times of tens, hundreds, or even thousands of years (*2, 3, 7-9, 11*): something unheard of in studies of surface life.

What do we think we know? First, as we proceed downwards, there are very few eukaryotes - since the bacteria and archaea make up the base of the food chain in this non-photosynthetic environment, this makes sense, and again suggest that the rates of growth and biomass accumulation are extremely low. Second, as mentioned above, the estimated average growth rates are very low compared to surface organisms. Third, one thing that seems likely is that hydrogen will play a major role as an energy source in the deep subsurface. There are a number of a biotic mechanisms for hydrogen production, and many known pathways of hydrogen utilization b y Bacteria and Archaea.

What don't we know? First, we know virtually nothing about the species content or metabolic potential(s) of the microbes living in the deep subsurface. Who are these survivors, and how are they staying alive? What are they eating and what are they breathing? Third, we don't know where, or why, life ultimately is quenched at depth, and we don't yet k now where the measureable biosignatures become undetectably low. This includes the organic biomarkers, stable isotope fractionations, and morphological remnants.

Extracellular electron transport (EET): A less well-known part of microbial metabolism is the process of extra cellular electron transport (EET), which could provide some part of the solution to energy limitation, and long-term survival. EET was discovered in the late 1980's as a process allowing heterotrophic bacteria to survive and grow in anoxic conditions by using insoluble iron and manganese oxides as electron acceptors (*12, 13*), and has since been found in a variety of bacterial and archaeal groups. Using extracellular (membrane bound) enzymes, electron shuttles, and even conductive wires and matrices, bacteria are able to transfer electrons to solid substrates such as metal oxides and electrodes of fuel cells, as well as use solid substrates as sources of electrons for metabolic energy. These abilities open up a new realm of possibilities with regard to life in the subsurface.

What limits life in the subsurface? But what is it that limits life in the deep subsurface? The fact is, we don't know, and this unanswered question may be one of most important goals of the upcoming decades of deep subsurface research. While it is clear that energy is a key part of the equation (*1-11*), I would like to propose that nitrogen limitation is another important candidate. But why nitrogen? As opposed to phosphorous and sulfur, which are components of many minerals, nitrogen is found in almost no minerals (*14*), so that the only source of nitrogen will be dissolved nitrogen gas, which must be reduced to ammonium "fixed" in order to be biologically useful. Under extreme energy limitation, such nitrogen fixation will be difficult, perhaps impossible, so that for the deep subseafloor community, nitrogen recycling may be the only mechanism for cellular and/or community for long term survival. To this end, the report of rapid nitrogen assimilation by deep subseafloor microbes of great interest (*15*). Perhaps of equal importance, in the absence of available "new" nitrogen, is the notion that cell division might be viewed as a“ metabolic mistake" - the generation of one's "worst enemy" (i.e., another microbe with exactly the same metabolic requirements). While this may sound flippant, it isn't meant to be: when nutrional limitation is extreme, microbes must have mechanisms for sensing this, and entering a non-growth mode, in which survival is the only immediate goal. Over evolutionary time, this may be exacerbated and lead to cells that are far more fit for such a low-nutrient lifestyle, though it remains an interesting question of how Darwinian evolution "works" if growth rates are extremely slow!

Cell and genome size and content: Another phenomenon that is often encountered in nutrient depleted environments is that of genome reduction, and metabolic specialization. For example, many of the most abundant marine microbes in the nutrient-limited picoplanktonic niche have genomes of 2 million base pairs or less, only 40% or less DNA/cell than the microbes we commonly grow in our labs (*16*). These cells are necessarily very small in comparison to microbes with larger genomes, maximizing surface to volume ratio, and are usually non-motile. With such evolutionary maneuvers, these organisms spend much less energy replicating, or repairing cellular damage.

What might be expected? Based on what has been learned from nutrient-limited and other extreme environments, I suggest that the following might be expected in terms of the microbes and microbial communities in the subsurface:

1. Cells will be very small (low biomass), with very small genomes
2. Cells will grow slowly, and be metabolically specialized
3. Hydrogen will be a major energy source for the subsurface
4. Nitrogen limitation will be the rule for deep subseafloor life
5. The composition of cells (and communities) will have compositions that reflect the nutrient on which they are limited
6. Cells will be non-motile and non-chemotactic
7. Cells will engage in EET, and "community" life styles will be common
8. All nutrients will be efficiently recycled to be used for "repair"
9. Mixed communities will be the rule, probably as biofilms

Summary: Expectations and speculations are useful only if they provide a format for hypothesis formation and/or experimental design, and ultimately, useful experiments. I believe that many aspects of the above expectations qualify, and welcome discussion at this meeting.

References Cited:

1. S. D'Hondt *et al., Science* **306**, 2216 (Dec 24, 2004).
2. S. D'Hondt, S. D. Rutherford, A Spivack, *Science* **295**, 2067 (2002).
3. S. D'Hondt *et al., Proc Natl Acad Sci USA* **106**, 11651 (2009).
4. K J. Edwards, K. Becker, F. S. Colwell, *Annu. rev. Earth Planetary Sci.* **40**, 551 (2012).
5. F. Inagaki *et al., Proc Natl Acad Sci USA* **103**, 2815 (Feb 21, 2006).
6. B. B. Jorgensen, *Energy Exploration & Exploitation* **21**, 319 (2003).
7. B. B. Jorgensen, S. D'Hondt, *Science* **314**, 932 (Nov 10, 2006).
8. R. J. Parkes *et al., Nature* **436**, 390 (2005).
9. H. Roy *et al., Science* **336**, 922 (May 18, 2012).
10. M. 0. Schrenk, J. A. Huber, K J. Edwards, *Annu. Rev. Mar. Sci.* **2**, 279 (2010).
11. T. Hoehler, B. B. Jorgensen, *Nature Rev. Microbiol.* **11**, 83 (2013).
12. D. R. Lovley, E. J. Phillips, *Appl Environ Microbiol.54,* 1472 (Jun, 1988).
13. C. R. Myers, K. H. Nealson, *Science* **240**, 1319 (Jun 3, 1988).
14. D. G. Capone, R. Popa, B. Flood, K H. Nealson, *Science* **312**, 708 (May 5, 2006).
15. Y. Morono *et al., Proc Natl Acad Sci USA* **108**, 18259 (2011).
16. S. Yooseph *et al., Nature* **468**, 60 (Nov 4, 2010).

Scientific drilling in the Indian Ocean to unravel complex geo-scientific issues

Dhananjai K Pandey[1] and Rajan S.

National centre for Antarctic and Ocean Research, Ministry of Earth Sciences, Goa, India

([1]Email: pandey@ncaor.org)

Key Words: Arabian Sea, Bay of Bengal, Deep sea drilling

Compared to the extensive deep-sea drilling carried out through the world oceans, the northern Indian Ocean sector is marked by very few DSDP/ODP locations. The lack of critical deep ocean sampling has been a major constraint in scientific endeavors towards unraveling the history of the geological and climatic evolution of ocean basins in this region. Availability of sub-seabed cores buried underneath water column of up to 4km deep would certainly enhance our understanding of key geological processes. Since the northern Indian Ocean covers a vast area and is largely under-represented in terms of ocean drilling activities, a long-term, multi-leg project is favoured. There are a number of scientific proposals emanating from Arabian Sea and of Bengal regions at various levels within the IODP system waiting for implementation.

Recognizing the scientific potential of drilling in the Indian Ocean area, through Integrated Ocean Drilling Program (IODP) framework, India took an initiative to become an Associate Member. Ever since, Indian scientists have been participating in IODP expeditions and actively contributing to the IODP science plans. Considerable efforts have been put by Ministry of Earth Sciences (MoES) to encourage deep sea drilling research in India in last few years through supporting extramural post-cruise IODP research proposals to encourage frontier geoscientific research. With the financial support of MoES, IODP-India submitted a complementary project proposal (CPP) to understand the tectono-climatic linkages by drilling in the Arabian Sea.

In this continuity, an Indian Ocean IODP Workshop was hosted in Goa in October 2011 by the National Centre for Antarctic and Ocean Research (NCAOR). The workshop was co-sponsored by IODP-MI and ANZIC. During the workshop four key themes were identified for developing further new proposals. These included:

1) Cenozoic oceanography, climate change, gateways and reef development, which covered broad questions related to the Indian Ocean,

2) The history of the monsoons involved tectonics, uplift, weathering and erosion, sediment deposition, and climate and oceanography.

3) Tectonics and volcanism covered open questions in the Indian Ocean involving geodynamics; the evolution of oceanic crust including mid-ocean ridges; the formation of large igneous provinces; continental rifting and related deposition; and subduction, arc volcanism, earthquakes and tsunamis.

4) The deep biosphere including studies of "extremophile" microorganisms in sediments and basalts.

It is worth highlighting that through the collective efforts of scientists from all regions, now the proposal density in the Indian Ocean region has been improved (Fig. 1) and we hope that many of these strong proposals would succeed to the realization stage. Through the Chikyu+10 workshop, we would like to bring it to the notice of IODP community that with no scientific ocean drilling in the Indian Ocean for nearly a decade, the region poses a major gap in our understanding of global geoscientific processes, past and present, and their implications for the future. Therefore, we request the IODP platform operators as well as the community as whole to prioritize scientific drilling in this region in the coming years. This would facilitate bringing together an international team of scientists from various disciplines to analyze and exchange the multitude of scientific information in order to improve evolutionary process of this region.

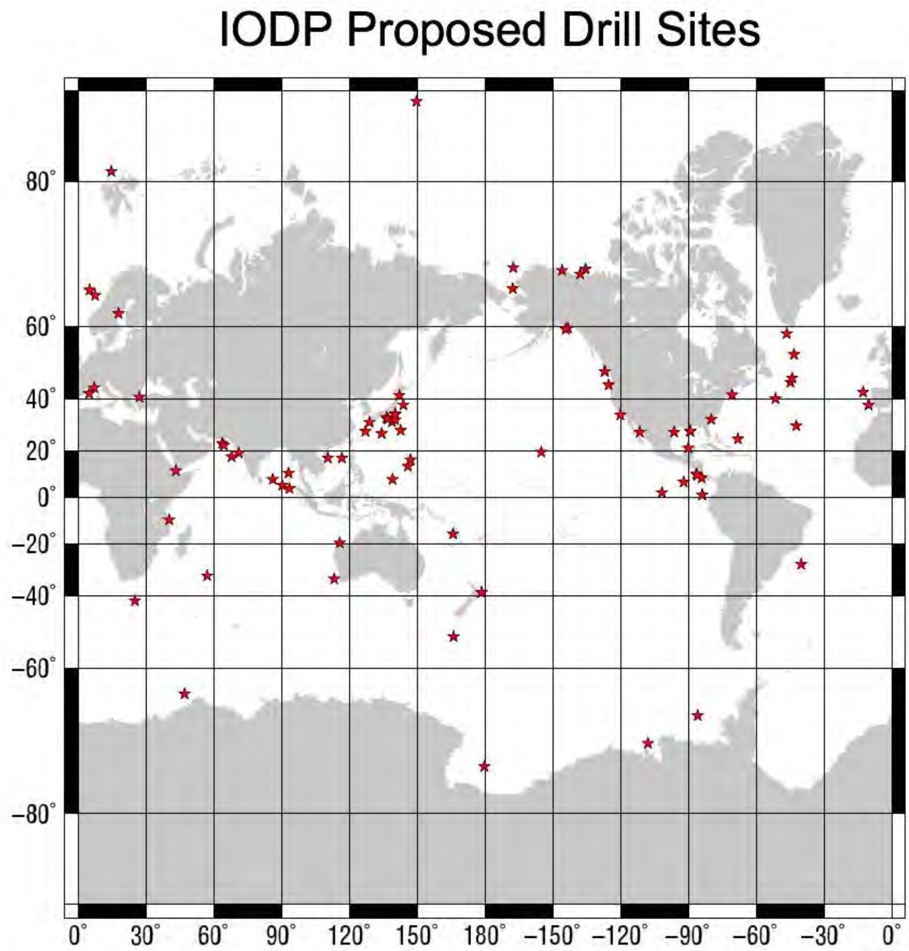


Figure 1: Proposed IODP drill sites around the world as on April 2012 (source: www.iodp.org).

Costa Rica SEISMOGENESIS Project (CRISP)

C.R. Ranero[1]; P. Vannucchi[2]; R. von Huene[3] and CRISP proponents

[1]ICREA at ICM-CSIC, Barcelona Center for Subsurface Imaging, Spain. [2]Royal Holloway University of London, UK. [3]UC Davis, USA; GEOMAR Kiel, Germany.)

Keywords: mega-thrust fault mechanics, seismogenesis, earthquake hazard.

An ongoing shift in paradigm: Our limited knowledge of the processes that govern earthquake seismogenesis has been periodically synthesized during the past ~40 years into different conceptual models to provide a basic framework for the understanding of the generation of *Great-magnitude Earthquakes* by subduction-zone mega-thrust faults. To our dismay, most basic predictions put forward by those hypotheses have been shaken by the unexpected occurrence of several *Giant Earthquakes* during the last decade.

In an early concept, it was proposed that the largest-magnitude earthquakes occurred in fast-converging subduction zones receiving thick trench-sediment infill which when under-thrusted should smooth irregularities in the mega-thrust fault structure and facilitate propagation of earthquake rupture. This hypothesis was partially disproven during the 2004 Aceh-Andaman Mw9.3 event occurring along a segment of the obliquely (slowly) converging Sumatra subduction zone. More recently, the 2011 Tohoku-Oki Mw9.0 event ruptured along a plate boundary that receives only a thin veneer of subducting sediment, indicating that a laterally homogeneous mega-thrust fault is not required for the generation of *Giant Earthquakes*.

In addition, the modern and abundant high-quality data obtained in relation to those events has also been used to show that a number of other frequently (and freely) utilized concepts are primarily incorrect.

For instance, the 2011 Tohoku-Oki Mw9.0 event re-ruptured a region that had been recently partially ruptured by Mw8.0-8.3 events. Such Mw8.0-8.3 earthquakes had previously been frequently regarded as “large enough” to release most of the stress. Thus, the 2011 Tohoku-Oki event was un-expected by most.

Another important matter indicated by the Tohoku-Oki Mw9.0 event - and paleoseismological data - is that, at least in some regions, the release of elastic energy by earthquakes may follow a cycle that is more complex that previously assumed. In Japan Trench, and possibly other regions like Cascadia, a decadal-centennial cycle of ~Mw8.0-8.5 *Great Earthquakes* may be “superimposed” to a longer-time scale cycle (perhaps millennia) of *Giant Earthquakes*.

A last example worth mentioning of an ongoing paradigm shift is the mounting evidence that the concept of the seismogenic zone of the mega-thrust fault has been too simplistically applied to the complex fault behavior occurring during earthquake nucleation, rupture and propagation. High-quality records inverted to map fault rupture of recent *Giant Earthquakes* including Aceh-Andaman, Tohoku-Oki, and Maule (Chile) strongly indicate that seismic rupture extended along the shallow portion of the faults to reach close to the deformation front, where conceptual models infer that deformation normally occurs a-seismically.

The above growing body of evidence points out that an insufficient understanding of fault mechanics and deformation at the scale of the mega-thrust fault has led to long-standing, oversimplified conceptual models. These models require evaluation by quantitative approaches that accurately calculate deformation at subduction zones. The result will necessarily imply a new appraisal of earthquake hazard at global scale. Accurate quantitative approaches will require high-resolution observational data including geodetic data, and in situ observations of the mega-thrust fault. *CRISP main goal is to obtain a deeper understanding of the* *processes governing the mechanical behavior of the mega-thrust and capture their time evolution*.

CRISP objectives: CRISP selected the mega-thrust of Costa Rica for 2 main reasons: **1**) An exceptionally well-studied region, with over-a-decade intense US-Margins/German-SFB574 programs involving hundreds of scientist and about 15 cruises. **2**) A shallow-depth seismogenic zone. Other favorable conditions are mild sea state year round, excellent seismic images including 3D volumes, and good transportation infrastructure.

CRISP investigates a mega-thrust dominated by tectonic erosion. About 50% of the world's subduction zones are erosional, including Japan Trench where the 2011 Tohoku-Oki event occurred. A comparison of the Japan Trench and Costa Rica shows considerable structural similarities (Figure 1).

CRISP Drilling, Monitoring and Laboratory Experiments have Four Major Goals: **1)** Quantify effective stress and plate boundary migration via focused investigation of fluid pressure gradient and fluid advection across the erosional plate boundary. **2)** Determine the structure and fault mechanics of an erosional convergent margin. **3)** Constrain how fluid-rock interaction affect seismogenesis by studying fluid chemistry and residence time, basement alteration, diagenesis, and low grade metamorphism. **4)** Obtain physical properties of a rock volume that spans the seismogenic zone.

CRISP science will test five hypotheses related to seismogenesis : **1)** The change from velocity strengthening to weakening in the plate boundary parallels the transition from a fluid-rich and broad fault zone, with distributed slip, to a narrower zone of active deformation with localized shear and fluid compartmentalization. **2)** Fluid pressure gradients and fluid advection affect the migration and mechanical coupling of erosional plate boundaries both temporally and spatially. **3)** The lithology, physical properties, and structure of eroded materials influence fault mechanics and the transition from velocity strengthening to weakening. **4)** Fluid chemistry, P-T conditions and residence time affect the state of eroded material through basement alteration, diagenesis and low-grade metamorphism. **5)** Lateral variability in subducted plate relief, subduction channel thickness, material properties and fluid distribution affect seismogenesis and rupture propagation.

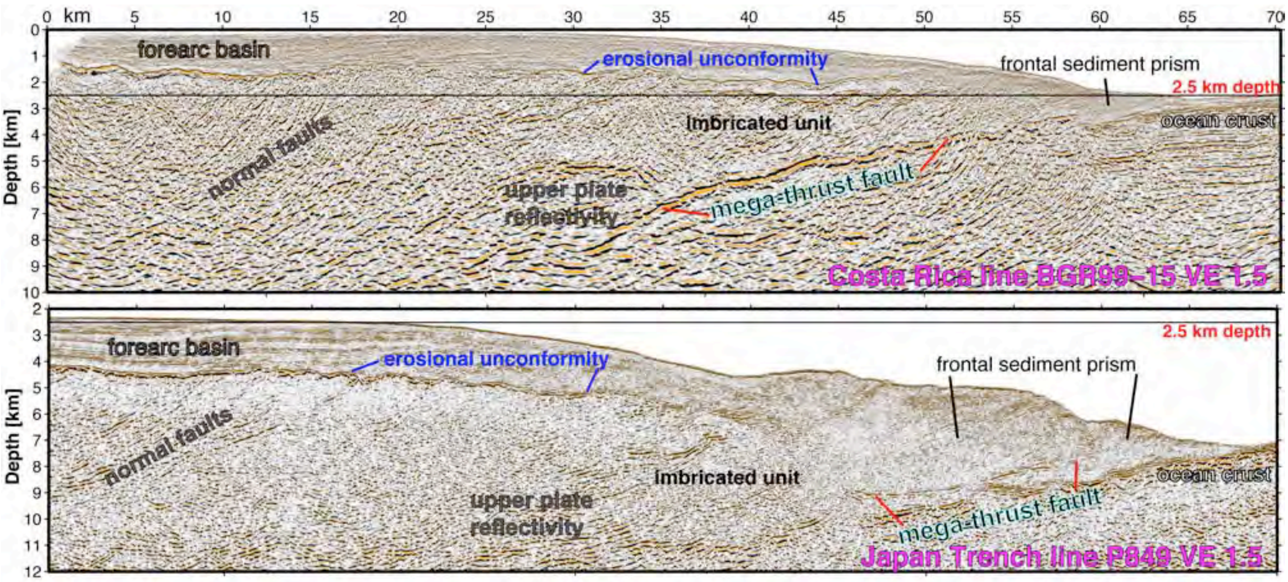


Fig 1. Comparison of Japan Trench and Costa Rica. Note structural similarities. Erosional plate-boundaries contain material removed from the upper plate mixed with under-thrusted sediment with unknown physical properties. Plate boundary drilling in Costa Rica at < 2.5km water depth may occur across the entire slope.

FORMATION OF THE CONTINENTAL CRUST AT CONVERGENT PLATE MARGINS: SCIENTIFIC DRILLING TO UNDERSTAND ARC CRUSTAL DIFFERENTIATION

Robert J. Stern

Geosciences Dept., U Texas at Dallas, Richardson TX 75080 USA

Keywords: Convergent margin, continental crust, island arc

Continental crust is a uniquely terrestrial feature, distinguished from oceanic crust by greater thickness and age and more siliceous composition. Because it takes a long time to form true continental crust and because it is so thick, we do not understand its formation and evolution as well as we understand the formation of oceanic crust, which forms quickly by seafloor spreading. Understanding continental crust formation is a first-order scientific problem, as demonstrated by the fact that this is a priority for IODP and US GeoPRISMS initiative. Understanding continental crust formation is societally important as well, because this is where most humans live and where most natural resources are found.

Formation of continental crust by plate tectonics mostly occurs at magmatic arcs associated with convergent plate margins, above subduction zones. Convergent plate margins may destroy as much or more continental crust as that produced, but here we only consider processes of crustal growth. Three main processes are required to form new continent by plate tectonic processes: – juvenile arc construction, vertical differentiation, and lateral accretion.

<u>Juvenile arc construction</u>: Individual arcs like IBM or the western Aleutians are nurseries of continental crust. Most of the growth of an individual arc may occur quickly, in the first few million years after a new subduction zone forms. Such intra-oceanic arcs are juvenile bricks cemented together by collision and progressively differentiated by anatexis and delamination to yield increasingly mature arc crust. Some continental crust is produced above as oceanic plateau above hotspots but this is subordinate to the arc component, as shown by the overall arc-like andesitic composition of bulk continental crust. Individual arcs thicken in a few million years to ribbons of mafic-felsic crust, locally approaching the 7x oceanic thickness of aged continental crust, or craton, but even if juvenile arcs approach continental crustal thickness, these tracts are too narrow to be considered as truly continental.

<u>Vertical Differentiation</u>: Arc crust is further processed over its active life, as it is continuously underplated by mantle –derived mafic melts, resulting in crust that is grossly layered: mafic and ultramafic at the base, volcanic on top, and intermediate to felsic in the middle crust. Magmatic underplating and intrusion injects ~1300°C magma, reheating the lower and middle crust to temperatures as much as 400°C above the water-saturated amphibolite solidus. Depending on the flux of underplating mafic magmas, establishment of a lower crustal hot zone encourages remelting of amphibolitic middle crust to form tonalitic to granodiorite secondary melts at the same time that fractional crystallization generates intermediate and felsic melts by magmatic differentiation. Such intermediate to felsic materials concentrate in the middle crust, which we propose to access via ultradeep drilling into the IBM forearc. Such chemical reprocessing of juvenile arc crust is uninterrupted over the life of a convergent plate margin. It begins when arc crust first forms and

continues during and after terrane accretion as long as there is a substantial magmatic flux from the upper mantle to the crust, which will happen as long as the arc is underlain by an active subduction zone. Magmatic differentiation and anatectic reworking is accompanied by fractional crystallization to form mafic/ultramafic cumulates and restite piles deep in the crust. Accumulations of dense pyroxene-rich or garnetiferous cumulates and restites delaminate as anti-diapirs, which episodically sink into the mantle wedge, progressively enriching arc crust in silica and incompatible elements and slowly shifting its bulk composition towards that of mature continental crust.

Lateral Accretion: The great breath of continents distinguishes them from ribbonlike arcs. This breadth requires that individual arcs and oceanic plateaus collide and suture together to form accretionary orogens or composite arc terranes. Collision zones are often marked by ophiolites, which mostly represent fragments of forearc crust. Collision thickens and weakens the crust, enhancing linked processes of underplating, crustal reprocessing, and delamination at the same time that the upper volcanic-rich layer is lost by erosion. Arc collisions thus accelerate evolution to an increasingly annealed and laterally isotropic crust with strong compositional layering. Ultimately, the breadth of a new tract of continental crust is limited only by the number of arcs and other crustal tracts that can be welded together, but crustal thickness rarely exceeds ~40 km, reflecting the combined effects of delaminating weak, dense (especially garnet-bearing) lower crust and lateral flow of weak middle crust by channel flow. These combined processes of continental crust evolution – juvenile arc construction, vertical differentiation, and lateral accretion - ultimately take hundreds of millions of years to mature from multiple juvenile arcs to ultrastable craton, typically encompassing a single supercontinent cycle. Aspects of this journey from island arc to craton can be studied using examples from each of the life stages: 1) formation of new subduction zones accompanied by rapid formation of new arc crust (e.g., IBM arc 50 Ma ago); 2) evolution of individual arc systems (e.g. ~50 Ma long evolution of Greater Antilles arc); 3) accretion of multiple arcs and their continued thermal reworking, for example the American cordillera or the Philippines; and 3) stabilization of multiple orogens as craton, for example the Arabian-Nubian Shield (ANS), exposed on the uplifted flanks of the Red Sea. The ANS is the exposed surface of a ~850-550 Ma old craton, composed of several juvenile arcs that formed around the margins of the Neoproterozoic "Mozambique Ocean". These arcs accreted together to form the ANS as a large, composite accretionary orogen.

We must understand the linked processes of juvenile arc construction, vertical differentiation, and lateral accretion if we are to understand how continental crust forms by plate tectonic processes. Field studies of surface exposures at sea and on land are very useful for studying juvenile arc construction and processes of lateral accretion, but understanding vertical differentiation requires target scientific drilling, such as that proposed to examine the nature and origin of IBM middle crust. Chikyu+10 thus represents an unparalleled opportunity to understand how continental crust forms by plate tectonic processes at convergent plate margins.

OCEAN CREATES CONTINENT:
Ultra-deep drilling to the middle crust of the IBM arc

Yoshiyuki Tatsumi
Kobe Univ. and IFREE/JAMSTEC

Continental crust, andesite, intra-oceanic arc, Izu-Bonin-Mariana

One characteristic feature of the planet Earth is the bimodal height distribution at the surface. This is caused by the presence of two types crust with different density and thickness, i.e. the oceanic and continental crusts. The oceanic crust having basaltic compositions have formed at divergent plate boundaries, whereas the average continental crust possesses intermediate compositions that typify arc magmatism and as a result it is believed to have been created at convergent plate boundaries. However, mantle-derived magmas produced in the modern arc-trench system are mostly mafic or basaltic. This is probably the greatest dilemma facing those interested in the origin of continental crust and more generally in the Earth evolution.

The Izu-Bonin-Mariana (IBM) arc system, extending 2800km to the south of Honshu (Fig. 1), is uniquely suited to the study of arc evolution and continental crust formation, because it is a juvenile intra-oceanic arc with no pre-existing continental crust, yet a thick middle crust layer with 6.0-6.8 km/s *Vp* identical to the average *Vp* of the continental crust is widely distributed in this arc (Fig. 2). The primary goals of sampling the *in situ* arc crust through drilling are: (1) to identify the structure and lithologies of the upper and middle crust, (2) to test seismic models of arc crustal structure, (3) to constrain the petrologic and chronological relationship of the middle crust to the overlying upper crust, (4) to establish the evolution of arc crust by relating this site with other regional drill sites and exposed arc sections, and (5) to test competing hypotheses of how the continental crust forms and evolves in an intra-oceanic arc setting. These objectives address questions of global significance, but we have specifically identified the IBM arc system as an ideal locale to conduct this experiment. The composition of the pre-subduction upper plate was normal oceanic crust, and the tectonic and temporal evolution of this arc system is well-constrained. Moreover, the IBM system is considered as the best-studied intra-oceanic arc on Earth by extensive sampling of the slab inputs

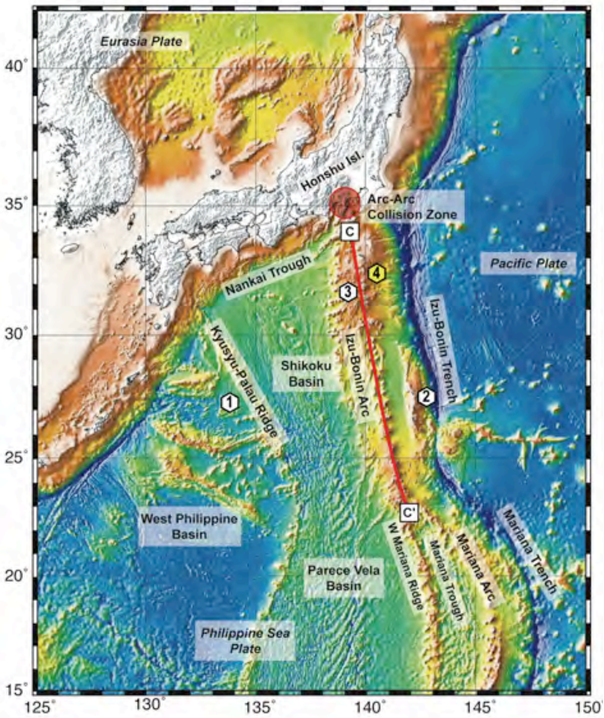


Fig. 1. Location map of the Philippine Sea region. The IBM arc-trench system forms the convergent margin between Pacific and Philippine Sea plates. Backarc basins such as Shikoku Basin, Parece Vela Basin and Mariana Trough were created by seafloor spreading between the formerly contiguous remnant arc (Kyushu-Palau and West Mariana ridges) and the active IBM arc. At its northern tip, the IBM arc has collided with the Honshu since 15 Ma. The red lines locates the along-arc t refraction and wide-angle reflection seismic data shown in Fig. 2. Numbers show a series of proposed drilling sites as Project IBM. Sites 1-3 are schedule to be drilled by JR.

and arc outputs through field studies and drilling, and by a series of recent, focused geophysical surveys.

We propose returning to the region of ODP Site 792 to drill, *via.* Eo-Oligocene upper crust, to the middle crust at proposed site IBM-4 (Figs. 1 and 3). The mid-crustal layer in this area is shallow enough to be reached by drilling with Chikyu, and heat flow is low enough for drilling to proceed at mid-crustal temperatures. Samples recovered from IBM-4 will complement the drilling objectives at other proposed sites in Eocene (IBM-2) and Neogene (IBM-3) arc crust and pre-arc oceanic crust (IBM-1), which are proposed separately and scheduled to be drilled by JR.

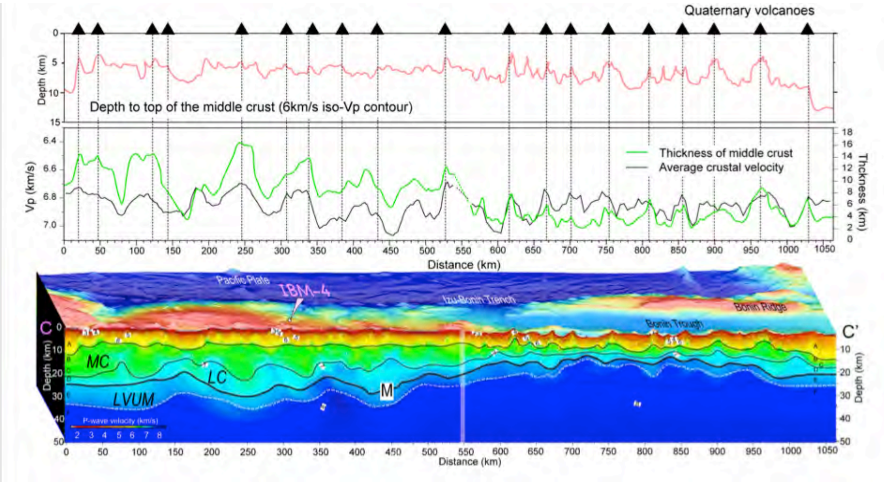


Fig. 2. *Vp* structure of CC' section along the volcanic front (Fig. 1) after Kodaira et al. (2007). The middle crust thickness, the average *Vp* of the total crust and the depth to the top of the middle crust correlate well with the volcano distribution (filled triangles). MC, middle rust; LC, lower crust; LVUM, low-V upper mantle; M, Moho discontinuity.

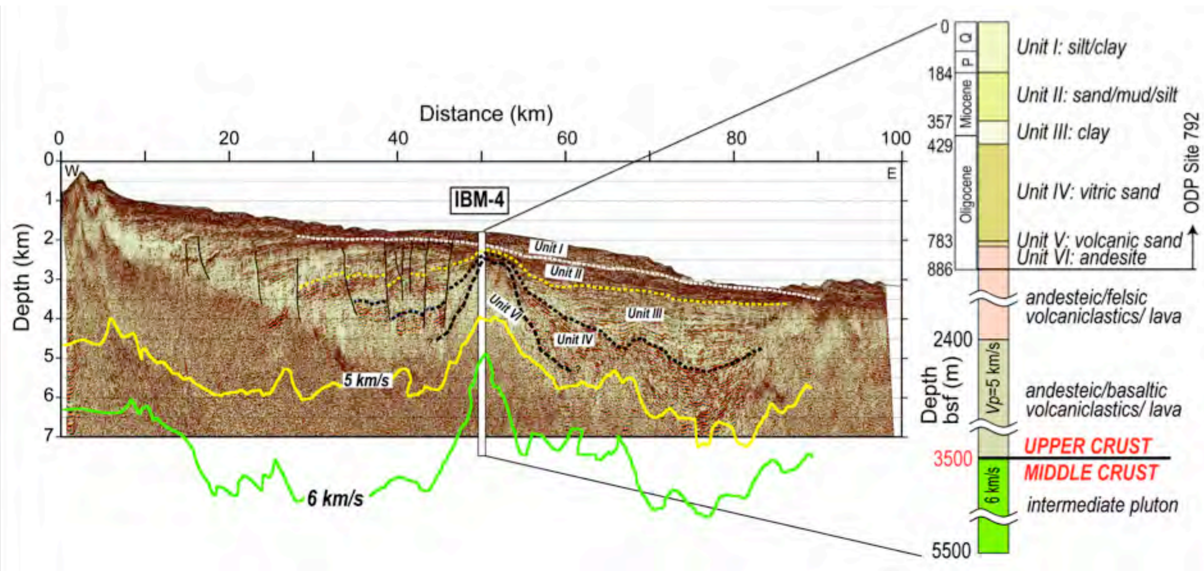


Fig. 3. Lithological interpretation of the seismic image along the IBM4-EW5 section based on the results of ODP792 (Taylor et al., 1992). Iso-*Vp* contours of 5 km/s and 6 km/s obtained by wide-angle OBS data are also shown.

How NASA Plans Its Decadal Program of Robotic Exploration of the Solar System

Gregg Vane

Jet Propulsion Laboratory, California Institute of Technology

Decadal planning; solar system exploration

As with the planning of decade-long campaigns for deep-ocean drilling, the planning of decade-long campaigns for exploring the solar system requires a careful interplay of many diverse elements. Over a decade ago, NASA requested the US National Research Council (NRC) of the National Academy of Sciences to independently create a set of recommendations that NASA could use in planning its program of exploration for periods of a decade in duration. The second such set of recommendations was released last year. The study, which has become known a “decadal survey” in the United States, is called “Vision and Voyages for Planetary Science, 2013-2022” and upon its release, NASA adopted it as the roadmap for the next ten years, dependent of course upon the budget that NASA is allocated annually by the US Congress and Presidential Administration.

The decadal survey planners began by assembling a group of some 60 internationally recognized planetary scientists and planetary mission managers, supported by an equal number of mission design specialists from the various NASA centers. The first task of the group was to assess the current state of knowledge and understanding of our solar system based on the prior decades of exploration. Armed with this knowledge, the group identified the key questions whose answers should be sought in the coming decade in order to advance our knowledge of the solar system in the areas deemed by the group to be the most important. Key questions were then translated into destinations at which the next phase of exploration should be directed. The destinations were organized into five groups representative of the diverse nature of the solar system: Inner planets, Mars, giant planets, satellites of the giant planets, and primitive bodies of the solar system. For each group of destinations, the scientific measurements require to address the key questions were identified, and from this, notional missions were devised whose costs were estimated and independently evaluated. The final step in the process was to prioritize the list of candidate missions on the basis of their scientific value and cost to NASA, measured against a notional annual budget consistent with that of the prior decade.

In my lecture I will describe in greater detail the process used by the NRC, summarize the key recommendations that were made to NASA, and focus special attention on the one major area of planetary exploration in which there is important synergy with the study of the earth’s deep-sea realm, namely, the exploration of Jupiter’s icy moon Europa. There is strong evidence that beneath a crust of ice some few to tens of kilometers thick lies an ocean whose volume is equal to or greater than the volume of all of Earth’s oceans combined. Moreover, Europa’s ocean is in direct contact with a rocky deep-sea floor that could have features such as the hydrothermal vents and smokers found beneath Earth’s oceans. Europa is seen, therefore, as one of the most likely locales in our solar system to harbor life today. Hence the exploration of Europa has emerged as a very high priority for NASA.

Probing the Deep Biosphere with the D/V Chikyu: Opportunities and Challenges

Nicholas W Hayman (University of Texas Institute for Geophysics, USA)
Katrina J Edwards (University of Southern California, USA)
Wolfgang Bach (MARUM, Bremen, Germany)

Keywords: Microbiology, Marine Geology, Oceanic Crust, Serpentinization, Geochemical Cycles, Structural Geology

Despite the obvious importance to our very existence, life's role in fundamental earth processes remains a frontier scientific pursuit. For example, roughly half of the Earth's nutrient production is from microscopic organisms, yet one of the most diverse microbial population has only recently been demonstrated to thrive on and within the crystalline rocks of the ocean crust (Santelli et al., 2008). Understanding this "dark energy biosphere" beneath the seafloor is not only a biological question, but also a geological one. Within the ocean crust microbes are sustained by fluid-mineral reactions (McCollom and Shock, 1997; Bach and Edwards, 2003; Edwards et al., 2005). These reactions can include the range of iron and sulfur redox reactions between fluids and rocks, microbial interactions with dissolved solutes in hydrothermal fluids, and CO_2 and H^+ exchanges with ultramafic materials (Rouxel et al., 2003; Proskurowski et al., 2008; Toner et al., 2009; Lang et al., 2010; Alt and Shanks, 2011). Moreover, biological activity ought to be enhanced within pores and fluid flow pathways such as faults and fracture systems. Therefore, both the mineralogy and structural geology of oceanic crust are linked with the biosphere.

An enormous opportunity for the D/V Chikyu is to explore this biosphere in a wide range of environments. Essentially, the approach is to conduct sampling from drill holes where the geological nature of samples can be directly compared with the biomarkers and gene sequences of microbiological communities that exist on the mineral surfaces and in pore fluids. The key is to minimize the amount of inference that comes with only retrieving one piece of the puzzle. For example, one can document the microbial diversity through analysis of 16sRNA-defined operational taxonomic units (OTUs). Yet, without corresponding geological and structural data, the environment and metabolic pathways are uncertain. Similarly, textural, mineralogical, and isotopic evidence for biological activity can be documented, but without direct sampling of microbial signatures, one can only speculate on their presence. And lastly, without downhole constraints on temperature, permeability, and pore-water composition, the environmental controls on the subseafloor ecosystem remain an unknown but potentially vital control on the biosphere.

The challenges to microbiological-geological investigations are great, though they in turn offer opportunities for advancement in both technology and science approach. At it's root, how can we best use the riser technology of the D/V Chikyu to advance this science, yet have plans that are nimble enough to use riserless drilling? For example, the most direct approach to understanding microbial biodiversity is via analysis of 16sRNA. Such materials are sensitive to temperature and time, as well as contamination. How can we confront these potential obstacles during sample recovery and preservation by a riser-drilling operation? Similarly, many tools have been developed for monitoring biological activity down-hole in riserless operations, either employing CORKs, or via logging tools. How can we translate such efforts to the D/V Chikyu?

There is some precedent to overcoming these challenges. Notably, drilling programs in convergent margins such as the NanTroSEIZE program have employed downhole tools such as multi-dynamic testers (MDTs), FLOCS, smart- and genius-plugs, along with more conventional monitoring and logging tools have been used to document the structure, permeability, microbiology, and pore-fluid composition of the subsurface (e.g., Orcutt et al., 2010, 2011). Exporting such technological advancements and operational experience to the crystalline crust (and upper mantle) is likely not trivial, but possible; even sedimentary materials in convergent margins are dominated by fractures (e.g., Boutt et al., 2011), for example.

Opportunities abound to conduct such combined microbiological-geological investigations in crustal and upper mantle materials. To date, much of the ocean crustal microbial diversity has been documented on oxidized lavas that erupt on the seafloor, and in scientific drill holes that sample the upper few hundred meters of basaltic crust. Yet, at least 25% of the world's seafloor consists of deeper materials that have been brought to the surface by tectonic activity. The authors of this white paper are targeting localities in the Mid-Atlantic Ridge for such investigations. However, several slow- and ultraslow spreading centers in the Southwest Indian Ocean and western Pacific regions are characterized by similar geological composition and structure. Additionally, though older than the ~<8-10 Ma age window of most 'geochemically active' crust, rifted margins and trenches are sites of active serpentinization of exhumed mantle sections, and exposed and faulted deeper crustal sections, and could therefore serve as suitable laboratories.

We suggest that the discussion of interdisciplinary geological and microbiological investigations be raised to a new level via consideration of D/V Chikyu applications. Ultimately, such an application could prove vital, if not indispensable, in testing hypotheses surrounding: (i) the limits of life in the oceanic crust and upper mantle, (ii) the nutrient and transport pathways that support microbial communities and control their spatial diversity, and (iii) the ways that microbial activity in turn affect ocean crustal composition and structure, and are potentially linked with the overlying pelagic environment, and (iv) how life in turn affects the structure and composition of the oceanic crust.

References

Alt, J. C., and W. C. Shanks (2011), Microbial sulfate reduction and the sulfur budget for a complete section of altered oceanic basalts, IODP Hole 1256D (eastern Pacific), Earth and Planetary Science Letters, 310(1-2), 73-83.

Boutt, D.F., and multiple authors, 2012, Scale dependence of in-situ permeability measurements in the Nankai accretionary prism: The role of fractures, Geophysical Research Letters 39, doi:10.1029/2012GL051216.

Bach, W., and K. J. Edwards (2003), Iron and sulfide oxidation within the basaltic ocean crust: Implications for chemolithoautotrophic microbial biomass production, Geochim. Cosmochim. Acta, 67(20), 3871-3887.

Dick, H. J. B., M. A. Tivey, and B. E. Tucholke (2008), Plutonic foundation of a slow-spreading ridge segment: Oceanic core complex at Kane Megamullion, 23 degrees 30 ' N, 45 degrees 20 ' W, Geochem. Geophys. Geosyst., 9, 44.

Edwards, K. J., W. Bach, and T. M. McCollom (2005), Geomicrobiology in oceanography: microbe-mineral interactions at and below the seafloor, Trends Microbiol., 13(9), 449-456.

Edwards, K. J., C. G. Wheat, and J. B. Sylvan (2011), Under the sea: microbial life in volcanic oceanic crust, Nat. Rev. Microbiol., 9(10), 703-712.

Hayman, N. W., and J. A. Karson (2009), Crustal faults exposed in the Pito Deep Rift: Conduits for hydrothermal fluids on the southeast Pacific Rise, Geochem. Geophys. Geosyst., 10, doi: 10.1029/2008GC002319.

Hirose, T., and N. W. Hayman (2008), Structure, permeability, and strength of a fault zone in the footwall of an oceanic core complex, the Central Dome of the Atlantis Massif, Mid-Atlantic Ridge, 30N, Journal of Structural Geology, 30(8), 1060-1071.

Klein, F., W. Bach, N. Jons, T. McCollom, B. Moskowitz, and T. Berquo (2009), Iron partitioning and hydrogen generation during serpentinization of abyssal peridotites from 15 degrees N on the Mid-Atlantic Ridge, Geochim. Cosmochim. Acta, 73(22), 6868-6893.

Lang, S. Q., D. A. Butterfield, M. Schulte, D. S. Kelley, and M. D. Lilley (2010), Elevated concentrations of formate, acetate and dissolved organic carbon found at the Lost City hydrothermal field, Geochim. Cosmochim. Acta, 74(3), 941-952.

McCollom, T. M., and E. L. Shock (1997), Geochemical constraints on chemolithoautotrophic metabolism by microorganisms in seafloor hydrothermal systems, Geochim. Cosmochim. Acta, 61(20), 4375-4391.

Orcutt, B.N., Wheat, C.G., Edwards, K.J. (2010). Subseafloor ocean crust microbial observatories: Development of FLOCS (FLow-through Osmo Colonization System) and evaluation of borehole construction materials. Geomicrobiology Journal 27: 143–157.

Orcutt, B.N., Bach, W., Becker, K., Fisher, A.T., Toner, B.M, Wheat, C.G., Edwards, K.J. (2011). Colonization of subsurface microbial observatories deployed in young ocean crust. The ISME Journal 5: 692-703.

Proskurowski, G., M. D. Lilley, J. S. Seewald, G. L. Fruh-Green, E. J. Olson, J. E. Lupton, S. P. Sylva, and D. S. Kelley (2008), Abiogenic hydrocarbon production at Lost City hydrothermal field, Science, 319(5863), 604-607.

Rouxel, O., N. Dobbek, J. Ludden, and Y. Fouquet (2003), Iron isotope fractionation during oceanic crust alteration, Chem. Geol., 202(1-2), 155-182.

Santelli, C. M., B. N. Orcutt, W. Banning, W. Bach, C. L. Moyer, M. L. Sogin, H. Staudigel, and K. J. Edwards (2008), Abundance and diversity of microbial life in ocean crust, Nature, 453, 653-656.

Toner, B.M., Fakra, S.C., Manganini, S.J., Santelli, C.M., Marcus, M.A., Moffett, J., Rouxel, O., German, C.R., Edwards, K.J. (2009). Preservation of iron(II) by carbon-rich matrices in a hydrothermal plume. Nature Geoscience, 2(3): 197-201. doi:10.1038/NGEO433

Exploration of Deep Carbon Cycle and Limits of Life with CHIKYU

Fumio Inagaki[1], Kai-Uwe Hinrichs[2], Yusuke Kubo[3], and Expedition 337 Scientists

[1]Kochi Institute for Core Sample Research, Japan Agency for Marine-Earth Science and Technology (JAMSTEC), Nankoku, Kochi, Japan, [2]MARUM and Department of Geosciences, University of Bremen, Bremen, Germany, and Center for Deep-Earth Exploration (CDEX), JAMSTEC, Yokohama, Japan.

[Keywords] deep microbial life, hydrocarbon reservoirs, biogeochemical cycles, CO_2 sequestration

The IODP Expedition 337 was the first expedition dedicated to subseafloor microbiology that used riser-drilling technology on the drilling research vessel CHIKYU. The drilling site C0020 is located in a forearc basin formed by the subduction of the Pacific Plate off the Shimokita Peninsula at a water depth of 1,180 meters. Seismic profiles strongly suggested the presence of deep coal-bearing horizons at about 2 km subseafloor depth. Our primary objectives during Expedition 337 were to study the relationship between the deep microbial biosphere and the subseafloor coalbed and to explore the limits of life in horizons deeper than ever probed before by scientific ocean drilling. Among the questions that guided our research strategy was: Do deeply buried hydrocarbon reservoirs such as coalbeds act as geobiological reactors that sustain subsurface life by releasing nutrients and carbon substrates? To address these objectives and questions, we penetrated a 2.466 meters-deep sedimentary sequence with a series of coal layers at around 2 km below the seafloor. Hole C0020A is currently the deepest hole in the history of scientific ocean drilling. Drilling at this site extended the previous maximum penetration depth in scientific ocean drilling by 355 meters and provided the chance that our post-cruise research will extend the current evidence of deepest subseafloor life by up to 800 meters.

Riser drilling at Site C0020 provided an unprecedented record of dynamically changing depositional environments in the former forearc basin off the Shimokita Peninsula during the late Oligocene and Miocene. This record is comprised of a rich diversity of lithological facies reflecting environments ranging from warm-temperate coastal back-swamps to cool water continental shelf. Core recovery using riser drilling is remarkably high even in the great depth, which was 76.5% during Expedition 337 (12 of 32 cores were 90-100% recovery, including soft beach sand layers: see Table 1). A combined use of large diameter core barrel (LDC) with riser drilling was found to be useful for retrieving previously difficult lithologies such as conglomerates or gravels, also minimizing contamination of innermost core for geochemical and microbiological studies. The use of riser-drilling technology in very deep sediments created both unique opportunities and new challenges the study of subseafloor life. The use of drilling mud during riser drilling required implementation of a rigorous program dedicated to quality assessment and quality control (QA/QC) of the sampled materials and data. We successfully added chemical tracers to monitor the levels of drilling mud contamination of samples and quantified levels of mud-derived solutes in interstitial fluids. This data provides the framework for differentiating signals of indigenous microbes from those of contaminants. For the first time in scientific ocean drilling, we conducted downhole fluid analysis and sampling, and logging operations yielded data of unprecedented quality that provide a comprehensive view of sediment properties and water mobility at Site C0020. The estimated temperature gradient was 24.0 °C km^{-1} or slightly lower; estimated temperatures in coal-bearing horizons are around 50 °C and thus provide comfortable conditions, temperature-wise, for many microbes. To detect microbial activity in very deep habitats, we deployed a new radioisotope laboratory on CHIKYU. We also conducted gas analysis using a newly installed mud gas-monitoring laboratory. Gas chemistry and isotopic compositions provide the first indication of the existence of a subseafloor biosphere in deep horizons associated with the coalbed. Expedition 337 also provided a test ground for the use of riser drilling technology to address geobiological and biogeochemical objectives and was therefore a crucial step toward the next phase of deep scientific ocean drilling.

Potential benefits of the deep riser drilling for scientific communities are enormous. The riser borehole C0020A has been suspended; therefore, it is feasible to extend the drilling depth from 2,466 m down to the deepest Cretaceous coalbeds over 4,500 meters. The temperature at such great depth must be close to (or beyond) the habitable range of life; therefore, deepening the riser-hole C0020A will provide a complete view of the coalbed-associated subseafloor hydrocarbon system. In addition, Hole C0020A is useful as a subseafloor laboratory for active experimentation of CO_2 sequestration into the lignite coal-sand formation; the consequence of subseafloor CO_2 sequestration for Earth's carbon cycle and ecosystems has still remained largely unknown. These implementations will require the adaptation of CHIKYU's riser-drilling technology to the needs of both basic and applied sciences. The riser-drilling exploration with CHIKYU has a large potential to expand our scientific knowledge of life and Earth, which may also contribute to the creation of sustainable systems for the human society.

Table 1. Summary of riser coring operation during Expedition 337.

Coring Interval	1276.5 – 2,466 mbsf
Number of Spot Core	32
Over 90% Recovery	12 (out of 32)
Average Core Recovery	76.5%
Total Core Length	200.1 m

The Challenger Deep sediment coring

[Authors] Shinsuke Kawagucci[1 2 3] and Takuro Nunoura[1]

[Institutions] [1]Biogeos, [2]Precambrian Ecosystem Lab., and [3]SRRP, JAMSTEC

[Keywords] The deepest biosphere, The deepest coring, The Challenger Deep, serpentinization

[TEXTBODY]

There is the deepest point in the Earth's seafloor.
That is why Chikyu should go to the Challenger Deep.

Theoretical investigations and geochemical and microbiological characterizations of practical fields strongly suggested that H_2 is one of the most important energy sources for (sub)seafloor chemolithoautotrophic microbial ecosystems because of its metabolic diversity even to reduce CO_2. Thus abiotic H_2 generation is a key process to know the linkage between lithosphere and biosphere. One of the abiotic H_2 generation processes is serpentinization of olivine in peridotite that expands possible geographical distribution of H_2-driven (sub)seafloor microbial ecosystems not only in high-temperature hydrothermal systems, but also in any region where serpentinization occurs beneath the seafloor. Shinkai Seep field, located on the northern slope of the South Mariana trench, is the case, for example. The Shinkai Seep field harbors abundant vesicomyid clam communities associated with a serpentinite-hosted geofluid derived from fault-controlled fluid pathways connected to the decollement of the subducting slab. Noteworthy, there is only 80 km distance between the Shinkai Seep field and the Challenger Deep, Earth’s deepest point. Indeed, a 1.6 m sediment core taken from the bottom of the Challenger Deep by the ROV ABISMO contained elevated levels of H_2 and CH_4 with seawater-level sulfate, strongly suggesting notable flux of the reducing components from external sources of sediment, probably serpentinization-based geofluid. As geofluids emergence and their geochemical features have been regarded as window to view the invisible subseafloor environment, to study interstitial water chemistry of the Challenger Deep sediment taken by the HPCS coring permits us to achieve the preliminary understandings of the characteristics of the underlying geology and geofluid system for future deeper penetration using the drilling apparatus. The origin of methane in the Challenger Deep sediment, whether completely abiotic methanogenesis associated with serpentinization or microbial methanogenesis utilizing serpentinization-derived H_2, is of particular interest. The strong geochemical redox gradient in the Challenger Deep sediment core taken by ABISMO suggested the promise habitability for chemolithoautotrophic microbes in the term of energy source. The serpentinization-based H_2-driven subseafloor biosphere in the Challenger Deep is supposed to harbor unique features comparing to the previously known similar ecological systems such as the Lost City hydrothermal filed, the Mariana Forarc seamounts, and the Shinkai Seep field as described below.

1. The deepest serpentinization-dependent subseafloor biosphere on this planet.

2.The only sediment-hosted serpentinization-dependent subseafloor biosphere as we know.

The serpentinization-dependent biospheres have been found on the mid ocean ridge, island arc, and the trench sloop, and thus, the effects of sediments for the serpentinization-dependent biosphere have not been observed yet.

3. The effects of segregation by the trench geography for the subseafloor biosphere.

The effects of the geographical segregation on the distribution and evolution of macrofaunas have been reported. In the case of the Challenger Deep, primitive unique foraminifers have been reported. In addition, recently, amphipod that harbors a novel enzyme HG cellulase, which can efficiently convert cellulose to glucose, was purified from the Challenger Deep. In case of the microbial population, we found that the diversity of archaea in surface sediments and trench waters in the Challenger Deep was extremely small comparing to the ambient deep-sea sediments.

In addition to the scientific aspects, the Challenger Deep sediment coring has advantages in technical and social points of view. The touch by Chikyu to the deepest seafloor (more than ten km in water depth) will be one of the technical milestones for other Ultra-deep drilling projects (more than several km both in water depth and subseafloor depth). On the social aspect, the research targeting the deepest ocean on the Earth will surely attract people in non-scientific field and possibly bring public understanding and support for the seafloor drilling community.

MICROBIALLY MEDIATED SMECTITE-TO-ILLITE REACTION IN MUROTO, NANKAI TROUGH: A NEW GEOLOGICAL CONCEPT

Jinwook Kim[1], Takehiro Hirose[2], and Collaborators
[1]Department of Earth System Sciences, Yonsei University, Seoul, Korea,
[2]Kochi Institute for Core Sample Research, JAMSTEC, Kochi, JAPAN

Keywords: Smectite-to-illite Reaction, Microbial Fe-reduction, Physical property

1. Objective/Goals

Smectite-illite clay minerals are ubiquitous in siliciclastic sedimentary environments. The smectite to Illite (S-I) transformation is considered to be one of the most important mineral reactions [1], as the degree of the (S-I) reaction, termed "smectite illitization", is linked to the maturation, migration and trapping of hydrocarbons [2], the development of pore pressures [3], pore water chemistry [4], and the changes in petrophysical properties of sediments [5]. For example, a reduction of 13% in porosity and 100 times decrease in permeability is reported when 80% of smectite transformed to illite [6] and the typically random distribution of pores in smectite changes to a sub/parallel distribution with increasing smectite illitization [6] that affects the sound velocity and sediment structure. In addition, clay surface charge increases (0.25-0.60 to ~1.0 per formula unit) as smectite is transformed to illite. Surface charge is a controlling factor for flocculation properties of clay suspensions [7] which affect dynamic properties of sediments. Consequently, these changes can impact on the macroscopic geotechnical properties of the sediments. The degree of S-I transformation is also used frequently as an independent geothermometer [8] to predict the thermal history of sedimentary basins which is useful for the exploration of methane hydrates associated with hydrocarbon seeps. The S-I transformation has been thought that the reaction was entirely abiotic and to require burial, heat, and time to proceed. However, we propose to investigate the effects of microbes on the S-I transformation, an alternative model which challenges the conventional concepts of S-I reaction.
Thus, the objective of this research is to test the model for the active fault zone in Muroto, Nankai Trough and in particular definitively answer the following important questions: a) what is the microbial diversity with increasing depth, b) which microbial mechanisms influence the transformation, c) what are the associated reaction rates, d) in which diagenetic settings are microbial processes contributing to the transformation of smectite, e) to what extent do microbial processes contribute to the global transformation of smectite, and f) what is the implications of biologically induced S-I reaction to the petrophysical properties of sediment.

2. Motivation/Background

Recent laboratory studies provided for the first time, evidence suggesting that microbes can transform smectite to illite at room temperature within 14 days [9]. These results are of great interest because this reaction was thought to require much higher temperatures over an extended period of time. Numerous studies have emphasized temperature, pressure, and time as geological variables in either solid state or dissolution-precipitation S-I transformation mechanisms [10], but none have considered microbial reactions. We hypothesize that the role that microorganisms play is to link organic matter oxidation to metal reduction, resulting in the S-I transformation. Data from previous studies may support our hypothesis. For example, an increasing percentage of illite layers in mixed-layered smectite-illite (S-I) with increasing Fe^{2+}/Fe^{3+} in Cretaceous bentonites was reported [11]; however, the authors were unable to identify the cause for the varying Fe^{2+}/Fe^{3+} ratio. Moreover, the illitization rate of smectite in shale and bentonite of sediment at Nankai Trough showed a variation even at a same depth, indicating the other factors than temperature, pressure, or reaction time could catalyze the reaction. We suggest to consider the role of microbe during S-I reaction because shale ("black shale") contains more organic matter where the microbe use it as a carbon source comparing with bentonite [12]. The tensile strength of clays was shown to be increased by extracellular polymeric substances (EPS) secreted by bacteria [13] that could be an important factor that causing the changes in sediment stability. In abiotic systems, elevated temperatures are typically used in laboratory experiments to accelerate the smectite to illite reaction in order to compensate for a long geological time in nature [14]. In biotic systems, bacteria may catalyze the reaction, and elevated temperature or prolonged time may not be necessary. *The proposed study should change the fundamental understanding of the S-I* *reaction and has significant implications for sediment diagenesis affecting the stability/structure of sediments.*

3. Approach

The main focus of this proposal is to study how microbial reduction of smectite structural Fe(III), and associated microbial process, drives the S-I transformation using direct measurement of S-I as well as chemical products of S-I transformation. Moreover, the effects of the microbially induced S-I reaction on the changes in petrophysical properties such as permeability, porosity, and shear strength of sediments should be tested.

3.1 Site Selection

The candidate for the site to drill should be relatively young and active accretionary wedge area where the diagenetic modification of sediments is minimized and sediments are relatively settled in-situ so that the test of biological effects on S-I reaction can be feasible. To our best knowledge, location near to the Site 808 is the possible candidate.

3.2 Microbial Diversity

Microbial diversity with increasing depth will be tested and correlated with the illite formation and lithology. So far we are looking for the microbiologist to perform this task.

3.3 S-I transformations

S-I transformation of sediments with increasing depth will be monitored using X-ray Diffratometer (XRD), TEM and EELS. The percent of illite in mixed-layer I-S in the reaction products will be quantitatively determined in XRD patterns by comparing experimental and calculated patterns using NEWMOD program [15]. The illite peak will be intensified by polyvinylpyrrolidone (PVP) treatment and Mudmaster program [15] will be followed to calculate crystal size distribution to further delineated the smectite illitization mechanism. Analysis of high-resolution lattice fringe, selected area electron diffraction, and EELS will be carried out in each sample at selected time point. These data will allow direct determination of S-I ordering based on their layer spacings.

3.4 Reduction Experiments

The reduction experiments will be performed according to the thermal optimum of the bacteria in order to compare the observed S-I reaction in the drilling site. Sterilized smectite separates (less than 0.2 micron) will be inoculated with cell suspensions. Controls will be identical to treatments except that cells will be killed by microwave heating in serum bottles. The samples containing cell-clay mixtures will be shaken gently and incubated at various temperatures depending on the thermal optimum of the bacteria. Sampling time will be 0, 1, 3, 4, 7, 14 and 30 days, and this time sequence may be modified as the reaction continues. As temperature is increased, the rate of microbial reduction of Fe(III) is expected to increase.

3.5 Mechanism of microbially mediated S-I transformation

Percentage of illite layers in S-I will be plotted as a function of time for both biotic and abiotic systems. The difference in the extent and rate of the S-I transformation between the two systems will reflect the effect of microbes. If a large amount of octahedral Fe(III) is reduced in solid state, the smectite structure may become unstable because of the imbalance of surface charge and eventually break down resulting in K fixation to produce illite. The Si and Al release from mineral to solution will be used as an indicator to determine the dissolution rates of smectite. The dissolution rate will be expressed in terms of mol per surface area per time. Excess Fe resulting from the reductive dissolution of Fe-rich smectite can cause the precipitation of Fe-rich minerals as by-products, because illite contains less Fe than Fe-rich smectite. XRD will be performed to detect these minerals.

3.6 Petrophysical Properties

The tensile strength, porosity and permeability of sediments with increasing depth will be measured. The possible association of microbially induced S-I reaction with physical property changes in sedimenets will be tested. This notion is important because it may cause the accretionary wedge deformation.

References

1. Dong et al. *Am. Mineral*. **82**, 379-391 (1997).
2. Pevear, D.R *Proc. Nat. Aca. Sci.* **96**, 3440-3446 (1999).
3. Freed, R.L. & Peacor, D.R. *AAPG Bull.* **73**, 1223-1232 (1989).
4. Brown et al. . *Earth. Planet. Sci. Lett.* **194**, 97-109 (2001).
5. Boles et al. J. Sed. Pet., **49**, 55-70 (1979).
6. Kim et al., *GCAGS* **51**, 161-172 (2001).
7. Kim et al. Clays Clay Miner. 53, 572-579 (2005)
8. Pollastro, R.M. *Clays Clay Miner.* **41**, 119-133 (1993).
9. Kim et al. *Science*, **303**, 830 – 832 (2004)
10. Bethke, C.M. & Altaner, S.P. *Clays Clay Miner.* **34**, 136-145 (1986).
11. Eslinger et al. *Clays Clay Miner*. **27**, 327-338 (1979).
12. Masuda et al. *Clays Clay Miner.* **49**(2), 109-118 (2001).
13. Tolhurst et al.Fine Sediment Dynamics in the Marine Environment, 409-425 (2002)
14. Huang et al. *Clays Clay Miner.* **41**, 162-177 (1993).
15. Eberl et al. *Am. J. Sci.* **298**, 499-533 (1998).

Advancing Subsurface Molecular Biogeochemical Ecology in the Next Decade

Heath J. Mills
Department of Oceanography, Texas A&M University, USA
Biosphere, subsurface, standardization

Introduction

For more than a decade the living subsurface has been characterized in sediments with a multitude of ages, geochemical conditions, and geophysical constraints. As the Chikyu embarks on a new decade, the time is right to coalesce the strengths and address the weaknesses from these studies to develop a plan to standardize the biological exploration of the deep subsurface. To accomplish this goal, a multidisciplinary approach must be utilized to better incorporate and align current geochemistry, sedimentology and hydrology efforts with molecular biology. In addition, a standardization of the molecular techniques used should be considered and discussed to allow a more meaningful cross comparison between samples and sites. The Chikyu has the potential to take the lead in biosphere exploration, the fastest developing field within the drilling community, while pioneering the emergence of molecular biogeochemical ecology.

A unique challenge for the biosphere community has been receiving intellectual reciprocity from the drilling community. In many ways the biologists understand the need for collaborative data that describe the chemical, physical and geological parameters that constrain each sample obtained. However, the biologists are rarely consulted during core description or, even more harmful, during the core preservation efforts. While the former can produce an incomplete understanding of the subsurface, the latter could have damaging effects on legacy cores (Mills et al., 2012). It is time for the biologists to be invited by the other disciplines to discuss the effects of biology within the subsurface.

Relevance

As a community, we need to educate all subsurface scientists beyond a description of which microbes are present, to an understanding of the implication of the metabolic processes on the sediments. Within the next decade, results from the subsurface biosphere community will challenge long held theories regarding diagenetic processes, the paleo-record (ecology and magnetism), and subsurface geological evolution. These transformative advances will be realized only if a collective effort is made to standardize biosphere exploration so that direct comparisons can be made between samples, sites and expeditions.

Strategic Plan

A multiple step process will be required to provide subsurface biological exploration and interpretation at a scale relevant to the complexity of the biosphere. While each step alone will create minimal effort, together they will provide a transformative change in biosphere research. Initial efforts must address routine biological sampling, biologically relevant geochemical analysis, cell enumeration and molecular characterization.

Routine Sampling: Biology is the only major field of study within the IODP that does not currently have a routine sampling plan. Without a routine sampling plan, many basic questions associated with diversity, limits of life and overall biomass will remain elusive. A limiting factor in the establishment of a standard sampling protocol has been that biologic requirement for whole round cores. This effects core stratigraphy, sediment dating , and other geological parameters. If the biological community is going to obtain equal status with the other fields, then this challenge should be seen as one of the top goals. Such a sampling plan would open up many research opportunities for additional research and thus expand our field. Questions including frequency, storage conditions, sediment types and processing needs to be determined and now is the time to do it.

Geochemical Analysis: Standard geochemical analysis of core material fails to meet the requirements for biological analysis of the subseafloor. While the geochemical data set is robust and well constructed, key measurements including nutrients are not routinely samples. Missing these measurements makes biological interpretation difficult to impossible in some samples. The Chikyu and the other IODP platforms should have the capacity and desire to provide this biologically basic data set to all researchers for both active and archive-based research. Training should be provide to staff and oncoming scientist to ensure quality and reproducibility of this analysis.

Cell Enumeration: Recent advances in cell enumeration technologies can provide a standard measurement of the microbial biomass within the subsurface biosphere. The key to this goal is automation. Drs. Fumio Inagaki and Yuki Morono (Morono et al. 2009) describes an automated method that can and should become routine onboard. While this will require time for a technician to run the machine and prepare samples, this is no more labor intensive than what is currently being done by geochemical technician.

Molecular Characterization: The most ambitious goal will be standardizing the molecular characterization of the subsurface. But with each ambitious goal, it begins with a single step. The first step can be the Chikyu adopting a procedure that will collect more microbial samples. This step should be followed by the careful selection of a method for nucleic acid extraction and amplification. Technologies are advancing so that this can be come a high throughput, robust method that will provide a wealth of sequence data to all associated with the Chikyu. Procedures can be streamlined for shipboard analysis. This initiative will be the first of its kind for any large scale field research program. The initiative can be accomplished with the correct support.

Conclusion: Standardization of biosphere exploration will create a legacy resource and database for current and future research. The time is ideal for the Chikyu to lead the way. As research plans are being developed for the new program, initiatives like this one can gain the proper support to be a sustainable change in the drilling community. The description of the subsurface environment will improve with each incorporation of the biological data proposed here. There is support in the community now, but an initiative must be started, with leadership support, to advance Chikyu operations into the future.

References

Mills, H.J., B.K. Reese, and C. St. Peter. 2012. Characterization of microbial population shifts during sample storage. Frontiers in Extreme Microbiology: Deep Subsurface Microbiology. 3:49. doi: 10.3389/fmicb.2012.00049

Morono, Y., T. Terada, N. Masui, and F. Inagaki. 2009. Discriminative detection and enumeration of microbial life in marine subsurface sediments. ISME J. 3:503-511.

The Challenge of Contamination in Deep Life Exploration

Yuki Morono[1], Mark A. Lever[2], Tatsuhiko Hoshino[1], and Fumio Inagaki[1]

[1]Geomicrobiology Group, Kochi Institute for Core Sample Research, Japan Agency for Marine-Earth Science and Technology (JAMSTEC)

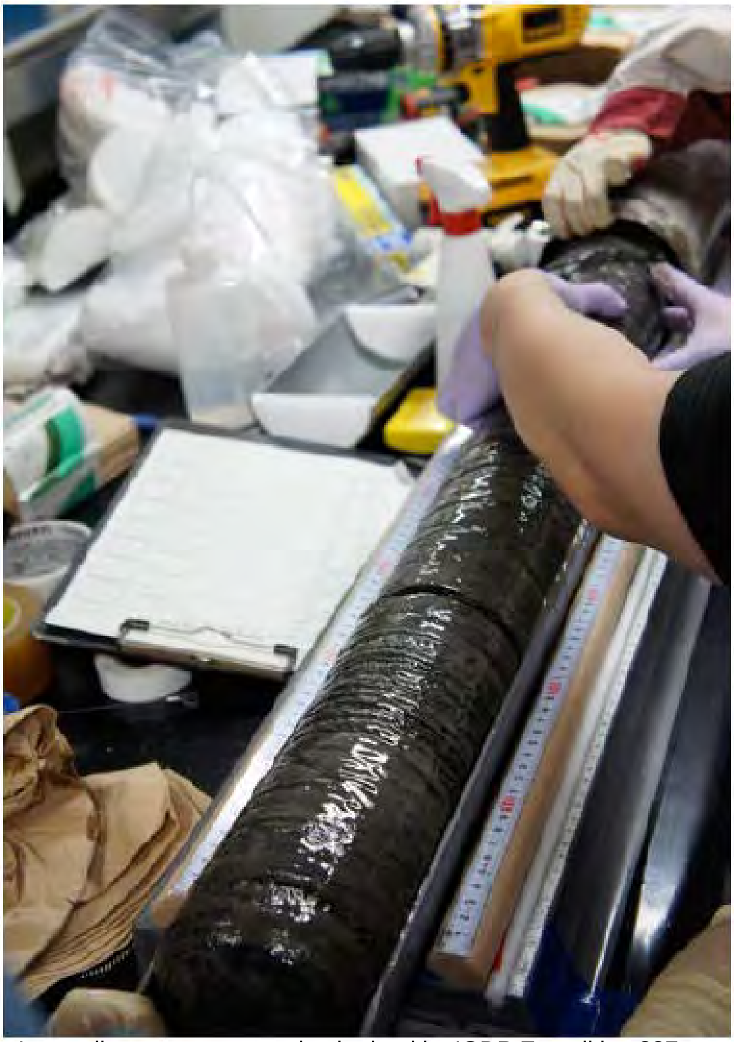
[2]Center for Geomicrobiology, Department of Bioscience, Aarhus University

[Keywords] deep subseafloor life, sample contamination, riser-drilling mud, clean experimental environment

What is the extent of the deep biosphere, and how do microbes survive in the deep subseafloor regime, are the fundamentally important themes that should be addressed by the CHIKYU's future mission. However, the exploration of deep life is a combat against contamination. The degree of contamination greatly varies depending on the coring system. In riser-less drilling, the hydraulic piston coring system (or advanced piston coring) is known to have the lowest contamination, which can only be applied to soft sediments (Smith et al., 2000; Lever et al., 2006). In the extended shoe coring system or rotary core barrel, which are used for more stiff formations, e.g. hard sediment or basaltic basement, only large intact pieces of cored samples are suitable for microbiological studies, whereas smaller fragments tend to be highly contaminated. Until recently, contamination of core samples obtained by riser drilling had not been quantified.

IODP Expedition 337 on the drilling research vessel CHIKYU was the first riser-drilling expedition dedicated to subseafloor microbiology and biogeochemistry. During this expedition, we were able to, for the first time ever, examine and quantify the extent of contamination induced to sediment cores during riser drilling. Unlike riser-less drilling, riser drilling uses synthetic drilling mud that is constantly circulated between mud tanks onboard the CHIKYU and the borehole during drilling operations. As we reported previously (Masui et al., 2008), there is a high concentration of microbial cells in drilling mud, even before mud circulation for drilling (1-2×10^8/cm^3 of drilling mud). During Expedition 337, we found that the concentration of cells in drilling mud remained at the same level after the onset of drilling and throughout the riser-drilling operation. The high concentration of cells in drilling mud increases the risk of core contamination to samples obtained by riser drilling. In comparison to riser-less drilling, which uses sea water as drilling fluid, the concentration of contaminant cells is at least 200 to 1000 times higher during riser drilling, posing a significant concern to microbiological studies on riser-drilled samples. For example, if we want to measure the microbial cell abundance on samples containing ~10^3 cells/cm^3, only one drop of the drilling mud contamination (assuming the volume is 10 μl, which should contain 10^6 cells) causes a ~1000 fold increase in cell numbers within the sample. Furthermore, current sensitivity for tracing drilling mud intrusion into samples is, at best, 0.02 μL of drilling mud, which still corresponds to contamination by ~10^3 cells/cm^3. Thus, even for samples with drilling fluid contamination below the detection level, we cannot be sure that the sample is devoid of significant contamination.

Therefore, it will be critical to develop riser-drilling technology on the CHIKYU that enables (nearly) contamination-free core sampling in the coming years. To reliably explore the limits of life in the deep biosphere, it will be necessary to obtain core samples with ≤10 contaminant cells/cm^3 of sample. To achieve this goal, there are several requirements: (1) reducing drilling fluid intrusion into cores during drilling, (2) reducing the concentrations of contaminant cells in drilling mud, and (3) obtaining clean inner material from core samples that are contaminated in the outer parts. Cleaner coring operations are challenging, but are a primary goal of the CHIKYU in the future. Reducing the contaminating cells from drilling mud is straightforward but also challenging to implement. Also, the cost of synthesizing clean drilling mud, and difficulty to reclean circulating mud will be major obstacles in achieving clean drilling. The last requirement, cleaner laboratory sampling of less contaminated core interiors is the easiest one to implement, though insufficient if drilling fluid intrusion remains high. Avoiding contamination through drilling is partially studied by the CDEX for years as "gel-core technology", of which concept is to cover the drilled core *in situ* with polyacrylamide gel. While we are not saying that the gel-core technology is the only technique that enables obtaining clean core samples, it has potential to reduce core contamination significantly even using current drilling mud. Large diameter coring also have a possibility to reduce contamination in inner part of samples through reduction of cracks during coring. However, for both of the coring technology, taking longer time to obtain cores should be another issue in terms of operational efficiency. Obtaining clean inner material from contaminated core samples does not always relate to drilling itself, but to subsampling in the shipboard microbiology laboratory. For instance, removal of contaminated core exteriors prior to accessing the less contaminated inner parts is essential to avoid cross contamination of less contaminated core interiors. Moreover, introducing core samples with high contamination on the exterior into clean areas results in a high risk of cross contamination to clean inner core parts. Thus, a step-wise cleaning protocol with designated areas, e.g. clean booths, for different cleaning steps could be established to ensure contamination-free sampling of inner cores.


Large diameter core sample obtained by IODP Expedition 337 (Photo was taken by F. Inagaki)

The current situation on the riser-drilled core samples by Expedition 337 is that even very carefully collected samples are not free of microbial contamination signals. Therefore we need careful examination of all available lines of evidence to obtain a comprehensive view of the potentially deepest subseafloor ecosystem ever studied. To further explore the deep subseafloor biosphere in the future, technological advancements to obtain cleaner core samples will be of highest importance to all analyses related to microbiology and biogeochemistry.

Reference

Lever, M.A., Alperin, M., Engelen, B., Inagaki, F., Nakagawa, S., Steinsbu, B.O. et al. (2006) Trends in Basalt and Sediment Core Contamination During IODP Expedition 301. *Geomicrobiol J* **23**: 517 - 530.

Masui, N., Morono, Y., and Inagaki, F. (2008) Microbiological assessment of circulation mud fluids during the first operation of riser drilling by the deep-earth research vessel Chikyu. *Geomicrobiol J* **25**: 274-282.

Smith, D.C., Spivack, A.J., Fisk, M.R., Haveman, S.A., Staudigel, H. & ODP Leg 185 Shipboard Scientific Party (2000) Tracer-Based Estimates of Drilling-Induced Microbial Contamination of Deep Sea Crust. *Geomicrobiol J* **17**:207-219.

Quantifying Necromass in the Oceanic Deep Biosphere

Ramírez, Gustavo A.[1] and Edwards, Katrina J.[1]

University of Southern California, NSF-Center for Dark Energy Biosphere Investigations[1]

Key Words: Deep Biosphere, Microbial Ecology, Extracellular DNA, and ATP.

The Oceanic Deep Biosphere is functionally defined as life-containing habitats at a depth greater than ~1 meter under marine sediment. This habitat delineation inherently subdivides the biosphere into sedimentary and crustal realms. Extensive interrogation of the prevalence and activity of microbial life in the sedimentary Deep Biosphere is thus far indicative of highly heterologous distribution of biomass and extremely low metabolic rates as an adaption to life in extreme oligotrophy. Microbial community structure at depth follows predictable patterns based on the abundance of various oxidation-reduction couples and respective prokaryotic metabolic arsenals. Recently, targeted microbiological exploration of the crustal realm of the Oceanic Deep Biosphere has begun. Igneous basalts constitute a global sub-seafloor crustal aquifer and are the largest contiguous ecosystem on Earth. The implementation of microbial observatories on various IODP holes in the Eastern Pacific has allowed the unprecedented study of hydrogeological, geochemical and microbiological spatial-temporal coupling of this perpetually dark realm. Crustal aquifer hydrogeological networks are likely responsible for subseafloor microbiological dispersal and oxidant-reductant delivery. Recent work from subseafloor observatories located on the eastern flank of the Juan de Fuca ridge has reported the presence of diverse and dynamic microbial communities in venting formation fluids, *in situ* colonization experiments at depth and seafloor colonization experiments exposed to hydrothermal fluids as inoculant.

The majority of work described above has drawn conclusions about the prevalence and activity of life in the deep biosphere based on the interrogation of nucleic acids (predominantly DNA), microscope-based cell counts with fluorescent stains or targeted probes and/or biological markers such as prokaryotic membrane lipid distributions. The ephemeral nature of RNA coupled with low biomass associated with Deep Biosphere environments and complex sample chemistry often restricts nucleic acid analysis exclusively to DNA. With the exceptions of a few reports of microbial community structure based on 16S RNA sequencing, no targeted effort has been made to explicitly delineate the living fraction of microbial censuses produced by the indiscriminative amplification of total DNA extracts. Recently, we have begun exploring novel techniques aimed at addressing this inconvenient issue pervasive in the field of microbial ecology.

We propose the extracellular quantification of Adenosine 5’-triphosphate (ATP), a cellular nucleotide universally involved in energetics, as a rapid proxy for necromass or biological detritus. Traditionally, ATP has been employed as a biomass/activity proxy under the assumption that all detected quantities are of strict intracellular origin. We have utilized a commercially available

Luciferin/Luciferase-based enzymatic kit, containing an extracellular nucleotide digestion step, which allows the fractional quantification of intra vs. extra-cellar ATP in environmental samples via light integration. Notably, we have already detected copious extracellular amounts of ATP in shallow marine sediments (fig. 1). We speculate that the predominance of the biofilm phenotype in prokaryotic communities found in both major realms of the Deep Biosphere may account for exopolysaccharide-bound aggregates of otherwise unstable or readily metabolized intracellular contents.

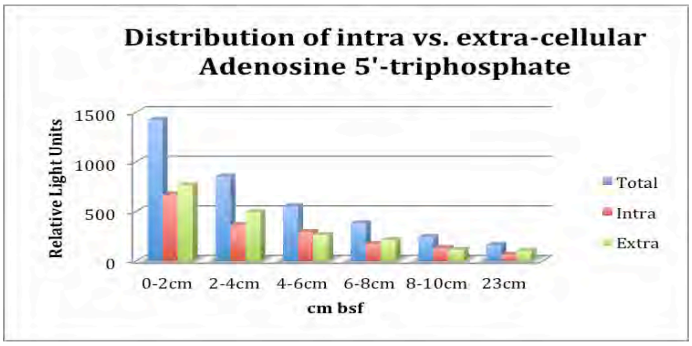
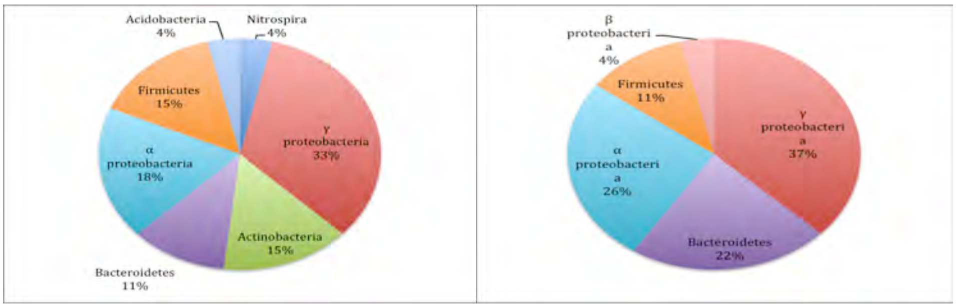


Fig. 1. Intra/extra cellular distribution of ATP in Catalina Harbor Sediments. . Ramirez & Edwards (*in prep.*).

Similarly, indiscriminate DNA amplification of 16S rDNA does not result in accurate microbial community censuses reflective of viable (metabolically active or with potential to become active) community members. We have utilized Propidium Monoazide (PMA), a DNA interchelating photo-active dye capable of forming a covalent bond between the strands of DNA upon light exposure, to inhibit PCR-based inactivation of detrital (extracellular) DNA and/or DNA that may be harbored in cells with compromised/damaged membranes. Sequencing of amplicons derived from total DNA or PMA-DNA as templates has revealed the dead (compromised membrane) and living (intact membrane) phylotype fractions in shallow marine sediments (fig. 2A & 2B). Our data indicate that the living phylotype fraction was mostly comprised of a subset of the total fraction.

Fig. 2. Full-length Catalina Harbor Sediment 16S clone libraries produced from PCR products of (A) total DNA or (B) PMA-DNA. Ramirez & Edwards (*in prep.*).



It is worth noting that both ATP and DNA are potential sources of N and P and may play important roles in Deep Biosphere nutrient cycling. The quantification of extracellular DNA prevalence in the subseafloor may also play an important role in the adaptation and evolution of organisms in this extreme environment by serving as unexpected reservoirs for potential lateral gene transfer events. Microbiological interrogation, using a combination of the above methods (in addition to other *in situ* discriminative life-detection technology currently in development), of Chikyu-retrieved sediment and rock core samples can better address the distribution of viable cells in the Deep Biosphere and provide insights into the role that biological detritus, in both sediment and crustal environments, may play in biogeochemical cycling and microbial ecology networks at work in this sub-oceanic, perpetually dark, world .

Realistic limits of biosphere in the Earth illuminated by integrated investigation of ocean drilling and post-drilling research activities

[Author (s)] Ken Takai[1,2,3]

[Institution (s)] 1Institute for Biogeosciences, 2Precambrian Ecosystem Laboratory, 3Submarine Resources Research Project, and Japan Agency for Marine-Earth Science and Technology (JAMSTEC)

[Keywords (six or less)] hydrothermal system, serpentinite seamount, subseafloor biosphere, limits of biosphere, artificial well, post-drilling investigation

[TEXTBODY] Distribution, significance and functions of microbial ecosystems in the deep oceanic subsurface environments have been poorly understood for the long time due to the difficult accessibility. By using deep-sea research drilling vessels, we are now able directly to access the deep biosphere and to explore the microbial communities, functions, genetic and functional resources. Recent exploration of the deep oceanic subsurface environments has in part disclosed that the deep biosphere is spatially enormous and stands on quite diverse physical and chemical conditions. The deep biosphere can be confined by many physical and chemical boundary conditions between the habitability and the uninhabitability. In other words, the deep biosphere directly faces limits of life in the Earth and hosts thousands of extremophiles. We have tried to explore the realistic limits of life and biosphere in the oceanic subsurface by integrated investigation of ocean drilling expeditions and post-drilling seafloor observations. For instances, ODP Leg 195 has provided quite important biogeochemical and microbiological data that have suggested the possible existence of boundary between the habitable and uninhabitable zones in the highly alkaline subseafloor environment of the South Chamorro Seamount, the Marina Forearc. In addition, ODP Leg 195 has provided the post-drilling focusing research opportunities by deployment of CORK. The post-drilling investigation is quite important to justify the hypotheses that have been delineated by the results from the ODP and IODP researches. IODP Exp 331, which was conducted by Chikyu in the Iheya North hydrothermal system, the Okinawa Trough, in September 2010, has also prepared excellent opportunities for us to explore the realistic limits of life and biosphere that would be controlled by high temperatures. The artificial hydrothermal vents established during the IODP Exp 331 have provided not only lots of scientific discoveries but also great social and industrial potentials to post-drilling-activities. In this presentation, I would like to introduce these scientific topics related with ocean drilling and post-drilling research activities. In addition, I would like to talk about the significance of post-drilling research activities to preserve the drilling-related scientific projects using Chikyu and to keep or enlarge the future international framework of Chikyu-dependent scientific and exploratory activities.

Nature of gas hydrate during the Earth's evolution

Hitoshi Tomaru[1], Katsunori Yanagawa[2], Atsushi Tani[3], Akihiro Hachikubo[4]

[1]Department of Earth Sciences, Chiba University, [2]Department of Earth and Planetary Science, University of Tokyo, [3]Department of Earth and Space Science, Osaka University, [4]Environmental and Energy Resources Research Center, Kitami Institute of Technology

gas hydrate, environmental change, resource, methane, deep biosphere

Ubiquitous distribution of gas hydrate on the continental margins has been recognized during a number of scientific and industrial drilling operations, however, the nature, as well as their occurrence and amount, of gas hydrate deposits in response to the short/long term environmental change during the Earth's history are not well understood. Recent researches have pointed to the local/global environmental changes due to the formation/dissociation of gas hydrate under the seafloor, which might have occurred many times as a result of Earth's evolution. Here are key aspects associated with the nature of gas hydrate that must be clarified by deep drilling expeditions.

(1) Mass of gas hydrate as an energy/carbon reservoir

Gas hydrate deposits have been regarded as unconventional natural gas resources, which are also an unconsidered carbon reservoir for decades. Total amount of hydrocarbons enclosed in gas hydrates is essential for understanding resource potential and reconstructing carbon cycle at the Earth's surface.

(2) Source and origin of hydrocarbons (methane) in gas hydrate

There have been two major pathways to generate hydrocarbons in sediments; abiological pathways such as thermal degradation of organic matter and microbiological pathway mainly consisting of carbon dioxide reduction coupled to molecular hydrogen oxidation and acetate fermentation. Recent researches have unveiled that the latter has great contribution for shallow energy system, however, our knowledge of the deep biosphere remains very limited.

(3) Causes of stabilization/destabilization of gas hydrate

Because gas hydrate stability is a function of pressure and temperature, sea-level drop and bottom water warming may decompose gas hydrate, on the other hand, sea-level rise and bottom water cooling may accelerate gas hydrate formation. Global environmental changes (warming/cooling) have potentially controlled gas hydrate stability, however, the timing and scale of gas hydrate stabilization/destabilization during the Earth's history is still a matter of debate.

(4) Response and impacts of gas hydrate dissociation

Dissociation of gas hydrate due to environmental changes might have caused a series of environmental impacts as illustrated below (Fig. 1). Massive release of methane enhances the activity of chemosynthetic and benthic communities and precipitation of carbonates, however, it also results in the destabilization of sediments (slope failure) and anoxia of shallow sediment and bottom water which potentially results in mass extinction. Further release of methane into the atmosphere may cause temperature increase that also enhances gas hydrate dissociation.

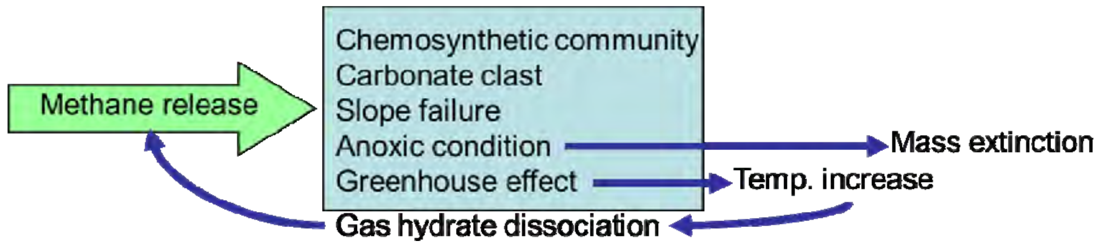


Fig. 1: A series of environmental impacts caused by massive release of methane from gas hydrate.

(5) Behavior and environmental impacts of gas hydrate in the future

Generation and migration of hydrocarbons and accumulation of gas hydrate have been active and ongoing during the Earth's history. To understand entire gas hydrate system discussed above can provide an insight into the future human activities such as resource control, deep ecosystem, environmental disruption, etc. (Fig. 2).

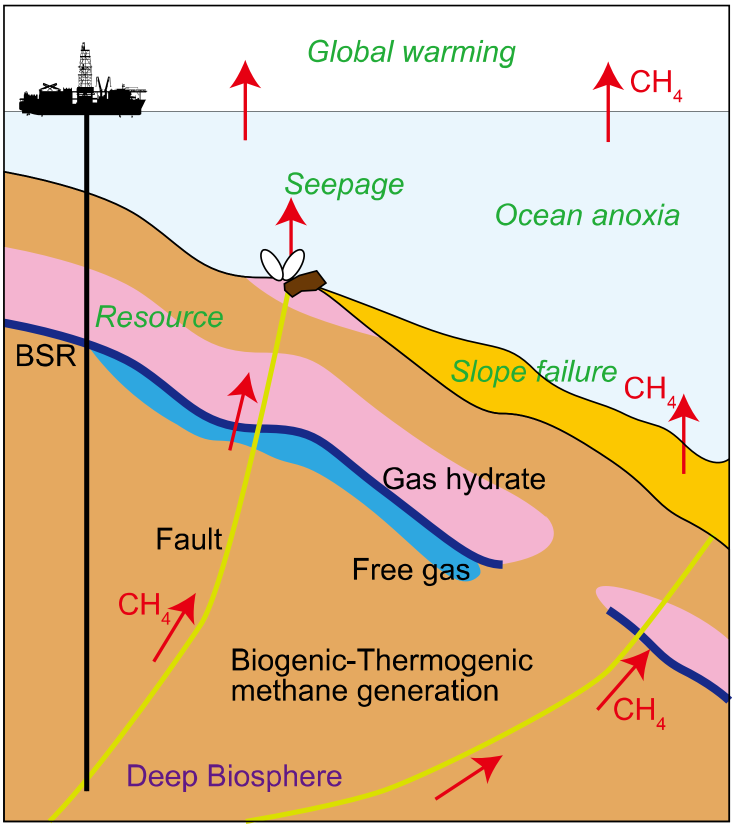


Fig. 2: Schematic showing active and ongoing gas hydrate system on the continental margin. Deep-sourced hydrocarbon is transported upward and preserved in gas hydrate deposits and free gas zone. Massive methane release from gas hydrate causes drastic impacts on the marine environments.

Curation of Deep Biosphere Samples (DeBIOS)

Nan Xiao[1], Lallan P. Gupta[1] and Naokazu Ahagon[1]

Kochi Institute for Core Sample Research, Japan Agency for Marine Earth Science and Technology (JAMSTEC) [1]

Keywords; deep biosphere samples (DeBIOS), drilling core, deep freeze, geo-microbiology, cell-alive system

As one of the core repository of Integrated Ocean Drilling Program (IODP), Kochi Core Center (KCC) stores and curates drilling core samples obtained by deep riser-drilling vessel *Chikyu*. These precious samples have been contributing to the geophysical, geochemical and geo-biological research on the global scale. For post-cruise research on geo-microbiology, extensive care is necessary to keep the quality of biopolymers like DNA, RNA, lipids, polycarbonate, e.g., the core samples stored at 4˚C arenot suitable for long-term preservation because of the growth of contaminating aerobic bacteria from the air and/or physical and enzymatic degradation. Considering the rapid development of molecular biological and biogeochemical techniques, future technologies may provide more detailed global pictures of subseafloor live and the biosphere. In this regard, KCC started a systematic curation of storage the core samples at -80˚C from 2009. The frozen core samples are named as deep biosphere samples (DeBIOS).

Curation of DeBIOS includes aseptical sampling on DV *Chikyu* soon after core recovery, storage of core samples in -80˚C deep freezers/liquid nitrogen tanks, development of freezing technique and sub-sampling methods, and processing the sample requests from scientists. KCC is now holding totally 390 samples in -80˚C deep freezer; 214 of them were obtained from 8 IODP expeditions, and 174 of them were obtained from 5 JAMSTEC expeditions in the past few years, and information of DeBIOS is open to the public through webpage after one-year moratorium. Although scientists are not fully aware of the existence of these frozen samples, KCC has received and processed several sample requests. The key point of sub-sampling from DeBIOS is keeping the frozen and aseptic condition of the samples. We have developed two kinds of methods to do sub-sampling properly. One is an electric saw system using diamond tipped blade that can cut the extremely hard frozen whole round core to small pieces, the other is using diamond-tipped core drill bit to drill mini-core from frozen cores. These methods successfully provided samples to the requesters with assuring sample qualities. KCC also keeps doing advertisement at international conferences to let scientists know about DeBIOS. These efforts make KCC as well as DV *Chikyu* contribute to the fair distribution of core samples, the progress of geo-microbiology, and maximizing scientific utility or benefit of IODP expeditions.

During the curation of DeBIOS, 2 points are still difficult and need to be discussed. One is about onboard sampling and the other is the development of freezing technology. The sample frequency of DeBIOS is recommended as per interstitial water sample, however, the frequency is usually lower than that. For keeping the possibility of the post-cruise research using DeBIOS, our best hope is to keep a high frequency of onboard sampling of DeBIOS such as one 10cm- whole round core per core. This discussion relates to the next point of curation of DeBIOS, developing the technology of freezing whole round core. Freezing of a subject that has a volume like 10cm- whole round core (about 360cc) usually proceed slowly from outside to inside. It causes formation of large ice crystals, which can interbed micribial cell membranes and could kill the microbes and also destroy the microstructure of the sediment. To minimize freezing-related alterlation of the core samples, we have tried a new freezing technology called 'cell alive system (CAS)', which utilizes alternating magnetic field to vibrate water molecule and keeping the water as liquid in supercooled state. Through this, the samples are uniformly cooled and resulted in uniform formation of small ice crystals after lowering the temperature. We have tested freezing sediment samples using CAS, and compared the cell abundance of microbes in the sediment with that were frozen at -20˚C and -80˚C, and found that CAS kept cell abundance higher than frozen in the general freezers. Also, we have tested of the effect of CAS freezing on magnetic characteristics of the core and minimal effect was observed. KCC hopes to have a larger CAS freezer, which can freeze and keep over 20 of 10cm whole round cores on DV *Chikyu* for enabling to freeze the core samples right after recovery. After freezing using CAS, core samples can be splitted by saw system into pieces without disturbing structure and part of them are stored at -80˚C deep freezer or liquid nitrogen tank in KCC. The improvements of high frequency of DeBIOS sampling and the new freezing technology will make more capabilities of utilization of DeBIOS in geo-microbiology, and also maximize their utilization by broader scientific fields.

DeBIOS was started as a part of IODP core sample curation, though it became a regular onboard sampling and onshore storage work. KCC will continue making every endeavor to improve the whole process of curation including the maintenance of samples, freezing technique to assure sample quality, the advertisement of our activities and provide samples to scientists.

Brothers submarine arc volcano: contrasting hydrothermal systems at one location

Cornel E.J. de Ronde[1], Wolfgang Bach[2], Susan Humphries[3], Junichiro Ishibashi[4], Fernando Barriga[5], Maurice Tivey[3], Anna-Louise Reysenbach[6], Richard Arculus[7], Chris Yeats[8] and the Lisbon Working Group.

1, Department of Marine Geosciences, GNS Science, New Zealand
2, Department of Geosciences, University of Bremen, Germany
3, Department of Geology & Geophysics, Woods Hole Oceanographic Institution, USA
4, Department of Earth & Planetary Sciences, Kyushu University, Japan
5, Departamento de Geologia da Faculdade de Ciências da Universidade de Lisboa, Portugal
6, Department of Biology, Portland State University, Oregon, USA
7, Research School of Earth Science, The Australian National University, Australia
8, CSIRO Earth Science and Resource Engineering, Perth, Australia

Keywords: Brothers volcano, magmatic volatiles, metals

Volcanic arcs are the surface expression of magmatic systems that result from the subduction of mostly oceanic lithosphere at convergent plate boundaries. Arcs with a submarine component include intraoceanic arcs and island arcs that span almost 22,000 km on Earth's surface, with the vast majority located in the Pacific region. Intraoceanic arcs total almost 7,000 km, thus ensuring a steady supply of dissolved gases and metals to the oceans, and the potential for the formation of polymetallic mineral deposits.

Most mineralization along intraoceanic arcs is dominated by mineral assemblages representing high-sulfidation conditions, including elemental sulfur, polymorphs of silica, alunite and lesser pyrite. This mineralizaton is typically associated with relatively low temperature (≤120°), diffuse, acidic (pH <3), metal-poor but gas-rich emissions from seafloor hydrothermal systems. Less common are focused, relatively high temperature (~300°C), metal-rich fluids where Fe-Cu-(±Au)-Zn sulfides and barite/anhydrite predominate. Both types of venting show evidence for contributions from magmatic sources. These two types of venting represent end-members of a continuum that spans magmatic-hydrothermal to water/rock dominated systems, respectively. More mature vent fields are better able to deliver and accumulate metals at the seafloor.

The ~1,220 km long Kermadec arc is host to ~40 large volcanoes of which 80% are hydrothermally active, making it the most active arc in the world. Hydrothermal activity associated with these arc volcanoes, including both caldera- and cone-types, is dominated by the discharge of magmatic volatiles. This hydrothermal magmatic signature(s), including high concentrations of S and C species gases together with high Fe contents, coupled with the shallow depths (~1800-120 m below sea level) of these volcanoes, greatly influences the chemistry of the venting fluids, the mineralization that results from these fluids, and more than likely has important consequences for the biota associated with these systems. Given the high metal contents and very acidic fluids, these hydrothermal systems are also thought to be important analogues many of the porphyry copper and epithermal gold rich deposits exploited on land today.

Brothers volcano of the Kermadec arc is host to a hydrothermal system unique among seafloor hydrothermal systems. It has two distinct vent fields, known as the NW Caldera and Cone sites, whose geology, permeability, vent fluid compositions, mineralogy and ore forming conditions are in stark contrast to each other. The NW Caldera site strikes for ~600 m in a SW-NE direction with chimneys occurring over a ~145 m depth interval, between ~1690 and 1545 m. At least 100 dead and active sulfide chimney spires up to 7 m tall occur in this field, whose ages fall broadly into three groups: < 4 years, 23 and 35 years old. Two main types of chimney predominate: Cu-rich (up to 28.5 wt.% Cu) and more commonly, Zn-rich (up to 43.8 wt.% Zn). Vent fluids here are focused, hot (≤302°C) and metal-rich, with moderate gas contents.

The Cone site comprises the Upper Cone site atop the summit of the recent (main) dacite cone, and the Lower Cone site that straddles the summit of an older, smaller, more degraded dacite cone on the NE flank of the main cone. Huge volumes of diffuse venting are seen at the Lower Cone site, in contrast to venting at both the Upper Cone and NW Caldera sites. Individual vents are marked by low relief (≤0.5 m) mounds comprised predominately of native sulfur with bacterial mats. Vent fluids are very acid (pH 1.9) and gas-rich, though metal-poor. The NW Caldera and Cone sites are considered to represent water/rock and magmatic-hydrothermal dominated end-members, respectively. Drilling Brothers would provide an exciting opportunity to understand subseafloor volcanic architecture, hydrology, polymetallic ore deposition formation and the deep biosphere of intraoceanic arc volcanoes associated with convergent plate margins.

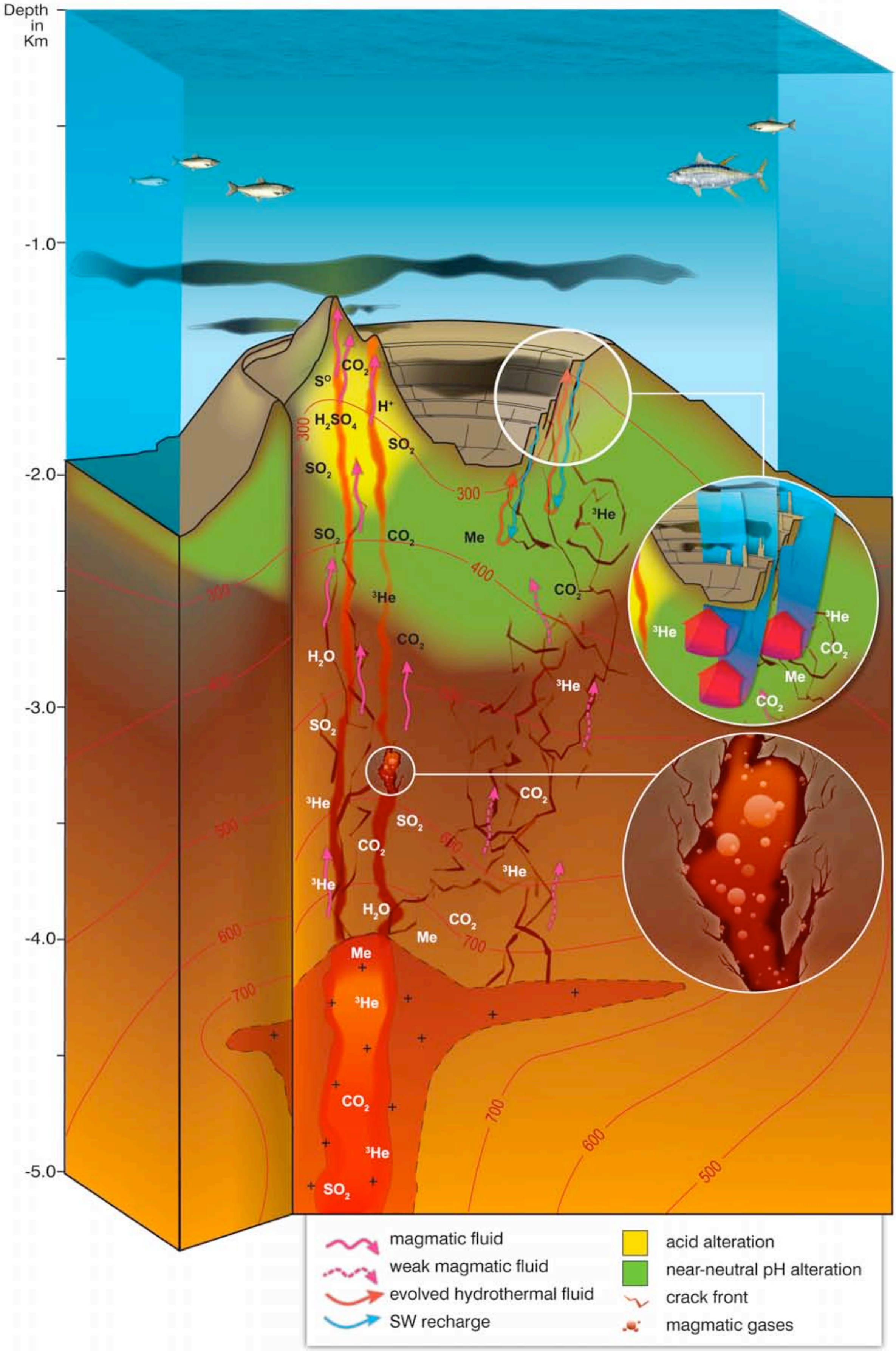


Figure 1. High resolution, AUV-derived data of seafloor geology, structure, geophysics and vent distribution, plus submersible sampling of rocks, mineralization, biology and vent fluids, has enabled a first-order model of the hydrothermal system at Brothers to be constructed (from de Ronde et al., 2011).

Direct capture of magmatic volatile species that control mineralization of seafloor massive sulfide ore deposits

[Author (s)] Jun-ichiro Ishibashi[1]
[Institution (s)] [1]Faculty of Science, Kyushu University
[Keywords] VMSD, ore genesis, phase separation, magmatic degassing, metal complex

[TEXTBODY] Formation of seafloor massive sulfide ore deposit is one of spectacle functions observed in an active hydrothermal field. Recently, present seafloor massive sulfides ore deposits are recognized as modern analogies of VMSDs (volcanic massive sulfide deposits) which formed during past geological history. This means that mechanism of ore genesis can be understand with a geochemical point of view as transportation, concentration and accumulation of metal elements, because studies on an active hydrothermal field provide opportunities to monitor ongoing process of mineralization.

Up to present, only a few ocean floor drillings (ODP 139, 158, 169, 193 and IODP 331) have been conducted with this context, but they demonstrated their valuable opportunities to access subseafloor directly and recover samples from the region where dynamic process are ongoing. Based on the results, it is building among scientists a new consensus that subseafloor mineralization is much more important for ore genesis than mineral precipitations observed above the seafloor as chimney or mound formations.

Especially, IODP 331 which drilled into the Iheya North Knoll hydrothermal field located in a back-arc setting demonstrated important role of volatile species for various geochemical processes within sediment layer. Among the core samples obtained from shallow depth, clay mineral assemblage formed by argillic alteration was often identified, which is considered as formed under acidic chemical condition of the pore fluid caused by involvement of volatile species such as CO_2 and H_2S. This idea is supported by high CO_2 concentration in the obtained pore fluid and also by the fact the cores sometimes showed void space implying accumulation of volatile species in the pore space. Acidic condition of pore fluid would be preferable for sulfide mineralization, since solubility of heavy metal elements increases drastically as pH of the fluid becomes lower. This idea is supported by the identification of sulfide minerals such as shalerite (ZnS) and galena (PbS) in the same core samples. The accumulation of volatile species in the surface sediment would be attributed to phase separation of the hydrothermal fluid that should occur beneath the seafloor and to preferable partition of volatile species into the vapor phase. The phase separation of the hydrothermal fluid in the Iheya North field has been demonstrated by the previous geochemical study on the hydrothermal fluid venting from the hydrothermal mound above the seafloor. As mentioned above, several lines of circumstance evidence has been accumulated for enhancement on subseafloor mineralization by enrichment in volatile species. However, it has been difficult to obtain direct evidence, since conventional drilling facilities are not designed to contain volatile species in the core sample.

As more intrinsic problem for ore genesis, it has been debated among scientists for a long term, whether metal elements originate from the magma or surrounding crust. For the scientists insisting the magma-origin model, volatile species are considered as an important carrier of metal elements by degassing process from the magma. This idea has been confirmed by experimental which demonstrated theoretical possibility that metal elements forms chloride complexes stable in the magmatic fluid condition. Moreover, circumstance evidence has been studied using fluid inclusions in samples collected from the deep region which can be considered as had been located just above the magma chamber. This intrinsic problem should move toward resolution by direct capture of magmatic volatile species during a drilling into the main body of a hydrothermal system. For such a drilling project, high heat conditions may be an obstacle. However, direct drilling into a high heat magma body has been already successfully challenged in onland geothermal fields.

Volcanism and hydrothermal systems of submarine volcanoes

Martin JUTZELER[1, 2]
[1]University of Otago, New Zealand and [2]National Oceanographic Centre of Southampton, UK
Submarine volcano, hydrothermal system, seamount, caldera, volcanic architecture, submarine explosive eruption

The DSDP, ODP and IODP drilling programs have chiefly focused on petrology of the upper oceanic crust, plate-tectonic features, paleo-oceanography and climatology studies. These programs have been extremely successful, and brought immense scientific knowledge that is essential for our current understanding of the Earth at global and regional scales. Igneous petrology made tremendous discoveries on geochemistry of the oceanic crust, but was rarely focused on eruption processes, or transport and sedimentation of volcanic clasts. Only a couple of volcanic aprons of subaerial volcanic islands (e.g. Canary Islands, Lesser Antilles; Schmincke and Sumita 1998; Expedition 340 Scientists 2012) have been drilled, and nothing has been published from that work that focused on the primary sedimentation of pyroclasts in water. In fact, submarine volcanic edifices have been intentionally avoided until now, because it is difficult to achieve high core recovery from them, though some small basaltic guyots were cored. Entirely submarine volcanoes of silicic composition have been mostly studied from uplifted outcrops, but alteration (diagenesis, hydrothermal alteration) and tectonic damage (faults, other deformation) obscure some textures and disrupt lateral continuity of the beds, while limits to exposure prevent confident whole-eruption or whole-volcano reconstructions. Recent ROV sampling and dredging (Wright et al. 2003; Allen et al. 2010; Schipper et al. 2010; Barker et al. 2012) gives information on only the uppermost deposits. Many submarine silicic volcanoes were discovered in the last decade (Fiske et al. 2001; Wright et al. 2006; Wright et al. 2008; Gardner 2010; Leat et al. 2010), and are known to erupt violently, and to be accompanied on occasion by tsunamis and subaerial plumes (Nakano et al. 1954; Fiske et al. 1998) that threaten local and distant coastal populations.

A better understanding of the deposit distribution around submarine volcanoes would be the first step in the comprehension of the eruption and sedimentation processes of pyroclasts under water, as well as allowing a better preparedness for their associated hazards. Ocean drilling around and radially from selected volcanoes would be ideal to reveal the 3-dimensional distribution of volcanic beds, and their relationship to each other, from proximal to distal facies.

In addition, hydrothermal systems are associated with submarine volcanoes, and hosts of high-quality ore bodies (volcanic-hosted massive sulfide, VHMS) that are currently mined all over the continents for their metals (e.g. Au, Ag, Cu, Pb, Zn), and possible host of deeply buried life. In-situ drilling into low-grade hydrothermal system would also be of upmost importance in understanding the formation and depth of these hydrothermal systems, and would certainly attract industry interests.

I intend to write an IODP drilling proposal in the next months for drilling one of the best known and appropriate island arcs, (Izu-Bonin, Mariana or Kermadec) depending on the best targets found, and seismic profiles at disposition. For instances, drilling submarine volcanoes in the Izu-Bonin arc would be an important addition to the past (ODP 126) and future (IODP 350, 351, 352, a nd proposal 698) expeditions in this arc. Discussions on this subject during the workshop would be greatly appreciated.

References cited:

Allen SR, Fiske RS, Tamura Y (2010) Effects of water depth on pumice formation in submarine domes at Sumisu, Izu-Bonin Arc, western Pacific. Geology 38:391-394.

Barker SJ, Rotella MD, Wilson CJN, Wright IC, Wysoczanski RJ (2012) Contrasting pyroclast density spectra from subaerial and submarine silicic eruptions in the Kermadec arc: implications for eruption processes and dredge sampling. B Volcanol 74:1425-1443.

Expedition 340 Scientists (2012) Lesser Antilles volcanism and landslides: implications for hazard assessment and long-term magmatic evolution of the arc. IODP Prel Rept 340.

Fiske RS, Cashman KV, Shibata A, Watanabe K (1998) Tephra dispersal from Myojinsho, Japan, during its shallow submarine eruption of 1952-1953. Bull Volcanol 59:262-275.

Fiske RS, Naka J, Iizasa K, Yuasa M, Klaus A (2001) Submarine silicic caldera at the front of the Izu-Bonin Arc, Japan; voluminous seafloor eruptions of rhyolite pumice. Geol Soc Am Bull 113:813-824

Gardner JV (2010) The West Mariana Ridge, western Pacific Ocean: Geomorphology and processes from new multibeam data. Geol Soc Am Bull 122:1378-1388.

Leat PT, Tate AJ, Tappin DR, Day SJ, Owen MJ (2010) Growth and mass wasting of volcanic centers in the northern South Sandwich arc, revealed by new multibeam mapping. Mar Geol 275:110-126

Nakano M, Unoki S, Hanzawa M, Marumo R, Fukuoka J (1954) Oceanographic features of a submarine eruption that destroyed the Kaiyo-Maru No. 5. J Mar Res 13:48-66

Schipper CI, White JD, Houghton BF, Shimizu N, Stewart RB (2010) "Poseidic" explosive eruptions at Loihi Seamount, Hawaii. Geology 38:291-294

Schmincke H-U, Sumita M (1998) Volcanic evolution of Gran Canaria reconstructed from apron sediments: Synthesis of Vicap Project drilling. Proc Ocean Drill Program: Sci Results 157:443-469

Wright IC, Chadwick Jr WW, de Ronde CEJ, Reymond D, Hyvernaud O, Gennerich HH, Stoffers P, Mackay K, Dunkin MA, Bannister SC (2008) Collapse and reconstruction of Monowai submarine volcano, Kermadec arc, 1998-2004. J Geophys Res, [Solid Earth Planets] 113:B08S03.

Wright IC, Gamble JA, Shane PAR (2003) Submarine silicic volcanism of the Healy caldera, southern Kermadec arc (SW Pacific): I - Volcanology and eruption mechanisms. Bull Volcanol 65:15-29

Wright IC, Worthington TJ, Gamble JA (2006) New multibeam mapping and geochemistry of the 30°-35° S sector, and overview of Kermadec arc volcanism. J Volcanol Geotherm Res 149:263-296

Riser Drilling to Investigate Hydrothermal Fluid Circulation through Mafic-Ultramafic Composite Lithology

Hidenori Kumagai[1, 2] Kentaro Nakamura[1], and Ken Takai[1, 3]

[1]Precambrian Ecosystem Laboratory, JAMSTEC, [2]IFREE, JAMSTEC and [3]BioGeos, JAMSTEC

[Keywords] hydrothermal recharge zone, Kairei Field, Indian Ocean, riser, real time gas monitoring

Seafloor hydrothermal activities greatly attract broad interest of multi-disciplinary studies since their discovery. Thus, numbers of investigations have been performed even by ODP-IODP community; however, such studies were mostly limited to the very vicinities of the fluid discharges, i.e. vent areas. Recent studies of the discharge fluids based both on observation and on computational approaches revealed that lithologies of the recharge zone mainly control chemical composition of the discharging fluids (e.g. Nakamura et al., 2009). Although a drilling proposal of Lost City Hydrothermal Field focusing on serpentinization-related unique hydrothremalism (758Full2) is ready to drill one including investigations in fluid recharge zones, any direct sampling of the formation fluid is not included in their plan. It plans to recover in-situ sequences from sediment through basement on Atlantis Massif to document the lateral variation both along-ridge and age-dependent directions. Applying MSP with shallow wire-line coring facility, it proposes totally 11 holes with penetrations down to 100 m in the up-flow region. Such strategy is fairly proven its efficiency to retrieve cores in fluid discharge zone by Exp. 331, "Deep Hot Biosphere," however, it overlook vertical lithological variations in the drill holes: typical thickness of mafic-ultramafic transition zone in ophiolite exceeds >300m (Miyashita et al., 2012). In addition, large lateral and vertical heterogeneities are anticipated beneath Atlantis Massif as the typical nature of slow spreading; mosaic of intrusions both ultramafic and mafic compositions consists in the reaction zone and recharge area of the hydrothermal fluids. It is hard to resolve solely by a sequence of shallow drillings. Furthermore, a riser-drilling is required to achieve direct observation of the fluid circulation.

We have proposed drilling operations by using the riser system, which enables us to retrieve cuttings and real-time gas and fluid data from the formation (744-Pre and 780-Pre). The real-time gas monitoring system is now available on D/V Chikyu from Exp. 337. We have proposed three holes with rather deep-penetration down to 2000 mbsf on Hakuho Knoll and associating topographic highs near the Rodriguez Triple Junction, Indian Ocean (Fig. 1). On the western frank of Hakuho-Knoll, another-ultramafic hosted hydrothermalism known as Kai rei Field develops. Although Hakuho-Knoll seems to be an almost typical abyssal hill near Mid-Ocean Ridge, consisting of mafic lavas, it is surrounded by ultramafic exposures and its fluid compositions strongly controlled by serpentinization of ultramafics. In the previous proposals, we tried to figure out including direct sampling of formation fluid from the inferred pathway or reservoir recognized on seismic reflection image (Figs. 2 and 3). We certainly recognize high risk of the deep-drilling in the hydrothermal region, induced from the high temperature and highly sticky deposits prohibits the penetration, however, it is necessary to document characteristic length/thickness of the intrusion. Even Hole

C0014 drilled in Exp.331 on Iheya-north Knoll revealed that there is a shallow reservoir of hot fluids above 200 °C approx. 50 mbsf, however, there is less concern about such hazardous hot free-fluids beneath our proposing holes: beneath Hakuho-Knoll, expected magmatic heat sources are in the ridge axis side opposite to the proposed holes. To complement such deep-holes with small number in our previously proposed/deactivated pre-proposals, a transect of shallow holes as PEP review suggested may be efficient. We are now preparing our new proposal according to PEP review for previous one. In addition, any improvement of real-time monitoring capability of D/V Chikyu are welcome to achieve comprehensive and direct understanding of fluid recharge zones.

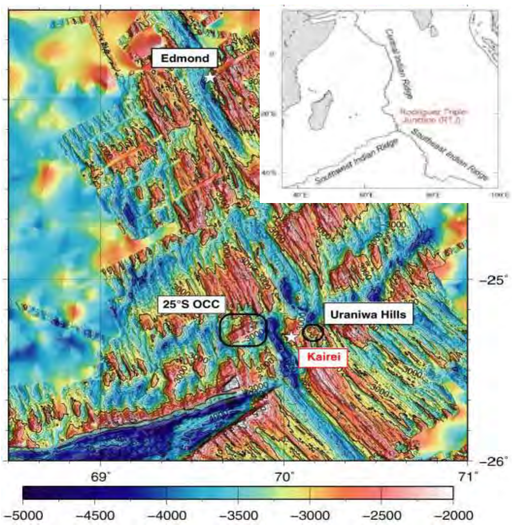


Fig. 1: Regional bathymetric map around the Kairei Hydrothermal Field. Inset shows Mid-Ocean Ridge System in the Indian Ocean.

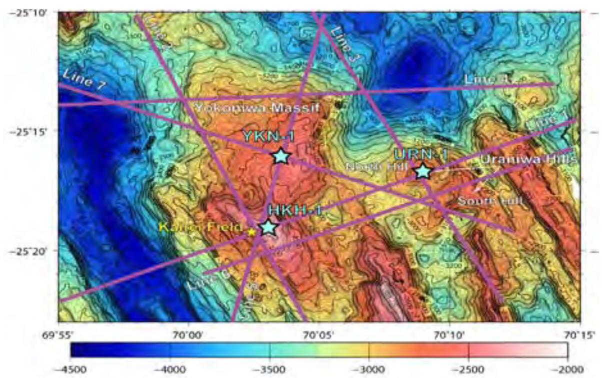


Fig. 2: Proposed drill site around Kairei Field. Purple lines indicate the tracks of single channel seismic reflection survey. Stars with pale blue colors indicate the proposed drill sites in 780-pre.

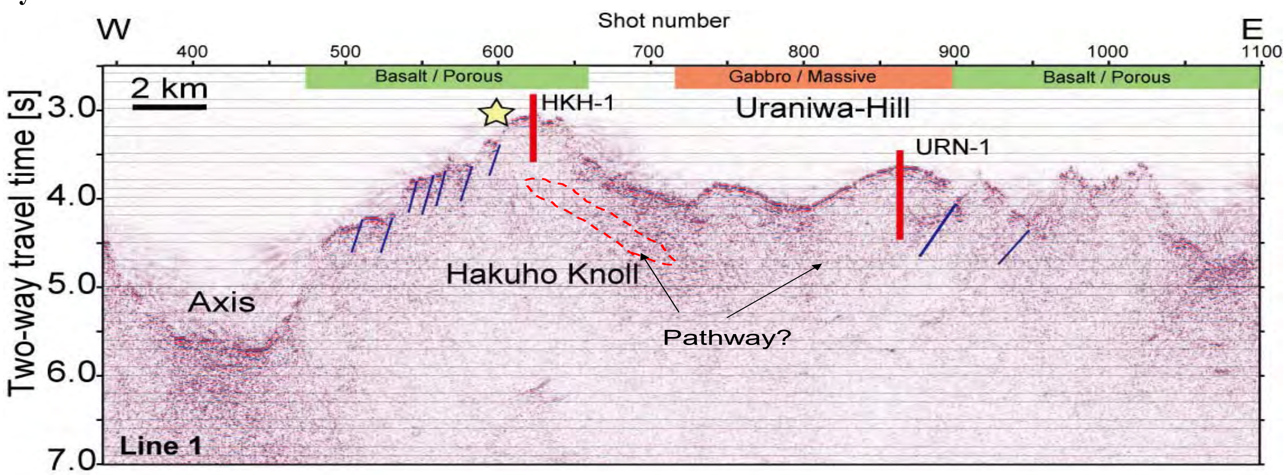


Fig. 3: A ridge perpendicular SCS image with interpretation: Line 1 on Fig 2. On this line two proposed holes are set indicated as red bars. Beneath the shallow valley between Uraniwa-Hill and Hakuho Knoll, where Kairei Field develop, partial reverse polarity zones are recognized. This suggests fluid reservoir or pathways.

References cited

S. Miyashita, et al. (2012) Field trip guide #3, ICGAPOM 2012, Muscat, Oman.

K. Nakamura, et al. (2009) Earth Planet. Sci. Lett., 280(1-4), 128-136.

Volcanic activity in forearc area

Tomohiro Toki

Faculty of the science, University of the Ryukyus

Forearc, Taketomi Hot Spring, volcanic activity

Taketomi Hot Spring is located on the seafloor at 22 m depth at the distance of several 10 m off Ishigaki Island (Figs. 1a, b, and d), where gas of mainly methane and hot water up to 64°C are venting (Yohena et al., 1968; Fukuta et al., 1969). In 1991, when Iriomote swarm earthquakes were observed, the relationship between the swarm earthquakes and Taketomi Hot Spring was investigated (Oomori et al., 1991; 1993). Carbon isotopic composition of methane and helium isotope in the venting gas suggest Taketomi Hot Spring would be related to magma activity (Oomori et al., 1991; 1993). Taketomi Hot Spring, however, is located at seaward of Wadati-Benioff zone, so that magma cannot be formed in theory. Actually, a recent arc volcanic front is observed at Hatoma Knoll and Daiyon Yonaguni Knoll as deep-sea hydrothermal activity, so that Taketomi Hot Spring is exactly located at a forearc area.

Volcanic activities around Taketomi Hot Spring are found in Nosoko formation of tuff in the Eocene, andesitic lava in 73 Ma, and granitic dike in 21 Ma (Nakagawa et al., 1982). Heat source of Green-tuff type hot spring is thought to be associated with spreading of Japan Sea in the Miocene, so that Nosoko formation and andesitic lava is too old to be heat source of Taketomi Hot Spring. Previous drilling operations at Taketomi Hot Spring showed that the hot spring penetrated Ryukyu formations in the Pleistocene, and coral reefs in the Holocene that are observed on the seafloor around Taketomi Hot Spring was not found just beneath Taketomi Hot Spring (Oomori et al., 1987; Kawana and Kan, 2000). The activity of the hot spring, therefore, would start from the Pleistocene. Volcanic activity after the Pleistocene was reported in 1924 as Iriomote Submarine Volcano (Fig. 1d), though the precise position has not been specified (Kato, 1982). There might be magma insertion related to the volcano, but the presence of magma has not been confirmed.

One of volcanic activities in forearc area that have previously been observed is Arima Hot Spring. The characteristics are the following; 1) venting gas is composed of mainly carbon dioxide, 2) helium isotope shows helium is significantly derived from mantle, and 3) many earthquake swarms have been observed around the area. In the case of Taketomi Hot Spring, helium isotope shows influence of mantle helium and earthquake swarms have been observed in 1991, but venting gas composition that is composed mainly of methane is different from the characteristics of Arima Hot Spring. However, it is possible that methane is added during migration through surface sediment (Urabe et al., 1985), so that the application of Arima type to Taketomi Hot Spring is conceivable. But the mechanism of Arima type has been not verified yet as well as that of Taketomi. Possible source of such a hot spring is fluid from dehydration of slab, which has been inferred by low velocity anomaly of seismic reflection data at several km below the seafloor around Taketomi Hot Spring (Irabu et al., 2005). Taking account of the water depth of Taketomi Hot Spring of 22 m, the depth of low velocity anomaly zone is accessible for D/V *Chikyu*.

The scientific significance of drilling Taketomi Hot Spring is clarification of mechanism of volcanic activities in forearc area that cannot be explained by the plate tectonics theory. In this investigation, in the addition of drilling Taketomi Hot Spring, another site at the seaward of Taketomi Hot Spring, at the arcward of Taketomi, and on the same line of Taketomi will be drilled for verification of the uniqueness of Taketomi Hot Spring and the heterogeneity of the forearc area.

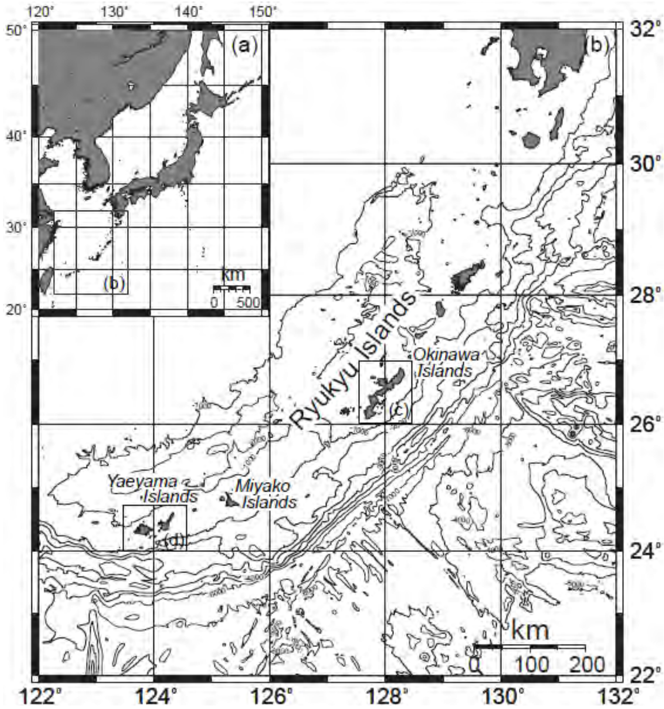


Fig. 1 (a) A map showing the location of Ryukyu Islands. The box indicates the area of Fig. 1b.
(b) A map showing the location of Ishigaki Island. The box indicates the area of Fig. 1d.

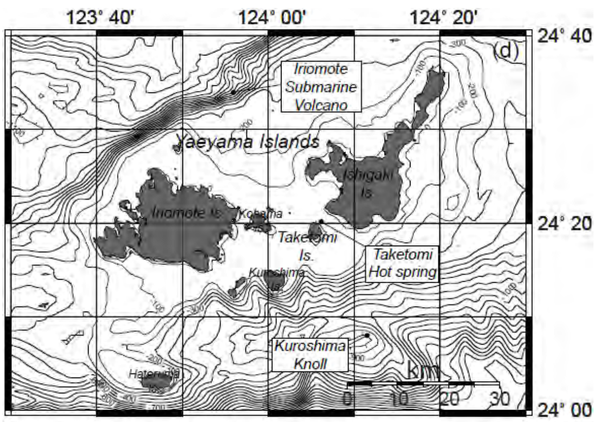


Fig. 1d A map showing the location of Taketomi Hot Spring, together with Iriomote Submarine Volcano.

Riser drilling of high temperature seafloor hydrothermal systems in the Manus Basin: important insights into metallogenesis, crustal fluid processes and the limits and origins of life

Christopher J Yeats
CSIRO Earth Science and Resource Engineering, Perth, Australia

metallogenesis, extreme life, fluid processes, volcanology, high temperature, back arc

Many of the island nations of the Western Pacific and Asia have limited land area with scarce mineral resources, but massive maritime territories with largely unexplored mineral potential. The economic attraction of the nascent deep sea mining industry to these countries is obvious. Both Government and marine mineral explorers are keen to see investment in this domain and are open to providing in-kind (access to data and vessels) and potentially direct fiscal support to drilling proposals that target prospective volcanic arcs and back arcs. It's estimated that more than a million square kilometres of seafloor in the Asia-Pacific Region is under exploration licence, providing researchers with an outstanding opportunity to leverage the often high-quality site survey data generated by mineral explorers to draft drilling proposals that will address fundamental scientific questions related to volcanology, crustal fluid fluxes, subduction input of volatiles into the oceans and the limits and origin of life on Earth.

Although many of the arcs and back arcs of the region are of high scientific interest; two of the most heavily surveyed areas, of interest to both the scientific community and the minerals industry, are Brothers Volcano, in the Kermadec Arc north of New Zealand (the subject of a separate White Paper to this meeting), and the Manus Basin between New Britain and New Ireland, Papua New Guinea (PNG), which is discussed below. Other regions also worthy of consideration and of interest to mineral explorers include the Lau back arc basin, North Fiji Basin, and New Hebrides Arc.

The Manus back arc basin lies at the convergent boundary between the major Indo-Australian and Pacific plates, and exhibits a complex tectonic history, including reversal of subduction due to the Ontong Java Plateau. The Eastern Manus Basin (EMB) is dominated by oblique rifting and contains excellent examples of single-centre and rift-associated felsic submarine volcanism. The volcanic rocks of the EMB are chemically and genetically related to the New Britain Arc. There are at least nineteen active sites of hydrothermal activity within the Manus Basin (Figure 1), making the area an ideal natural laboratory to investigate the controls on and inputs into ore forming processes on both a regional and local scale. The basin has also attracted the interest of explorers for seafloor massive sulfide mineralization, most significantly Nautilus Minerals (who have plans to mine the Solwara 1 seafloor massive sulfide), and is therefore well surveyed relative to other back arc basins.

Ocean Drilling Program Leg 193, which drilled the PACMANUS site (Solwara 4, 6, 7 and 8; Figure 1) on Pual Ridge in the Eastern Manus Basin in 2001, remains one of the ODP/Integrated ODP's two forays to a felsic-volcanic hosted seafloor hydrothermal system. The other, Leg 331 to the Okinawa Trough, had a strong biological focus. Despite the technical challenges of drilling in a highly heterogeneous hard rock sequence, which resulted in very poor overall core recovery, Leg 193 was highly successful scientifically, providing important insights into the volcanic stratigraphy, subsurface alteration and hydrology, role of seawater and deeply-sourced fluids in the system, and the subsurface biosphere. Borehole temperature measurements and existing seismic data strongly suggest that the intrusive heat source that drives both volcanic and hydrothermal activity at the site is located only 1.5km to 2km below the seafloor. Thus a relatively shallow water (~1650mbsl), shallow depth riser hole could be drilled into the high temperature reaction zone and the margins of the intrusion, providing for the first time important data on high temperature alteration, the deep source of fluids, volatiles and metals, and the degree of deep penetration of seawater (present throughout the 380mbsl interval drilled by Leg 193) in an active ore forming system.

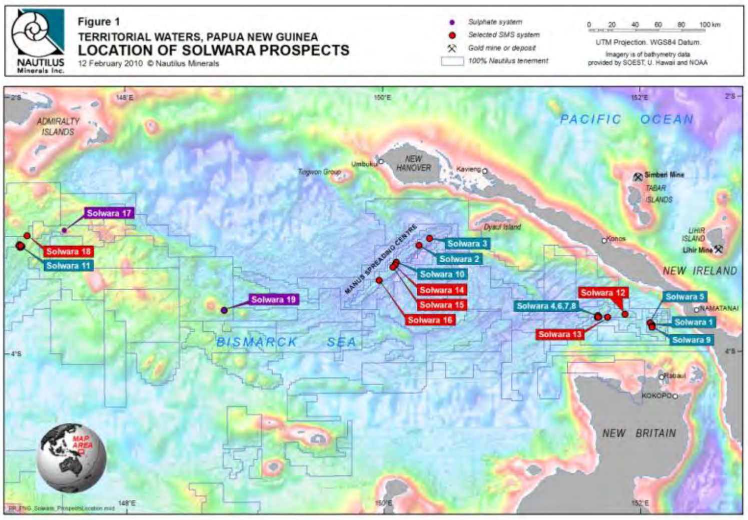


Figure 1: Bathymetry and known sites of seafloor massive sulfide mineralization in the Manus Basin, PNG. Figure taken from Nautilus Minerals website (http://www.nautilusminerals.com).

The SuSu Knolls site (Solawara 1 and 5; Figure 1) is also a highly attractive target for riser drilling. The contrast between a relatively mature, strongly mineralized system at Solwara 1 (1500mbsl) and a strongly hydrothermally active, less mineralized system at nearby North Su (Solwara 9, 1150mbsl) provides a unique opportunity to investigate the critical factors leading to ore formation in the submarine environment. including fluid recharge and discharge, fluid flux and the role of magmatic fluids as a source of volatiles and metals. Hydrothermal venting at SuSu ranges from highly acidic, sulfur-rich, clearly magmatically derived fluids, to metal-bearing hydrothermal fluids, providing an opportunity to study the subsea biosphere in a range of extreme biogeochemical environments. The activities of Nautilus Minerals in the Eastern Manus Basin have generated an enormous quantity of high-quality site survey data at SuSu, including extensive visual mapping and surface sampling by ROV, 20cm-resolution bathymetry, deep tow magnetic and electromagnetic surveys and approximately 200 shallow drill holes, to depths of ~40m below the seafloor. The company is receptive to scientific research, and the combination of scientific interest and high quality near surface data make SuSu Knolls a highly attractive target for a future IODP riser drilling Leg.

OUTSTANDING EXPOSURE OF AN INTACT, UNMETAMORPHOSED UPPER TO MIDDLE CRUSTAL OCEANIC ARC SECTION: ANALOG TO THE PROPOSED SITE OF CHIKYU DRILLING

BUSBY[1], Cathy, and DEBARI[2], Sue

[1]Department of Geological Sciences, University of California, Santa Barbara CA 93106, USA, and

[2]Geology Department, Western Washington University, Bellingham, WA 98225, USA

oceanic arc section, upper crust, middle crust, volcaniclastic rocks, plutons, rifted arc

We propose a multi-disciplinary collaborative study of a very close field analog to the approved (IBM-3) and proposed ultra-deep drilling sites.

The Cretaceous Alisitos arc in Baja California (Fig. 1) is an outstanding analog for what might be expected during drilling of the Izu Bonin arc. It is structurally intact, unmetamorphosed, and has superior three-dimensional exposures of an upper- to middle-crustal section through an oceanic arc. A geologic map framework exists for it (Busby et al., 2006), which will allow us to focus in on key questions complementary to the IBM drilling sites. Its upper crustal section is lithologically heterogeneous, and the section "captures" the upper- to middle-crust transition. The view shown in Figure 1 is not a reconstruction; it is a down-dip cross section made directly from a 60-km long segment mapped in detail (Busby et al. 2006). The section is structurally intact (all faults are synvolcanic), unmetamorphosed, and very well exposed, permitting detailed examination of the

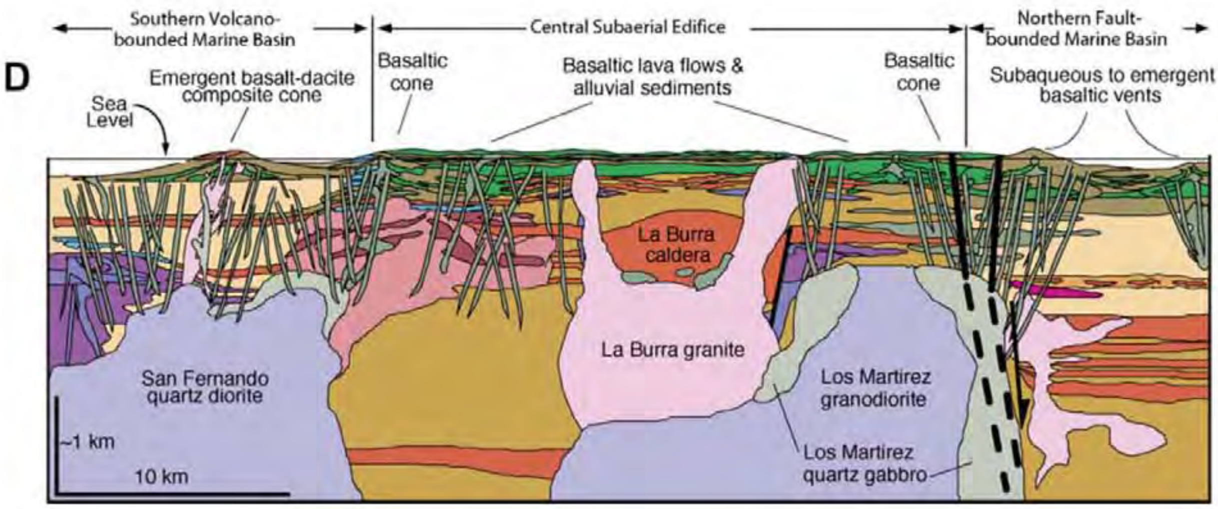


Figure 1

segment has a central subaerial edifice, made largely of andesite and dacite lava flows; these are capped by a silicic caldera and related granites that formed in response to extension (Busby et al.

2006). This central edifice was flanked by a down-faulted deep-water marine basin to the north, and a volcano-bounded shallow-water marine basin to the south. Basins around the central subaerial edifice preserve products of mass wasting, subaqueous pyroclastic flow activity, and deepwater silicic caldera collapse (Fig. 1). Extension and silicic caldera magmatism was immediately followed by widespread emplacement of mafic dikes and associated mafic dikes and plutons (except where they were occluded by the subcaldera granite, which must have still been hot); this is interpreted to record arc rifting (Busby et al., 2006). U-Pb zircon dates indicate that the entire 5 km-thick crustal section shown in Figure 1 was created in less than 1.5 myr. The original crustal thickness is not known, because the top is covered, and the base passes downward into unmapped deformed rocks. However, the exposed top of the section is probably not far from the original top, since strata at the base of the 5 km-thick section are zeolite grade (except for local contact hornfels).

We propose the following work plan, to best complement the IBM work:

1. *Reconnaissance geochemical study.* There are no geochemical data on this arc crustal section. We seek funding to carry out a reconnaissance geochemical study, which will require a sampling campaign, followed by a first round of laboratory work. We welcome the participation of IBM proponents in both the sampling and laboratory parts of this study. It would be ideal to have at least some of these results prior to the spring 2014 field workshop

2. *Field workshop to examine upper crustal levels of the arc, in advance of the approved IBM-3 drilling.* If the drilling is scheduled for fall 2014, the workshop should be scheduled for the previous spring (temperature in summer are too high for field work). This field workshop will allow participants to examine spectaculary well-exposed marine volcanic and volcaniclastic rocks that are very similar to those likely to be encountered by IBM-3 drilling.

3. *Detailed field and geochemical studies of the middle crust.* In this phase of the fieldwork, we will generate detailed geologic maps of the middle crust, which was given less attention than upper crustal rocks in the Busby et al. (2006) study. We will also extend the study into a deeper part of the middle crust, where deformed and metamorphosed rocks lie between plutons (not mapped by Busby et al., 2006). We welcome the participation of IBM proponents in this work.

4. Field workshop to examine the middle crust, in advance of the proposed ultra-deep drilling. This workshop would be scheduled to take place prior to the start of ultra-deep drilling (if it is approved). Any questions raised during this workshop will be addressed by follow-up mapping and geochemical work while the ultra-deep drilling takes place.

References

Busby C, B Fackler-Adams, J Mattinson, S DeOreo (2006) View of an intact oceanic arc, from surficial to mesozonal levels: Cretaceous Alisitos arc, Baja California *Journal of Volcanology and Geothermal Research*, 149, 1-46.

Using exposed arc sections in conjunction with IBM deep crustal drilling to understand the generation and growth of arc crust, and transferability to other active arc settings

Susan DeBari[1], Cathy Busby[2], Drew Coleman[3], Allen Glazner[3] and Jocelyn McPhie[4]
[1]Geology Department, Western Washington University, Bellingham, WA 98225, USA
[2]Department of Geological Sciences, University of California, Santa Barbara CA 93106, USA
[3]Department of Geological Sciences, University of North Carolina, Chapel Hill NC 27599 USA
[4]CODES – ARC Centre of Excellence in Ore Deposits, University of Tasmania, Australia

Arc crustal section, continental crust, IBM-4, volcanic arc

Investigation of arc crustal sections exposed on land provide an important companion study for any deep crustal drilling program. Although altered by syn- or post-accretion modifications, the study of paleo-arcs provides a larger, more volumetrically abundant record of both the intrusive and extrusive record of the processes that generate continental crust from mantle-derived magmas. In turn, deep crustal drilling can answer many questions that remain unanswered after examination of exposed sections, the activity of which ended long before they were amassed in their current locations. For example, through the direct petrological, geochemical, and geophysical characterization of the crust at site IBM-4, a reference section of intraoceanic arc crust can be generated. The cored rocks and borehole properties can be directly linked to the seismic velocity structure of the crust, providing the first in situ test of seismic velocity models against known rock types and structures within the deep arc crust. The IBM-4 site will provide an essential reference both for active arc crust and for accreted arc crustal terranes.

Many active arcs (except the Aleutians) have a middle crust with seismic velocities (V_p) of 6.0-6.5 (Fig. 1), which are interpreted to be intermediate to felsic plutonic rocks. Exposed arc crustal sections (e.g., the Talkeetna arc crustal section in the last panel of Fig. 1) typically include middle crust composed of

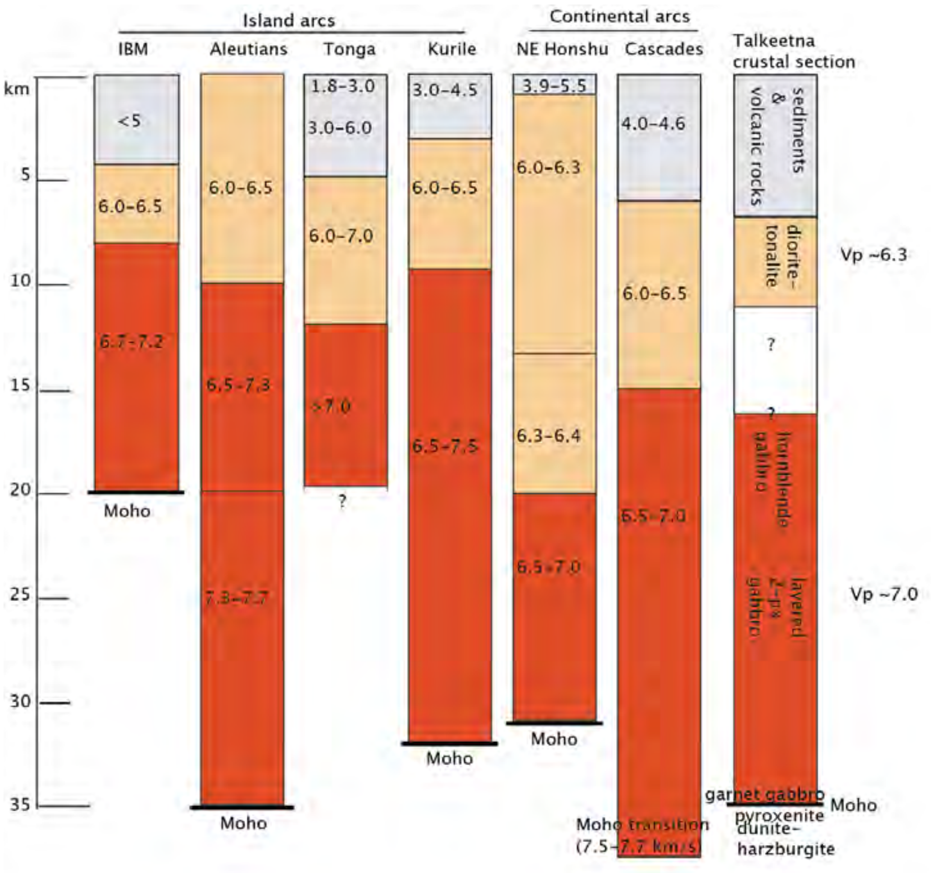


Figure 1. Seismic velocity profiles of various modern island arcs and continental arcs compared to the Talkeetna crustal section. The Izu-Bonin arc is from Suyehiro et al. (1996), the Aleutian arc is from Shillington et al. (2004), the Tonga arc is from Crawford et al. (2003), the Kurile arc is from Nakanishi et al. (2009), NE Honshu is from Iwasaki et al (2001), and the Cascade arc is from Parsons et al. (1998).

diorite to tonalite to granodiorite. These rock types have seismic velocities predicted to be ~6.3 based on models such as in Hacker and Abers (2004). The potential to drill into active arc crust at IBM provides an unparalleled opportunity to provide linked geophysical and lithological data that can then be transferred to other active arcs that are missing the lithologic data and to exposed crustal sections that are missing the *in situ* geophysical data. The results can be used to create the very first correlation of rock type and depth to *in-situ* measurements of temperature, density, and seismic velocities. Applying this new framework to other active arcs and crustal sections can then give us the broadest view possible of the evolution of juvenile arc crust and its subsequent transformation to continental crust.

Geochemical insights into the dynamics of crust formation

Heye Freymuth[1], Yoshihiko Tamura[2], Tim Elliott[1]

[1]Bristol Isotope Group, University of Bristol, [2]Japan Agency for Marine-Earth Science and Technology

Keywords: Crust formation, IBM-4, Aogashima, Evolution of IBM, Geochemistry, Mo isotopes

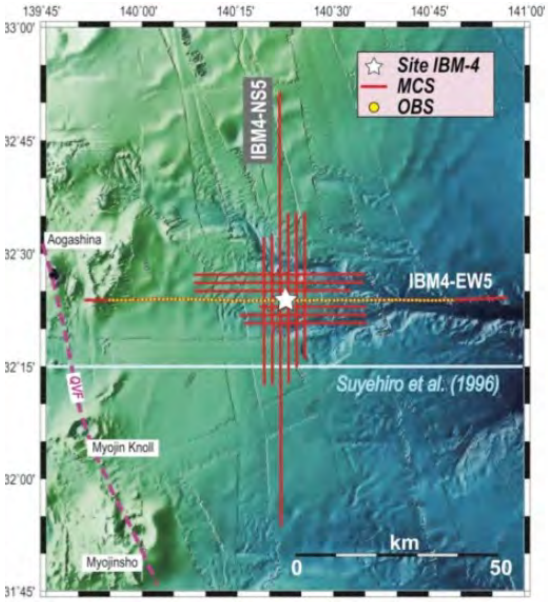


Fig. 1: Location of the proposed site IBM-4 (from Workshop Report: Ultra-Deep Drilling Into Arc Crust, Hawaii, 09.2012).

The proposed drilling site IBM-4 is located ~60 km East of Aogashima, one of the active volcanoes of the Izu arc front (Fig.1). Trace element compositions of volcanic rocks erupted on Aogashima are unusually low in ratios of large ion lithophile elements (LILE) to rare earth and high field strength elements (REE and HFSE) (Fig. 2, Taylor and Nesbitt, 1998), which suggest that Aogashima could be an end-member case with a minimum amount of trace elements transported by a fluid released from the subducting plate to the zone of melt generation in the mantle wedge. Initial results for the basement drilled at ODP site 792 (Taylor et al., 1990) show similar trace element compositions, thus suggesting that this unique geochemical signature might be a constant feature in this segment of the IBM arc.

Drilling at site IBM-4 will allow further analyses of older basement rocks and thus to investigate whether this is a long-living or temporally restricted geochemical signature and detailed geochemical and isotopic analyses will allow us to gain insight into possible changes in sources and processes leading to volcanism with time. We recently developed analytical techniques for the

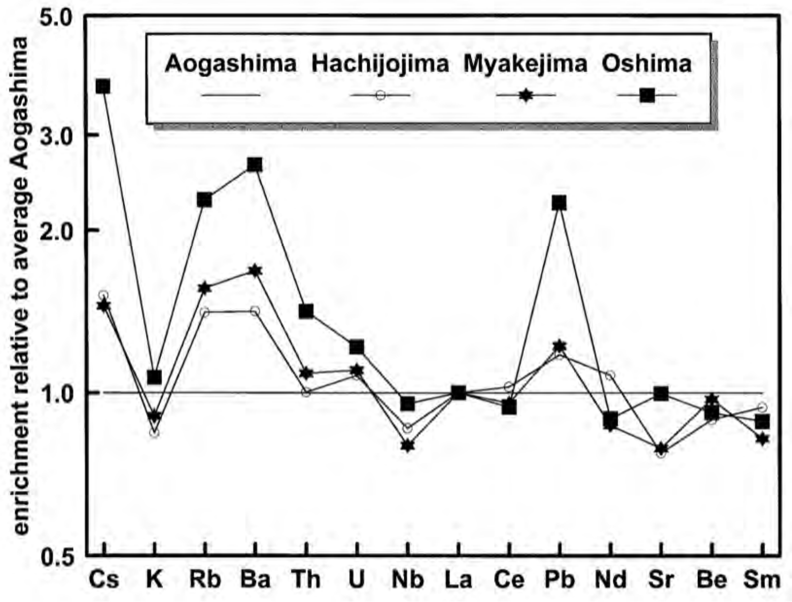


Fig. 2: Trace element compositions of volcanoes from the Izu arc front (Taylor & Nesbitt, 1998).

measurement of stable Mo isotopes in depleted volcanic rocks and initial results suggest that they are a sensitive tracer for fluid addition from the subducting slab. We therefore expect stable Mo isotopes to be ideal for this task in complement with trace element and radiogenic isotope data.

A thorough geochemical characterization of the volcanic basement can then be the basis for a geochemical study of the middle crust and comparison between the volcanic output of the arc and the plutonic rocks constituting the middle crust. Together with detailed petrological and geochronological studies it will help to investigate the processes of the formation of continental crust by basaltic input from the mantle (Fig. 3, Tatsumi et al., 2008) and address the problem of the dynamics of the formation of an intermediate composition middle crust versus dominantly basaltic volcanic output. In particular, it can allow to establish whether the formation of intermediate middle crust and basaltic volcanism can occur contemporaneously or whether one of the two processes dominates at any particular time. In the case that the two processes represent different magmatic regimes - one in which plutonic activity dominates and one that allows basaltic

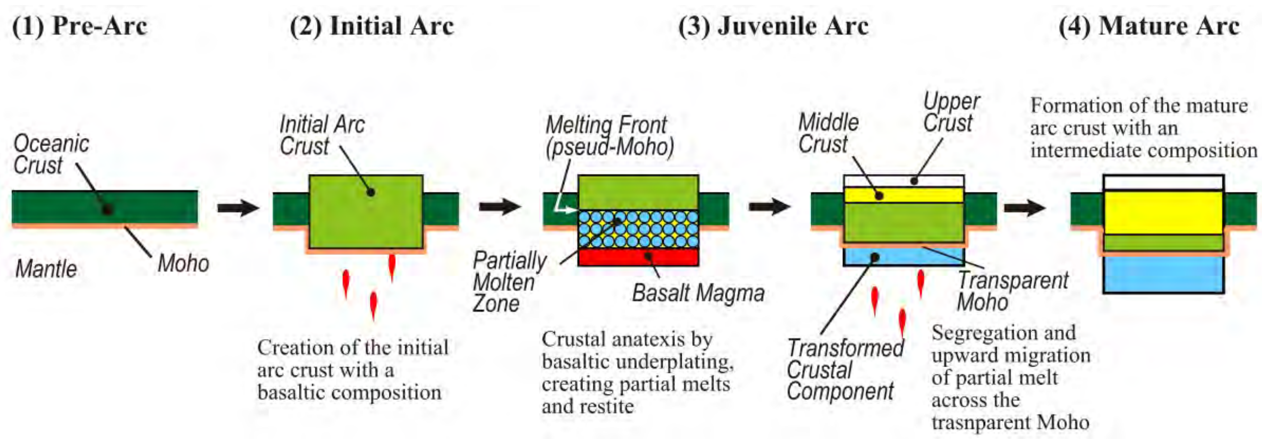


Fig. 3: Model for the formation of intermediate composition middle crust in the IBM arc (Tatsumi et al., 2008)

volcanism – temporal changes between them might be related to input parameters at deeper levels within the subduction zone, e.g. variations in the magma sources, magma production rate or amount of fluid input, which will lead to differences in the trace element and isotopic compositions of the intermediate middle crust and the basaltic volcanic rocks.

References:

Tatsumi, Y. Shukuno,H., Tani,K., Takahashi, N., Kodaira, S., Kogiso, T. (2008). Structure and growth of the Izu-Bonin-Mariana arc crust: 2. Role of crust-mantle transformation and the transparent Moho in arc crust evolution. *Journal of Geophysical Research* (113), 1-19

Taylor, B., Fujioka, K., et al., 1990. Proceedings of the Ocean Drilling Program, Initial Reports, Vol. 126

Taylor, R. N. & Nesbitt, R. W. (1998). Isotopic characteristics of subduction fluids in an intra-oceanic setting, Izu–Bonin Arc, Japan. *Earth and Planetary Science Letters* (164), 79–98

WHAT AT-SEA DRILLING STRATEGIES AND WHAT SHORE-BASED STUDIES ARE NEEDED TO ACHIEVE THE SCIENTIFIC OBJECTIVES?

James Gill

University of California Santa Cruz

Keywords: strategies

Drilling to the middle crust differs fundamentally from NanTroSEIZE or CRISP in that achieving the scientific objectives for the middle crust requires substantial core recovery. Consequently, high priority should be given to in-depth planning with CDEX engineers about how much, where, and by what methods coring can be done within a realistic budget. If, for example, only about a hundred meters of core below each depth of casing is possible, and the rest of the hole involves Logging While Drilling, Wireline Logging, and Sidewall Sampling, then that determines most other strategic decisions. Specifically, the depth of casing levels, the size and volume of cuttings per core length, and the total number of sidewall samples become crucial. If, instead, it is also possible to do spot coring and/or secondary slant hole coring, at depths other than just below casing, then this needs to be understood and its costs estimated. There may be a fundamental trade-off between total depth drilled and amount of core returned. Unless middle crust samples are lithologically homogeneous, the amount of core from the middle crust may be more important than the depth of penetration into the middle crust.

Four depth intervals were considered most essential for coring: (a) the sediment to volcanic transition previously cored at ~800 mbsf at Site 792; (b) the transition from mostly volcanic to mostly plutonic rocks; (c) the depth at which site survey work places the transition to ~6 km/sec (~3500 mbsf); and (d) the bottom of the hole (<5500 mbsf). Intervals (b) and (c) two may or may not be at the same depth, and either could be smeared out over hundreds of meters. However, they are the most crucial part of the section for models of crustal genesis and for transferability to exhumed rock sections. Other parts of the section that are especially high priority for core samples are: 1. the most mafic rocks (basalt, diabase, gabbro) because these most closely reflect mantle conditions and processes; 2. the most felsic rocks, because these contain zircons useful for U-Pb geochronology and Hf and O isotope geochemistry; 3. boninitic rocks, for their significance in models for subduction initiation processes; 4. levels of metallic mineralization and associated alteration; 5. metamorphic rocks associated with plutons; and 6. rocks that host life.

In light of the above, the shipboard party should include the standard IODP specialists and others at different stages of drilling. For example, experts on the first leg should include a benthic paleontologist, a pore water geochemist, a geomicrobiologist, a submarine process volcanologist, a volcanic igneous petrologist, and a sedimentary stratigrapher. Later legs should have experts in hydrothermal alteration and sulfide mineralization, deep geomicrobiology, structural analysis, batholith petrogenesis, and metamorphic petrology. Because of the importance of mud logging and cuttings, it may be valuable for some shipboard scientists to be trained in those skills by mining industry personnel prior to sailing and/or to have such personnel on board. There is interest in geobiology, especially the microbial colonization of different lithologies at high temperatures, but there is concern about the scarcity of core from key intervals. If some cuttings or core could be identified at sea as “having life”, then those intervals could be given higher priority for geobiological study.

It may also be important to add specific micro-analytical equipment for these legs such as a handheld XRF or equivalent (cf. NASA Curiosity analytical package) or even a microprobe or SEM. Mineral separation facilities optimized for zircon are important. Reflected as well as transmitted light microscopy will be needed. Finally, it may be necessary to adjust the on-board analytical approach to facilitate as close to real-time (at least same-day) chemical and mineralogical data flow, and to allow the scientific party to participate actively in analyses and methods. It is essential to establish sample management protocols and priorities prior to drilling. For example, effects of drilling mud must be removed quickly. Searching for zircon and monazite must be a high priority because U/Pb geochronology is so important to the scientific objectives. After crushing and sieving, the majority of the sample can be retained for other studies but a thin section must be taken beforehand.

Shore-based studies should include standard igneous and metamorphic mineralogy, petrology, and geochemistry (including major and trace elements, and Sr-Nd-Hf-Pb-O isotopes) are essential. U-Pb, O and Hf isotopic work on zircons from silicic pyroclastic rocks is also essential. High-precision U/Pb and Ar-Ar geochronology are essential and, therefore, searching for suitable minerals must have high priority. A walk-away VSP experiment, perhaps after completion of drilling, is essential in order to generalize the ground-truthed velocity structure of the site at scales applicable to exhumed terranes. Other desirable studies include: (a) hydrothermal alteration, contact metamorphism, and ore deposit petrology and geochemistry; (b) experimental mineral physics to determine the effect of water and temperature on the sound velocity of the primary minerals in the middle crust section; (c) structural analysis; (d) pore water chemistry and its relation to observed rock alteration; (e) melt inclusion analyses; (f) paleomagnetic determination of site paleo-latitude and the intensity and direction of rock magnetism in different lithologies, (g) thermochronology of apatite and zircon as a function of depth and temperature, and (h) microbial geobiology as appropriate. Micro-analytical methods (e.g., SEM, electron microprobe, LA-ICPMS, SIMS) will be essential.

Towards understanding of trigger and tectonic environment of subduction initiation

Osamu Ishizuka[1,2] and Kenichiro Tani[2]

[1]Geological Survey of Japan/AIST and [2]JAMSTEC

subduction initiation, arc basement, western Pacific

Trigger and tectonic environment of subduction initiation is still one of the fundamental questions to be answered. To tackle this problem, we propose two ways of approach. 1)Understanding of nature and history of arc basement, and 2) temporal variation of subduction initiation along the Western Pacific margin.

1) Understanding of nature and history of arc basement

The recent discovery of Mesozoic basement in the Izu-Bonin forearc (Ishizuka et al., 2011a) illustrates that pre-existing crust might have played an important role in the early development of the IBM arc. Two pillow basalts recovered trenchward and beneath 51-52 Ma gabbros produced identical plateau ages of 159.4 ± 0.9 Ma, indicating that these basalts resulted from Mesozoic magmatic activity. Geochemical characteristics of these basalts indicate that they are not accreted Pacific crust, but in situ Mesozoic basement. Recently, Tani et al. recovered Mesozoic diorite from northern Izu forearc.

Evidence of Mesozoic terrane, which could be a part of basement of the Izu-Bonin-Mariana arc has been obtained in multiple sites in the Philippine Sea Plate. 1) Huatung Basin: Gabbros and diabase from this basin, west of West Philippine Basin were dated at 199-133 Ma (e.g., Hickey-Vargas et al., 2008). 2) Daito Ridge Group: Mesozoic ages have been obtained from granite and arc volcanics from the Amami Plateau (Hickey-Vargas, 2005), arc volcanics, gabbros and tonalities from Daito Ridge (Ishizuka et al., 2011b; Tani et al., 2012, and volcanics from the Oki-Daito Ridge (Ishizuka et al., unpl. data).

Whereas the northern part of the IBM arc could have a basement consisting of Mesozoic arc terranes and ocean basins, other parts of the IBM arc might lack pre-Eocene basement. Current geographic relationship between the West Philippine Basin and Kyushu-Palau Ridge (i.e., remnant arc of the IBM arc) may imply that much of the southern part of the KPR, and corresponding parts of the IBM arc, might have been established on the growing West Philippine Basin ocean crust (e.g., Casey and Dewey, 2009).

The along-arc variability of arc basement could be an important factor controlling the following fundamental characteristics of the arc: crustal structure, variations in arc magma compositions, lithospheric mantle composition beneath the arc, etc.

We propose that this theme could be solved by 1) recovering forearc crust section down to the possible arc basement where different types of arc basement are expected (i.e., northern Izu forearc and northern Mariana forearc). 2) To understand the history and process of spreading of the West Philippine Basin and its effect on the Mesozoic arc terrane, recover crustal section along the transect between Mesozoic arcs and West Philippine Basin. This will also provide critical information about the temporal relationship between the IBM arc initiation and onset of the West Philippine Basin spreading, which put critical constraint to the tectonic environment at the subduction initiation.

2) Spatial variation of timing of subduction initiation along the Western Pacific margin

How subduction begins and its consequences for global tectonics remain essential outstanding problems of plate tectonics. Two different endmember mechanisms for subduction initiation have been hypothesized (Stern, 2004): spontaneous (e.g., Regenauer-Lieb et al., 2001; Stern and Bloomer, 1992), and induced (or forced; e.g., McKenzie, 1977; Gurnis et al., 2004). Numerical models (e.g., Gurnis et al., 2004) thus far suggest that subduction initiation is induced by externally forced compression along a preexisting discontinuity in an oceanic plate such as a fracture zone or transform faults (e.g., Uyeda and Ben-Avraham, 1972; Hilde et al., 1977). Stern (2004), however, has pointed out that spontaneous subduction must have occurred at some point in Earth's history to initiate plate tectonics

The contemporaneousness of the IBM forearc magmatism with the major change in plate motion in Western Pacific at ca. 50 Ma suggests that the two events are intimately linked. Published numerical models of subduction initiation require at least 100km of convergence before a subduction zone nucleates, with self-sustaining subduction occurring shortly thereafter (Hall et al., 2003). During the earliest stage of subduction, rapid trench retreat causes extension and decompression melting to generate forearc basalts from asthenospheric mantle. If this is correct, then 51-52 Ma age for onset of the basaltic magmatism can be considered as the age of initiation of slab sinking followed by self-sustaining subduction.

This age nearly coincides with the best estimate of the change in motion of the Pacific Plate deduced from the age of the Hawaiian-Emperor bend (c. 50 Ma: Sharp and Clague, 2006). Because the volcanism appears to be nearly synchronous with the change in plate motion, it appears that it was the onset of subduction that changed the plate motion. But it is still too early to reach this conclusion since we need to understand the period of subduction nucleation along the entire length of western Pacific margin with better precision. Precise estimation of time difference between subduction initiation and change of plate motion as well as timing of subduction initiation in each arc along the western Pacific margin. Systematic geochronological, petrological and geochemical study of the submarine forearc section will provide critical constraints to this problem, and could contribute to finalize the discussion about whether subduction initiation is spontaneous or induced. Drilling to recover forearc crustal section in the forearc such as Tonga-Kermadec arc in addition to the Izu-Bonin-Mariana forearc will provide necessary samples.

References: Casey, J.F.,Dewey, J.F. (2009) AGU Fall abstracts T21A-1782; Gurnis, M, Hall, L., C., Lavier, L. (2004) Geochem. Geophys. Geosyst. 5 Q07001, doi:10.1029/2003GC000681; Hall, C.E., Gurnis, M., Sdrolias, M., Lavier, L.L., Muellar, R.D. (2003) Earth Planet. Sci. Lett. 212, 15-30; Hickey-Vargas, R. (2005) The Island Arc 14, 653-665; Hickey-Vargas, R., Bizimis, M., Deschamps, A., (2008) Earth Planet. Sci. Lett. 267, 255-267; Ishizuka, O., Tani, K, Reagan, M.K., Kanayama, K., Umino, S., Harigane, Y., Sakamoto, I., Miyajima, Y., Yuasa, M., Dunkley, D.J., (2011a) Earth Planet. Sci. Lett. 306, 229-240**;** Ishizuka, O., Taylor, R.N., Yuasa, M., Ohara, Y. (2011b) Geochem. Geophys. Geosyst., 12: Q05005, doi:10.1029/2010GC003440; McKenzie, D.P., (1977) In: Talwani, M., Pitman, W.C. (Eds.), Maurice Ewing Ser., 1. AGU, Washington, D. C. pp. 57-61; Regenauer-Lieb, K., Yuen, D.A., Branlund, J., (2001) Science 294, 578-580; Sharp, W.D., Clague, D.A., (2006) Science 313, 1281-1284; Stern, R.J., Bloomer, S.H., (1992) Geol. Soc. Am. Bull. 104, 1621-1636; Stern, R.J., (2004) Earth Planet. Sci. Lett. 226, 275-292; Tani, K., Ishizuka, O., Ueda, H., Shukuno, H., Hirahara, Y., Nichols, A.R.L., Dunkley, D.J., Horie, K., Ishikawa, A., Morishita, T., Tatsumi, Y. (2012) *American Geophysical Union, Fall Meeting 2012, abstract;* Uyeda, S., Ben-Avraham, Z., (1972) Nature Phys. Sci. 240. 176-178.

Obtaining prolonged records of volcanism and crust forming processes in the IBM and Aleutian arcs via Chikyu ultra-deep drilling

Brian R. Jicha[1], Gene M. Yogodzinski[2], Peter B. Kelemen[3], David W. Scholl[4], Kaj Hoernle[5]
[1] University of Wisconsin-Madison; [2]University of South Carolina; [3]Lamont Doherty Earth Observatory;
[4] USGS Pacific Coastal & Marine Science Center; [5] GEOMAR, Helmholtz Center for Ocean Research
Keywords: IBM arc, deep drilling, Aleutians, Adak, forearc, backarc

Challenge #11 of the International Ocean Discovery Program (IODP) science plan asks "How do subduction zones initiate, cycle volatiles, and generate continental crust?" Chikyu drilling proposed for the Izu-Bonin-Mariana (IBM) arc is aimed at sampling the middle crust which has Vp= 6.0-6.5 km/s that is interpreted to be juvenile, continental crust (IODP proposal 698-Full3). It will also recover an extended record of IBM arc magmatism. This white paper emphasizes the importance of obtaining protracted records of arc volcanism, as would be obtained by IBM-4, and recommends future drill sites for Chikyu.

We currently have a detailed understanding of the origin and evolution of a single intra-oceanic arc—the Izu Bonin-Mariana (IBM) system. Decades of work have revealed the timing (Ishizuka et al., 2011) and compositional evolution of IBM magmatism (Reagan et al., 2010). The basic premise is: at ca. 51-52 Ma, the Pacific plate began to spontaneously sink perhaps due to fracture zone collapse, and subduction initiated along the Izu-Bonin-Mariana arc. This was accompanied by voluminous generation of forearc basalt and subsequent boninite. Ishizuka et al. (2011) estimated that it took ~7 Ma before a stable magmatic arc was established. The IBM initiation model appears to apply to the Tonga Kermadec system to the south (Meffre et al., 2012), but it remains unclear if the model can be applied globally because very little is known about subduction initiation and crustal evolution in most other intra-oceanic arcs.

An ultra-deep drill hole into the IBM arc crust offers the unique opportunity to link the magmatic processes that have operated in the mid-crust following arc inception, and the byproducts of such processes, with the observed geophysical signals. These new findings could then be used to infer processes in other active arcs whose geophysical structures are characterized. Limited data on other intra-oceanic island arcs suggest a range of velocity structures that fall between the IBM and Aleutian arcs. Unlike IBM, the Aleutian arc lacks a comparable mid-crustal layer with velocities of 6-6.5 km/s. Its middle crust has velocities of 6.5-7.3 km/s, and is interpreted to be predominantly mafic (Holbrook et al., 1999; Shillington et al., 2004). Deep drilling to both the IBM and Aleutian arcs would likely capture most of the range of magmatic processes and crustal compositions produced at intra-oceanic arcs. The Aleutians, unlike other intra-oceanic arcs, hosts extensive outcrops of felsic plutons that crystallized in the mid-crust. We recommend at least one ICDP drill site in exposed plutonic rocks, perhaps on Adak Island.

Deep drilling in the central Aleutians will not only provide a rich record of initiation and crustal evolution of the mafic endmember intra-oceanic arc, it will also allow us to test the IBM initiation model and more fully address IODP challenge #11 by answering questions such as: Do forearc basalts and boninites exist in the Aleutians? How long did initial voluminous volcanism last? Is the mid-crust analogous to low Mg# arc basalts or high Mg# andesites observed in the western Aleutians (Yogodzinski et al., 1995)? There is additional motivation to drill into the Aleutians because it was identified as the highest priority primary site within the framework of the Subduction Cycles and Deformation initiative of the U.S. NSF-GeoPRISMS program. The lack of back-arc extension and longitudinal intra-arc rifting means that the entire record of Aleutian arc growth is mostly preserved.

The timing of Aleutian arc initiation has important implications for the Eocene evolution of the entire circum-Pacific. Aleutian arc subduction is posited to have initiated along an E-W trending fracture zone, similar to the IBM system, capturing part of the Mesozoic Kula or Resurrection plates (Scholl et al., 1986). The formation of the Aleutian subduction zone likely coincided with the termination of magmatism along the Beringian margin. Stern et al. (2012) recently proposed an alternative explanation, suggesting that the Bering Sea basin opened as a Paleogene backarc basin and the central and western Aleutian arc is composed, in part, of a rifted remnant of the Beringian arc. Evaluating the various tectonic models of Aleutian arc formation as well as addressing the proposed questions regarding early arc production and crustal evolution described above can likely be done via deep drilling into the central Aleutian Adak Island area. The advantage of deep drilling (depths >1 km) is the potential for sampling continuous and intact stratigraphic sequences of magmatic activity that reach back in time to the initial stages of arc formation and development. Intact stratigraphic records cannot be sampled on islands or by dredging in the forearc. Outcrop and dredging records will always be fragmentary compared to those that might be sampled by deep drilling. Manned submersible sampling and deep drilling of the IBM forearc produced the key observations that led to the current working model for subduction initiation and early arc evolution. There has been relatively little exploration of the Aleutian forearc, but ROV observations and related sampling have revealed good exposures of volcanic and plutonic basement rocks up to 38 million years old in Adak Canyon, immediately southwest of Adak Island (Jicha et al., 2006). This is important, because although arc basement extends seaward to near the trench, accretionary growth of a 15-30-km-wide frontal prism in the late Cenozoic buried the seaward edge of basement (Scholl et al., 1983). So the early products of arc magmatism are buried beneath and behind a mélange of accreted sediment. As a result, selection of drill sites near Adak will require more detailed knowledge of the Aleutian forearc than is currently available, but which can be obtained by additional mapping, dredging, and seismic imaging. We anticipate opportunities in the next 3-5 years, especially through U.S. collaboration with German and German-Russian projects, which have identified the early history of the Aleutian arc as a priority topic for focused research. For these reasons, at least one Chikyu deep drilling site chosen on the basis of these surveys should sample the Aleutian forearc.

An additional opportunity for drilling into the early history of the Aleutians lies in the thick wedge of sediment that drapes the back of the arc massif and inter-fingers with Bering Sea sediment to the north. The upper part of this wedge probably consists of volcaniclastic greywacke and tephra that record much of the volcanic history of the arc (see Figure 2 & Table 1, Scholl et al., 1983). These units likely overlie coarse and massive hyaloclastites, pillow lavas and related volcaniclastic debris produced early in the evolution of the arc. For many elements, especially the rare-earth and high field strength elements, including Hf, Nd, and Pb and possibly Sr isotopes in fresh phenocrysts, these materials will faithfully record the geochemistry of the volcanic output of the arc. The backarc deposits may record other key geologic events in the arc's history as well, such as the unroofing of plutons exposed on several islands including Adak.

Sediment thickness in the Bering Sea, along the north end of the arc near Adak, is approximately 2.5 km (Cooper et al., 1981). A 3 km deep Chikyu drill hole located just north of the arc will penetrate into early arc massif deposits and potentially recover a continuous record of volcanic activity spanning the lifetime of the arc. A shallower Chikyu or JOIDES Resolution hole could achieve this goal, depending on the details of the subsurface geology. A state-of-the-art seismic image across the arc will be needed to illuminate the geometry of the backarc sediment wedge and its relationship with the northward thinning arc massif which it overlies. There will be an opportunity to collect such an image because a GeoPRISMS lithospheric-scale reflection-refection study in the Aleutians will likely encompass the Adak area. The opportunity to explore the backarc sediment wedge is exciting because it is unlikely to be preserved in an accreted arc system, and because to our knowledge, it has never been explored in an active arc.

In summary, ultra-deep drilling into the IBM mid crust should be given the highest priority due to its numerous magmatic and geophysical implications for intra-oceanic arcs. Complementary deep drill holes in the central Aleutian arc should be given strong consideration as a future endeavor for Chikyu because it would provide an extensive record of volcanic output that will document fundamental changes in the arc through time, test the generality of arc initiation models based on IBM studies, and allow us to link the magmatic processes to the geophysical structure of the North Pacific with arcs in the western Pacific.

References Cited

Cooper, A.K., Marlow, M.S., Ben-Avraham, Z., 1981. Multichannel seismic evidence bearing on the origin of Bowers Ridge, Bering Sea, Geol. Soc. Am. Bull. 92, 474-484.

Holbrook, W.S., et al., 1999. Structure and composition of the Aleutian island arc and implications for continental crustal growth. Geology 27, 31-34.

Ishizuka, O., et al., 2011. The timescales of subduction initiation and subsequent evolution of an oceanic island arc: Earth Planet. Sci. Lett., 306, 229–240, doi:10.1016/j.epsl.2011.04.006.

Jicha, B.R., et al., 2006. Revised age of Aleutian Island arc formation implies high rate of magma production, Geology, 34, 661–664.

Meffre, S., et al., 2012. Basalts erupted along the Tongan fore arc during subduction initiation: Evidence from geochronology of dredged rocks from the Tonga fore arc and trench, Geochem. Geophys. Geosyst., 13, Q12003, doi:10.1029/2012GC004335.

Reagan, M.K., et al., 2010. Forearc basalts and subduction initiation in the Izu-Bonin-Mariana system, Geochem. Geophys. Geosys. 11, Q03X12, doi:10.1029/2009GC002871.

Scholl, D. W., Vallier, T. L., and Stevenson, A. J., 1983. Arc, forearc, and trench sedimentation and tectonics, Amlia corridor, Aleutian subduction zone, AAPG Memoir, 413-439.

Scholl, D. W., Vallier, T. L., and Stevenson, A. J., 1986. Terrane accretion, production, and continental growth--a perspective based on the origin and tectonic fate of the Aleutian-Bering Sea region: Geology, v. 14, p. 43-47.

Shillington, D.J., et al., 2004. Composition and structure of the central Aleutian island arc from arc-parallel wide-angle seismic data, G-cubed 5, Q10006, doi.org/10.1029/2004GC000715.

Stern, R.J., et al., 2012. Did the Bering Sea Form as a Cenozoic Backarc Basin? 2012 AGU Fall Meeting abstract.

Yogodzinski, G.M., Kay, R.W., Volynets, O.N., Koloskov, A.V., Kay, S.M., 1995. Magnesian andesite in the western Aleutian Komandorsly region: Implications for slab melting and processes in the mantle wedge. Geol. Soc. Am. Bull. 107, 505-519.

Calc-alkaline affinity, oxygen fugacity, and the formation and evolution of arc crust

Katherine A. Kelley[1], Elizabeth Cottrell[2], and Matthew Jackson[3]

[1]Graduate School of Oceanography, University of Rhode Island, [2]Department of Mineral Sciences, Smithsonian Institution, and Department of Earth and Environment, Boston University

Keywords: continental crust, oxygen fugacity, magmatic differentiation, subduction, oxidation state

Ultra-deep drilling into the arc middle crust at proposed Site IBM-4 is aimed at recovering key arc magmatic products, including a time series of arc volcanics and plutonic/cumulate records of arc magmatism. These materials will provide a vital record of the petrological and geochemical drivers of crustal evolution and continental crust formation in a mature arc setting. High oxygen fugacity (fO_2) is among the petrological criteria thought to be responsible for creating continental crust, which has calc-alkaline affinity similar to many arc volcanoes. Calc-alkaline affinity is the extent to which magmas become depleted in Fe during early differentiation (here shown on Fig. 1 as the Tholeiitic Index [THI] of Zimmer et al. [2010], where values >1 indicate Fe enrichment [tholeiitic], and <1 indicate Fe depletion [calc-alkaline]), and is thought to be at least partially controlled by fO_2 due to the role of high fO_2 in enabling early saturation of Fe oxides in magmas. Measurements of the oxidation state of Fe, a proxy for magmatic fO_2, corroborate this hypothesis (Fig. 1). The lavas at ODP Site 792, proximal to the proposed location of the ultra-deep site IBM-4, are strongly calc-alkaline (Fig. 1), and the samples recovered through ultra-deep drilling here will provide critical petrological tests of the role of oxygen fugacity in the evolution of arc magmas and in the creation of continental crust.

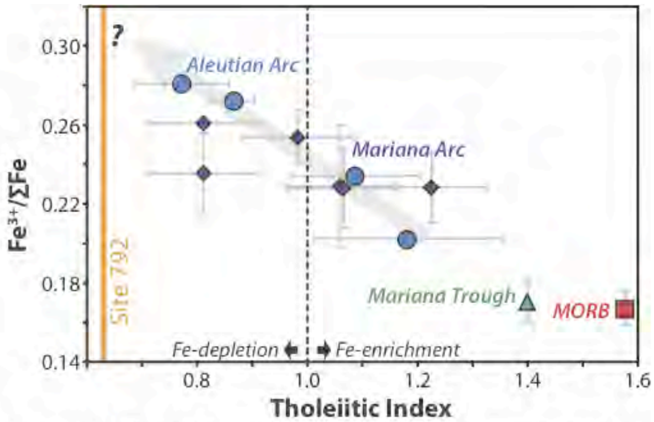


Figure 1. Plot of Tholeiitic Index (THI) vs. $Fe^{3+}/\Sigma Fe$ ratio for naturally glassy olivine-hosted melt inclusions from the Aleutian-Alaska (blue circles) and Mariana (purple diamonds) arcs, showing a trend towards greater calc-alkaline affinity for more oxidized magmas. The orange bar shows the THI for Site 792 volcanics, which are strongly calc-alkaline. Also shown are averaged data from mid-ocean ridges (MORB; red square) and the Mariana trough back-arc basin (green triangle). Data sources are Cottrell & Kelley (2011), Kelley & Cottrell (2009), Zimmer et al. (2010), Brounce (unpub. data), and Kelley & Cottrell (unpub. data).

Ultra-deep drilling will provide an unprecedented magmatic time series for a single arc volocano, and when constrained in age, isotopic composition, and igneous redox state, such a series will provide key constraints on how (if at all) arc magmatic redox, calc-alkaline affinity, and slab contributions to the arc change through time, and how these factors may be related. Among the key factors that may be constrained is how arc magmas acquire their high fO_2, be it either through a differentiation process or through influence from the subducted slab.

Moreover, the observed relationship between THI and Fe redox (Fig. 1) suggests that the Site 792 volcanics may represent a strongly oxidized magmatic system. Establishing the petrological relationships between the volcanics and the cumulates/plutonics at Site IBM-4, including the role of fO_2, will provide key constraints on how proto-continental crust may be manufactured, and valuable perspectives on how mature continental crust evolves from its juvenile state, as recorded within the IBM system.

GEOCHEMICAL WELL LOGGING OF THE JUVENILE UPPER AND MIDDLE ARC CRUST AT IBM-4 ULTRA-DEEP RISER DRILL HOLE

Jun-Ichi Kimura[1], Takashi Miyazaki[1], Chang Qing[1], Toshiro Takahashi[1], Yuka Hirahara[1], Ryoko Senda[1], and Vaglarov Bogdan Stefanov[1]

[1]IFREE/JAMSTEC

Key: crust formation, cuttings, geochemistry, middle crust, upper crust, well logging

The geochemistry of the continental and arc crusts has been a central issue in the geochemical studies of the Earth because incompatible elements concentrate mostly in the crust. The upper crustal composition has been estimated by averaging the surface exposure of rock types and their average compositions, or alternatively, by using loess or shale compositions, which are believed to be the averaged mixture of the powdered surface rocks. Studies on the middle and lower crusts are harder than for the upper crust due to poor exposure of these rocks that delimits information either of the rock types or rock chemistry. Furthermore, the bulk continental crust forms mostly by accretion of various subduction-zone products including island arc crust at various evolution stages. Therefore, heterogeneity of the continental crust is enormous and the components of each accreted arc should be evaluated.

The proposal on ultra-deep drilling into young (~50 My old) oceanic arc middle crust, “IBM-4” proposal as part of Project IBM, has been well accepted by IODP Science Advisory Structure and the current status of the project is in Operation Task Force waiting for technical and logistic feasibility studies. The principal interest of the IBM-4 drilling is to drill through the entire sequence of the upper and uppermost middle crust formed in an early juvenile oceanic arc (50-35 Ma with magmatic activities of early MORB-like tholeiite, through boninite, and followed by arc tholeiite) and to confirm that these rocks with Vp = ~6 km/s comprising the middle crust at >4 km deep perhaps formed by magmatic accretion and fractionation. The recovery of the rocks from the upper volcanic sequence (upper crust) and possible tonalitic middle crust may elucidate the magma accretion–fractionation history during the early juvenile arc stage. This, in turn, can provide information on the nature and formation processes of the very early stage middle crust, which would be free from any later overprinting processes like those which are ubiquitous either in the eroded exposures of the deep continental crust or in tectonically exhumed ophiolite sequence.

Given the opportunity for sampling of the unmodified (plutonic) middle crust in conjunction with the upper crustal volcanic counterparts, we propose an ancillary but essential project which describes the entire rock sequence of the ultra-deep hole by using drill cuttings. Providing consecutive sampling of rock materials without coring is one of the advantages of the Riser system. Consecutive sampling of the drill cuttings is available by using Riser system due to the circulating drill mud in the Riser pipe that carries the cuttings continuously. The recovery of the drill mud is delayed due to travel in the Riser pipe and the cuttings from the drill bits are partially mixed with the earlier cuttings. However, the spatial resolution of the first-arrival sample would be better than in the few tens of meters depth down hole and the composition of the mixed cuttings can be determined by running average. Sample size normally range from wheat-grains to ball-bearing size.

With these properties of the cuttings, effective analytical techniques are two folds. One is by bulk-rock analysis of the cuttings and the second is by analysis of the crystals by micro analytical techniques. The bulk rock analyses can be done with XRF and solution ICP-MS for major and trace elements. Sr-Nd-Hf-Pb isotopic analyses are also possible using the same solution prepared for ICP-MS by using TIMS and MC-ICP-MS. The bulk analyses, however, include risks of contamination from drill mud and metal equipment or of biases from the grain size fractionation. To amend the bulk-rock analyses, in-situ mineral micro analyses are useful. For example, plagioclase is relatively strong against weathering and is ubiquitous in the arc rocks of any type. Simultaneous major and trace element analysis of plagioclase crystals can be done using LA-ICP-MS. Pb and Sr isotope analyses using LA-MC-ICP-MS are also available using the same plagioclase crystals (Fig. 1). Analysis of other mineral fragments such as olivines, clinopyroxenes, spinels, and glass inclusions in the minerals are possible if cuttings are fresh enough.

Once the entire geochemical sequence is established we can then examine the elemental fractionation processes in the middle and upper crust or even deeper. The absolute advantage of this proposal over spot coring strategy is the potential to provide the entire sequence of the geochemistry of the early juvenile upper and uppermost middle crust. This is a true opportunity to obtain both average composition and variation in the upper and middle crustal rocks of this particular juvenile IBM arc. We thus believe that the rigorous dataset obtained by this project can provide a landmark data for understanding the genesis of the Earth's crust.

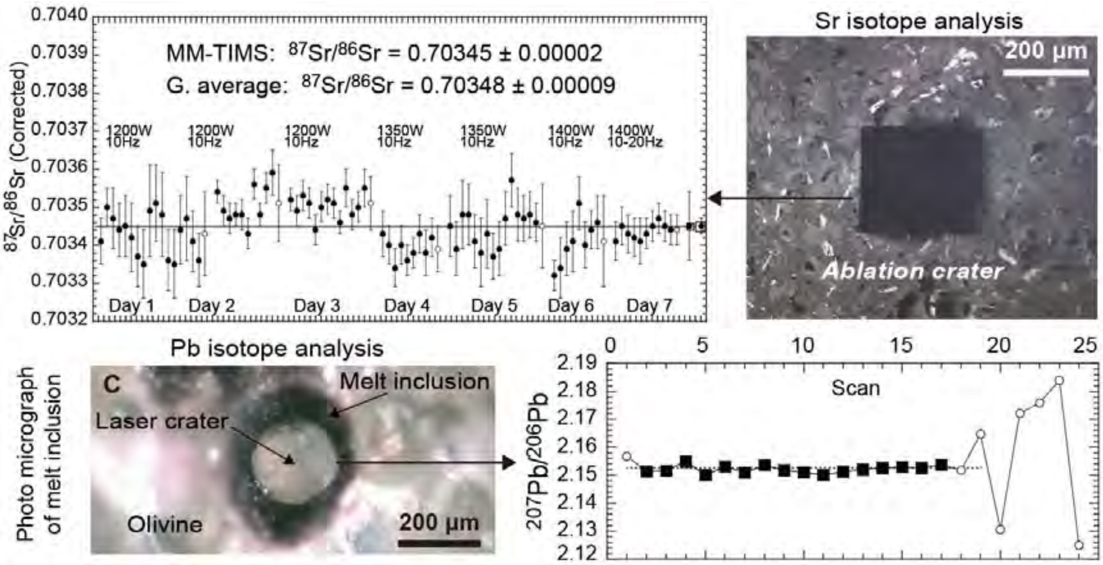


Fig. 1. Examples of Sr and Pb in situ analyses using LA-MC-ICP-MS

THE IMPORTANCE OF SAMPLING THE UPPER BOUNDARY OF THE MIDDLE CRUST DURING DEEP DRILLING TO HELP UNRAVEL THE GENESIS OF THE MIDDLE CRUST

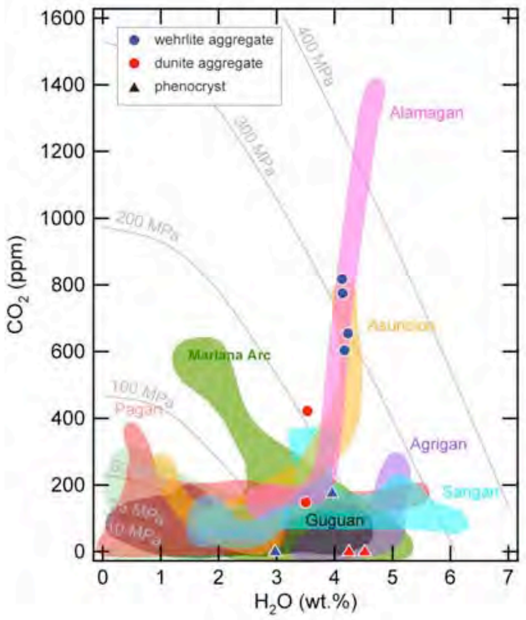
A. R. L. Nichols[1], Y. Tamura[1], R. J. Stern[2] and H. Shukuno[1]

[1]Institute for Research on Earth Evolution (IFREE), Japan Agency for Marine Earth Science and Technology (JAMSTEC), Yokosuka, Japan and [2]Department of Geoscience, University of Texas at Dallas, USA

arc basalts, melt inclusions, water, carbon dioxide, entrapment pressures, middle crust

Work on volatiles dissolved in melt inclusions hosted by crystal phases within magmas from the modern Mariana Arc suggest that magmas stall at a common depth of between 6 and 12 kmbsl (e.g., Newman et al., 2000; Shaw et al 2008; Kelley et al, 2010; Fig. 1), which corresponds to the middle crust. This is also supported by recent work we have conducted on the volatile contents of melt inclusions hosted in olivines from wehrlite and dunite crustal xenoliths and olivine phenocrysts contained within basalts recovered by the ROV Hyper-Dolphin at West Zealandia Seamount, in the southern Mariana Arc (Fig 1). The H_2O-CO_2 contents of the inclusions from the wehrlites (maxima 4.23 wt.% and 809 ppm, respectively) suggest final equilibration at ~300 MPa, equivalent to depths of ~11 kmbsl. Inclusions in the dunites and phenocryst olivine populations (maxima 4.52 wt.% and 402 ppm, respectively), which are also more evolved, suggest final equilibration at ~180 MPa, equivalent to depths of ~6 kmbsl (Fig. 2). Beneath West Zealandia these depths correspond to the lower-middle crust and middle-upper crust boundaries, respectively. Similar primitive volatile contents maxima have been measured in volcanic front magmas from other arc systems (e.g., Ruscitto et al., 2012) suggesting that stalling of magma at these depths is not unique to the Mariana Arc, but is typical of arcs worldwide. If this is the case, why are magmas stalling at this depth? Does a primitive magmatic H_2O content of ~4 wt.% compel the magmas to degas at these depths? Or does it reflect the crustal structure, with density contrasts at these depths causing the magma to stall? If so, this implies a fundamental relationship between magma stalling and differentiation, and the generation of the middle crust formed in the Izu-Bonin-Mariana Arc system and other arcs.

Deep drilling to the middle crust in the Izu-Bonin Arc system using the riser-drilling platform D/V Chikyu will enable these questions to be addressed. As time and budget limitations will prevent full coring of the entire depth drilled, depths of interest will have to be discussed and prioritized for the possibility of full coring. One such depth is around the inferred seismic boundary layer, marking the top of the middle crust, where magmas may be stalling. Full coring at this depth will increase the likelihood of being able to investigate the questions outlined above than would be the case if direct sampling at these depths was limited to cuttings and sidewall cores. If degassing is occurring here, full coring will allow us to look for evidence that released gases and fluids are interacting with the surrounding rock and investigate what role these play in altering the rocks and the possibility that they are helping to support life at these depths in the crust.



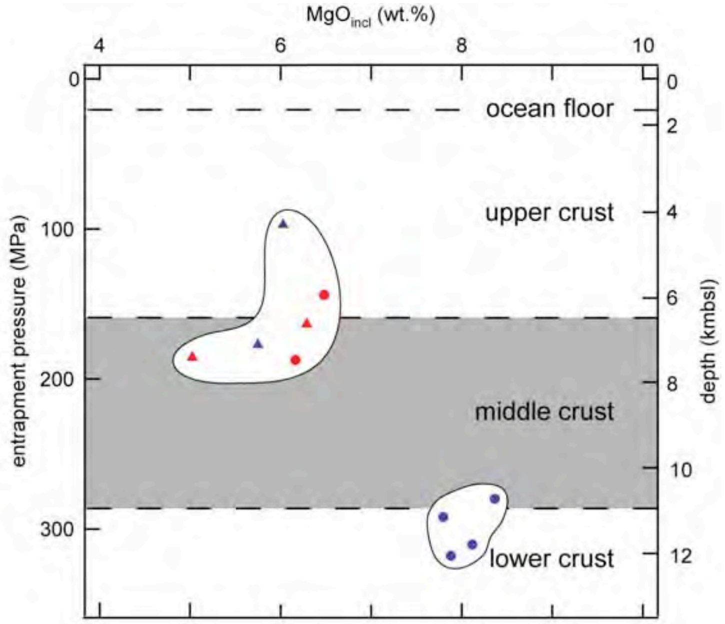


Figure 1 (left): H_2O-CO_2 for melt inclusions from West Zealandia Seamount (symbols) compared to other volcanoes in the Mariana Arc (colored fields) (Newman et al., 2000; Shaw et al., 2008; Kelley et al., 2010). Isobars calculated using VolatileCalc (Newman and Lowenstern, 2002). Figure 2 (right): Entrapment depths and MgO content of melt inclusions from West Zealandia compared to crustal structure beneath West Zealandia (crustal structure from Takahashi et al., 2007).

References:

Kelley K. A., Plank T., Newman S., Stolper E. M., Grove T. L., Parman S. and Hauri E. H., 2010, Mantle melting as a function of water content beneath the Mariana Arc. Journal of Petrology, 51, 1711-738, doi: 10.1093/petrology/egq036

Newman S., Stolper E., and Stern R., 2000, H_2O and CO_2 in magmas from the Mariana arc and back arc systems. Geochemistry Geophysics Geosystems, 1, doi: 10.1029/1999GC000027

Newman S. and Lowenstern J. B., 2002, VolatileCalc: a silicate melt-H_2O-CO_2 solution model written in Visual Basic for excel. Computers and Geoscience, 28, 597-604, doi: 10.1016/S0098-3004(01)00081-4

Ruscitto D. M., Wallace P. J., Cooper L. B. and Plank T., 2012, Global variations in H_2O/Ce: 2. Relationships to arc magma geochemistry and volatile fluxes. Geochemistry Geophysics Geosystems, 13, doi: 10.1029/2011GC003887

Shaw A. M., Hauri E. H., Fischer T. P., Hilton D. R. and Kelley K. A., 2008, Hydrogen isotopes in Mariana arc melt inclusions: Implications for subduction dehydration and the deep-Earth water cycle. Earth and Planetary Science Letters, 275, 138-145, doi: 10.1016/j.epsl.2008.08.015

Takahashi N., Kodaira S., Klemperer S. L., Tatsumi Y., Kaneda Y. and Suyehiro K., 2007, Crustal structure and evolution of the Mariana intra-oceanic island arc. Geology, 35, 203-206, doi: 10.1130/G23212A.1

Continental Crust Formation and Mass Fluxes Through Arcs

Susanne M. Straub[1], Terry Plank[1] and Brian Jicha[2]
[1]Lamont Doherty Earth Observatory at the Columbia University, Palisades NY 10964, U.S.A (smstraub@ldeo.columbia.edu, tplank@ldeo.columbia.edu); [2]Department of Geoscience, University of Wisconsin-Madison, Madison, WI 53706 (bjicha@geology.wisc.edu)
Keywords: Izu Bonin mid-crust, arc growth rates, arc magmatic fluxes

CHIKYU drilling proposed for the intra-oceanic Izu Bonin arc is designed to reach the low-Vp velocity mid-crust layer (~6.0-6.8 km/s) that resembles continental crust and may be tonalitic in composition [IODP proposal 698-Full3]. This mid-crust layer holds the key to understanding the flux of material from the upper mantle and slab within the ~50 Myr Izu Bonin's arc evolution. As a modern analog to Archean crustal growth, understanding the genesis of the Izu Bonin mid-crust bears on the main theme “*Earth Connections: Deep Processes and Their Impact on Earth’s Surface Environment*" of the IODP Science Plan for 2013-2023 "*Illuminating Earth's Past, Present, and Future*". The purpose of this White Paper is to emphasize that deep-drilling the Izu Bonin mid-crust will also provide major strides towards the quantification of arc magmatic fluxes.

Arc crustal growth and arc elemental outflux are directly related to each other, as evident from the following equation:

elemental outflux = element abundance * arc density * arc growth rate

The arc density (or density of melts) has a limited range of (~2.3-2.8 g/cm3). Hence, the arc outflux is primarily dependent on the elemental abundance (concentration of an element in the primary mantle melt), and the arc growth rate which is the mass of mantle melt added to crust per unit time (minus any pre-existing or accreted material). In other words, the arc outflux is a function of the composition and volume of the primary arc melts produced. However, despite decades of research, no consensus exists with respect to the composition of primary arc melts that cross the Moho to build arc crust.

Among the models of arc magma petrogenesis, two contrasting groups emerge. The first group proposes that initial arc melts were basaltic melts from a metasomatized subarc mantle. These basalts then differentiate to high-silica melts in the overlying crust, by such processes as fractional crystallization and crustal contamination in the lower crust (e.g. Annen et al., 2006). Andesite crust may then form by continuous upwards segregation of silicic melts (mid-crust) and periodic delamination of mafic residues (Tatsumi et al., 2008). The second group of models proposes the generation of silicic melts in the mantle wedge through interaction of reactive mantle materials with silicic, hydrous components from slab (e.g. Yogodzinski et al., 1995; Kelemen et al., 2003; Straub et al., 2011). Either genetic model has different consequences for arc crustal growth and outflux. A basaltic flux to the Moho implies that pre-existing crust acts as a barrier, slowing the ascent of mantle magmas through physical interaction and chemical modification. Much of the arc outflux is likely recycled overlying crust (e.g. Tamura and Tatsumi, 2002). If the mantle yields a much broader spectrum of basaltic to silicic melts, however, the overlying crust could be much more permeable. Hence, the turnover of recycled elements – including the climatically active volatiles – would be much increased and more closely associated with slab input. Much of the arc crust may grow by direct accretion of mantle melts rather than intra-crustal differentiation.

Figure 1 contrasts the compositions of different primary melts with the erupted magmas of the Izu Bonin Mariana arc. Panel A assumes the primary melts to be high-Mg# basalts (green box), whereas panel B assumes a range of primary basaltic to dacitic high-Mg# primary magmas (Straub et al., 2011; Yogodzinski et al., 2011). Significantly, in either model, it is obvious that magmas must undergo significant crustal differentiation to produce the low-Mg# melts.

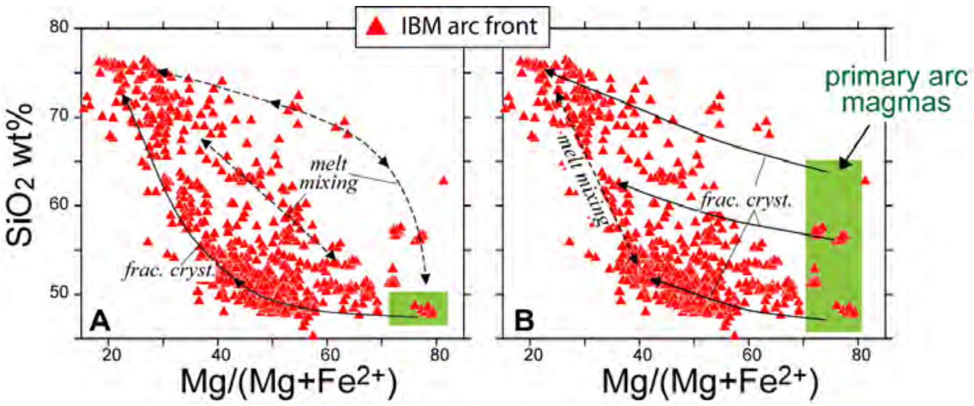


Fig. 1: Potential pathways of crustal differentiation in SiO2 wt% *vs*. molar ratio of Mg/(Mg+Fe2+) (=Mg#) space of Quaternary arc front magmas in the Izu Bonin-Mariana arc (IBM). **A**. Assuming basaltic primary magmas. **B**. Assuming basaltic to dacitic primary magmas.

The pathways of crustal differentiation (*black arrows* in Fig. 1), however, will differ depending on the compositions of initial melts. Much of the information on which evolutionary path the mantle magmas may have followed can only be incompletely reconstructed from the extrusive series (*red triangles* in Fig. 1), but is contained in the intrusive counterparts. Technological advances now allow for deep drilling into oceanic arc crust and retrieve in-situ complementary extrusive and intrusive series closelyrelated in time and space. As such, deep drilling into the Izu Bonin arc provides an unique opportunity in making major strides towards quantifying arc magmatic fluxes and assessing their role in the broader geochemical cycles on Earth.

References Cited

Annen, C., Blundy, J.D., Sparks, R.S.J., 2006. The Genesis of Intermediate and Silicic Magmas in Deep Crustal Hot Zones. J Petrol, 47(3): 505–539, doi:10.1093/petrology/egi084.

Kelemen, P.B., Yogodzinksi, G., Scholl, D.W., 2003. Along-strike Variation in the Aleutian Island Arc: Genesis of high-mg# andesite and implication for the continental crust. In: Eiler, J. (Ed.), Inside the Subduction Factory. Geophys Monograph. Amer Geophys Union: 223-276.

Straub, S.M., Gomez-Tuena, A., Stuart, F.M., Zellmer, G.F., Espinasa-Perena, R., Cai, M.Y., Iizuka, Y., 2011. Formation of hybrid arc andesites beneath thick continental crust. Earth Planet Sci Lett, 303: 337-347, doi:10.1016/j.epsl.2011.01.013.

Tamura, Y., Tatsumi, Y., 2002. Remelting of an andesitic crust as a possible origin for rhyolitic magma in oceanic arcs: an example from the Izu-Bonin Arc. J Petrol, 43(6): 1029-1047.

Tatsumi, Y., Shukuno, H., Tani, K., Takahashi, N., Kodaira, S., Kogiso, T., 2008. Structure and growth of the Izu-Bonin-Mariana arc crust: 2. Role of crust-mantle transformation and the transparent Moho in arc crust evolution. J Geophys Res, 113: B02203, doi:10.1029/2007JB005121, 2008.

Yogodzinski, G.M., Arndt, S., Turka, J.R., Kelemen, P.B., Vervoort, J.D., Portnyagin, M., Hoernle, K., 2011. Nature and Significance of the High-Sr Aleutian Lavas (Invited) AGU Fall Meeting, San Franciso, V32C-02.

Yogodzinski, G.M., Kay, R.W., Volynets, O.N., Koloskov, A.V., Kay, S.M., 1995. Magnesian andesite in the western Aleutian Komandorsly region: Implications for slab melting and processes in the mantle wedge. Geol Soc Am Bull, 107(5): 505-519.

Challenge to the deepest chemolithotrophic biosphere in hard rock

[Author (s)] Ken Takai[1,2] and Kentaro Nakamura[2]

[Institution (s)] [1]SUGAR project, JAMSTEC and [2]Precambrian Ecosystem Laboratory

[Keywords (six or less)] sulfur-oxidation, iron-oxidation, deep biosphere, IBM, Chikyu, new drilling and post-drilling technology

[TEXTBODY] The upper ~500 m of igneous ocean crust is fractured and permeable, harboring the largest hydrologically active aquifer on Earth. Most of the oceanic crust is hydrologically active (at least 60%; Fisher, 2005), with a fluid flux through the crust that rivals global riverine input to the oceans (Wheat et al., 2003). Solutes and colloids (including microbes) circulate actively through the crustal aquifer, and the hydrothermal fluid circulations provide the spatially largest province where active subseafloor microbial communities would be sustained. Most of the subseafloor microbial components in the basaltic crusts are hypothesized to live with the chemolithotrophic metabolisms utilizing the unweathered sulfide and ferrous iron minerals in the basalt (Bach and Edwards, 2003). The IODP expeditions to explore such deep rocky microbial communities in the upper oceanic crusts have been conducted.

Would such deep rocky microbial communities be present only in the relatively young upper oceanic crusts? The key constraints are hydrological activity and energy sources. Here we would like to express our interest in the possible incidence of deep rocky microbial communities in the ultradeeep lithostratigraphic interfaces in the oceanic-to-continental (arc) crusts in the Izu-Bonin-Mariana subduction zone. The ultradeep drilling project of IBM arc crust is already proposed and approved in the IODP framework. In the project, there are four primary drilling sites proposed. We are now very much interested in a synergetic investigation of deep biosphere and solid earth initiatives at the proposed drilling site IBM4 (Figure 1). The site IBM4 is proposed to drill maximally down to 5500 m below seafloor (mbsf) (Figure 1). The site is expected to consist of 8 lithostratigraphic units based on the seismic survey of subseafloor structure and the 8 units are further classified into the upper crust such as sediments, volcanic deposits, andesite lava and the middle crust of intermediate pluton (Figure 1). The sequence of these different lithostratigraphic units provides multiples inter-units discontinuities and interfaces based on their different physical and chemical properties. The inter-units boundaries also serve as active hydrologic regimes driven by the different thermal histories and capacities. This implies that the inter-units boundaries at the Site IBM4 would be excellent habitats of deep chemolithotrophic microbial communities sustained by the rocky energy sources such as unweathered sulfide and ferrous iron minerals. In addition, the predicted temperature gradient of the Site IBM4 shows that the deepest and second deepest interfaces at around the upper and middle crusts are still within the possible habitable temperature range below 125 ˚C and probably host potentially hyperthermophilic chemolithotrophic microbial communities (Figure 1). The hypothesized felsic and basaltic volcanic activities and the plutonic magmatisms may induce numerous fractures and ruptures of lava and crustal rocks at the seafloor and the deep curst and may provide not only the indigenous rocky energy sources (sulfide and Fe(II)) and magmatic volatiles (sulfide, COS and CO) but also the additional mechanochemical energy sources (H_2) and even the serpentinization-driven energy sources (H_2 and CH_4) although they are not so abundant.

At Site IBM4, the riser-drilling operation is proposed. To achieve and maximize multidisciplinary scientific objectives for deep biosphere and solid earth initiatives, we would like to propose synergetic operation strategies of logging, drilling and post-drilling investigations. First, LDW survey will be conducted to the full depth of Site IBM4 and the mud-fluid chemical analyses will be simultaneously performed. The LWD survey and the mud-fluid analyses can identify the locations of inter-units boundaries, representative staratigraphic units and specific biologically active zones. After the LWD survey, the side-wall drilling and coring operation of the LWD hole will be adopted for the specific depths of interests. The multiple side-wall cores can be obtained by this operation. These multiple cores will be applied to the hard rock, fluid and biological researches. Furthermore, the hole should be cased and the post-drilling physical, chemical and microbiological observatory should be established as a window to the ultradeep rocky world for the future revisit and research of the drilled hole. These well designed synergetic strategies for ultradeep logging, drilling and post-drilling investigations will provide great insights into understanding ‘Earth Connections: Deep Processes and Their Impact on Earth’s Surface Environment’ and ‘Biosphere Frontiers: Deep Life, Biodiversity, and Environmental Forcing of Ecosystems’ declared in the Science Plan for 2013-2023 of IODP.

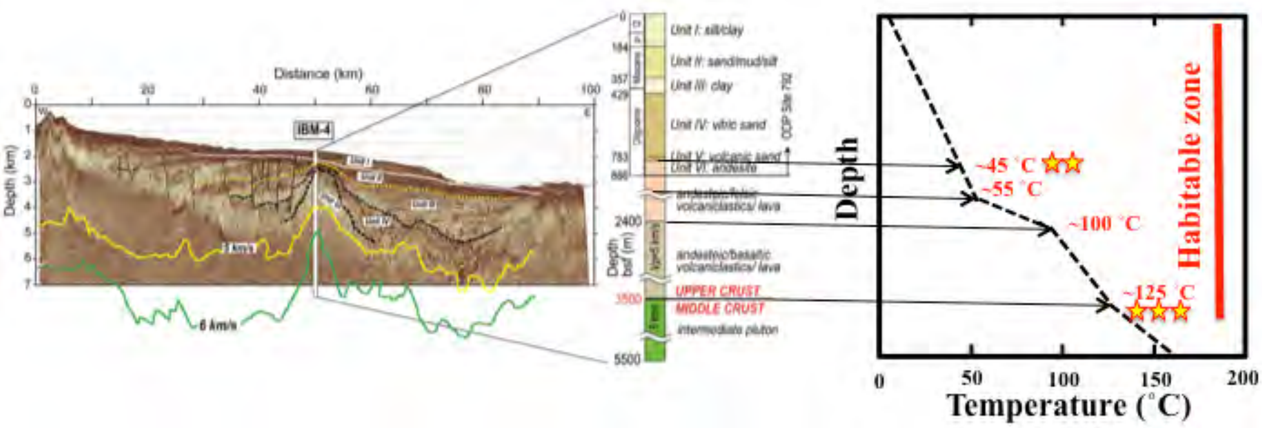


Figure 1. The proposed drilling site IBM4 and the predicted subseafloor structure, lithostratigraphic units and the temperature profile. All the inter-units boundaries are within the habitable temperature range below 125 ˚C and may provide the ultradeep rocky habitats for chemolithotrophic microbial communities.

Ultra-Deep Drilling into Arc Crust: Workshop report from Hawaii, September 2012

Yoshihiko Tamura[1], Shuichi Kodaira[1], James B. Gill[2] and Susan M. DeBari[3]

[1]JAMSTEC, [2]University of California, Santa Cruz and 3Western Washington University

[Keywords] Project IBM, Hawaii workshop, subduction zone, continental crust, IBM-4, 698-full3

[TEXTBODY] (11 pt, left-aligned) including figures

A workshop entitled "Ultra-Deep Drilling Into Arc Crust ~Genesis of continental crust in volcanic arcs~" was held at Kona, Hawaii from September 18 to September 21, 2012. This workshop aimed to gather a wide range of geophysicists, geologists, geochemists and petrologists who are interested in the nature of arc crust and how this is modified in collision zones and preserved in continental crust. Our goal has been to discuss the merits, methods and implications of "ULTRA-DEEP DRILLING INTO ARC CRUST" from both thematic (formation of continental crust) and regional (Izu-Bonin-Mariana) scope. We had 58 participants from 9 countries around the world. All participants got involved in discussion and in writing the workshop report. This Hawaii workshop report can be downloaded both as pdf (6 MB) and as word file (21 MB) from the workshop website (http://www.jamstec.go.jp/ud2012/).

Group photo of workshop participants at Waikoloa Beach Marriott Resort & Spa on September 21, 2012.

The scientific objectives of ultra-deep drilling into arc crust were discussed and revised based on the new findings obtained since the submission of the original proposals of Project IBM (695-Full2, 696-Full4, 697-Full3 and 698-Full3). Many of the attendees of the workshop have not been involved in these drilling proposals. Thus fresh ideas from young scientist and input from geologists who study exposed arc sections have widened the scientific objectives of the ultra-deep drilling. Most importantly, we are all eager for the drilling of IBM-4 (698-Full3). The workshop report is a comprehensive package of science and drilling strategy, which includes possible drilling cost and options. The following is a list of the topic in the workshop report:

- Geophysical overview of the Izu-Bonin-Mariana arc-back-arc system
- New ages of IBM basement and its implications for subduction initiation
- The generation of intermediate (andesitic) magmas and their relevance to growth of continental crust
- Using exposed arc sections in conjunction with IBM deep crustal drilling to understand the generation and growth of arc crust, and transferability to other active arc settings
- Models of crustal evolution in the oceanic arc and its collision: key observations and questions for the future IBM research
- Reasonable estimates of IBM-4 temperature at proposed TD = 5.5 km mbsf
- Utilization of downhole logging for deep drilling into arc crust
- Ultra-deep drilling options
- What should be the scientific objectives for deep ocean drilling?
- What at-sea drilling strategies and what shore-based studies are needed to achieve the scientific objectives?

The Workshop report, IODP proposals of the project IBM (695-Full2, 696-Full4, 697-Full3 and 698-Full3), and abstract of the attendees can be downloaded from http://www.jamstec.go.jp/ud2012/.

Plutonic & Volcanic Contributions to Crustal Genesis in Island Arcs

Gene M. Yogodzinski[1], Peter B. Kelemen[2], Kaj Hoernle[3], Esteban Gazel[4]

[1] University of South Carolina; [2]Lamont Doherty Earth Observatory; [3]GEOMAR, Helmholtz Center for Ocean Research; [4]Virginia Tech University

Keywords: IBM arc, deep drilling, Aleutian, plutonism, volcanism, magnesian, high-Sr

Drilling to the mid-crust of the Isu-Bonin Mariana (IBM) arc provides an outstanding opportunity to test ideas about crustal genesis in island arcs, and about the roll of arc magmatism in the formation of continents. The IBM arc is an ideal place to pursue this exciting and challenging project, because it is widely recognized as an end-member among active arcs on earth today, where melting is concentrated in a geochemically depleted mantle wedge, and where the volcanic output of the arc is dominantly basalt (Elliott et al., 1997; Tollstrup et al., 2010; Kelemen et al. 2003).

In the IBM arc, and in similar arcs worldwide, basaltic andesite, andesite, dacite and higher silica volcanic rocks are present in progressively smaller volumes, and are interpreted to be the products of basalt evolution by fractional crystallization and related processes (Gill, 1981; Tatsumi et al. 2008). The volcanic products of these processes show a strong clustering of compositions along a tholeiitic trend of sharply increasing FeO*/MgO with more slowly increasing SiO_2 from basalt to basaltic andesite. This trend for IBM volcanic rocks is important, because it is divergent from calc-alkaline evolutionary pathways for basalt, that are required to produce the composition of average continental crust, which by most estimates is andesitic, with 56-64% SiO_2 and FeO*/MgO~1.5 (Mg#~0.50). Trace elements patterns for IBM volcanic rocks, are relatively flat on chondrite or MORB-normalized multi-element plots (Elliott et al., 1997; Tollstrup et al., 2010; Tamura et al., 2010 and references therein), and so are also unlike bulk continental crust, which is enriched in large ion lithophile elements such as Th, La and Ce, compared to less strongly incompatible elements, such as Y, Yb and Lu (Taylor & McLennan, 1995). Products of IBM volcanism are thus systematically and broadly different from bulk continental crust in ways that require additional processes that might link IBM-type arc crust to the genesis of continents.

Plutonic contributions to IBM crust also appear to be a generally poor geochemical match to continental crust. The dominant gabbros and tonalites of the Tanzawa Plutonic Complex have generally unfractionated trace element patterns, with La/Yb that is approximately chondritic, and only modest enrichments of K, Rb, Ba and Th over La (Kawate & Arima, 1998). The Kofu Granitic Complex, which is more K-rich, and composed primarily of granodiorite and granite, have more fractionated trace element patterns and are geochemically closer to average continental crust, but these Miocene-age rocks are produced not by subduction, but during collision of the northern IBM arc with the Honshu arc (Saito et al., 2007).

An additional possibility is that plutonic rocks in the mid-crust of the IBM arc have compositions that are systematically different from the volcanic rocks that dominate the upper crust and our ideas about magma genesis and evolution. This appears to be the case in the Aleutians, where Eocene and Miocene-age plutons have higher average SiO_2 and are more magnesian (higher Mg#, lower FeO*/MgO) than average Aleutian volcanic rocks. This means that Aleutian plutons are more calc-alkaline than Aleutian volcanic rocks, and so are more similar to bulk continental crust (Kay et al., 1990; Kelemen et al., 2003; Kelemen et al. 2012a,b). If calc-alkalinity in magmatic systems is a reflection of elevated water content and perhaps oxygen fugacity (Sisson and Grove, 1993; Zimmer et al., 2010), then it is logical to conclude that magmas that do not erupt (plutonic rocks) may often be more calc-alkaline than the magmas that do erupt (volcanic rocks). The key effect of high water content is on the shape of the solidus, which will shift dramatically as magmas rise and degas, and undergo rapid, decompression-induced crystallization (Sparks and Pinkerton, 1978). Drilling into the IBM crust will provide an unprecedented opportunity to compare plutonic rocks emplaced in the mid-crust with Quaternary and Neogene-age volcanic rocks in the same location. If plutonic bodies in the IBM mid-crust are shown to be distinctly more calc-alkaline, and to contrast IBM volcanic rocks, then a possible mechanism connecting IBM magmatism to the genesis of continental crust will have been established. This mechanism will involve the emplacement of a more hydrous, silica-rich and more calc-alkaline igneous series in the mid-crust than the one that is expressed by IBM volcanism.

The opportunity to probe the IBM crust by drilling is particularly exciting in light of recent discoveries in the western Aleutians, where seafloor volcanism has produced a highly calc-alkaline igneous series in a purely oceanic setting. The broadly calc-alkaline nature of western Aleutian volcanism can be seen in the compositions of all samples collected west of the central Aleutian Adak area, which contrast sharply with IBM volcanic rocks, both in terms of average SiO2, and with respect to FeO*/MgO or Mg# (Kelemen et al., 2003). These characteristics reflect along-arc changes in major element compositions for Aleutian lavas, which have been linked to changes in primitive (high-Mg#) magma types, which are basaltic in the east and andesitic in the west (Kelemen et al., 2003).

The end-member expression of western Aleutian calc-alkalinity is in lavas dredged from volcanic cones on the seafloor west of Buldir Volcano, the western-most emergent volcano in the Aleutian system. These lavas span the compositional range from basalt to rhyodacite, but are mostly primitive (Mg#>0.60) and show little variation in Mg# or FeO*/MgO (Yogodzinski et al., 2011). The abundance of amphibole phenocrysts and absence of plagioclase from andesitic lavas containing as much as 60% SiO_2 confirm that many western Aleutian seafloor lavas have unusually high water contents, consistent with their highly calc-alkaline character. Isotope and trace element data indicate that the highly calc-alkaline series defined by western Aleutian seafloor lavas was not produced by fractional crystallization of primitive basalt, but more likely by mixing among primitive (high-Mg#) magmas with widely varying SiO_2 content. The high-Sr and highly fractionated trace element patterns and MORB-like isotopic compositions of dacites and rhyodacites in the series require a strong contribution from melts of subducted basalt that left a garnet and rutile-bearing residual mineralogy. This source component is most strongly expressed in the western Aleutians, but isotope-trace element mixing patterns demonstrate that it is present in lavas from all parts of the arc. If a similar source component is present in some IBM lavas, as proposed by Tollstrup et al. (2010), then it is reasonable to hypothesize that this component may be more strongly expressed in calc-alkaline plutonic bodies emplaced in the IBM mid-crust than in the overlying volcanic rocks. Deep drilling to the IBM mid-crust will provide an unparalleled opportunity to test this hypothesis.

References

Elliott, T., Plank, T., Zindler, A., White, W., Bourdon, B., 1997. Element transport from slab to volcanic front at the Mariana arc. Journal of Geophysical Research, 102: 14,991-15,019.

Gill, J., 1981. Orogenic Andesites and Plate Tectonics. Springer-Verlag, New York, 390 pp.

Kawate, S., Arima, M., 1998. Petrogenesis of the Tanzawa plutonic complex, central Japan: Exposed felsic middle crust of the Izu-Bonin-Mariana arc. The Island Arc. 7, 342-358

Kay, S.M., Kay, R.W., Perfit, M.R., 1990. Calc-alkaline plutonism in the intra-oceanic Aleutian arc, Alaska. In: Kay, S.M., Rapela, C.W. (Eds.), Plutonism from Antarctica to Alaska: Geological Society of America Special Paper 241, Boulder, pp. 233-255.

Kelemen, P.B., Yogodzinski, G.M., Scholl, D.W., 2003. Along-strike variation in lavas of the Aleutian Island Arc: Implications for the genesis of high Mg# andesite and the continental crust. In: Eiler, J. (Ed.), Inside the Subduction Factory, Geophysical Monograph 138. Washington D.C., pp. 223-276.

Kelemen, P.B., Hacker, B.R.,Behn, M., Jagoutz, O., 2012. Ongoing formation of continental crust: Batholiths are forever, Goldschmidt Conference Abstract

Kelemen, P., Behn, M.D., Jagoutz, O., 2012. Rethinking recycling in arcs, AGU Fall Meeting, V31E-04.

Saito, S., Arima, M., Nakajima, T., Misawa, K. & Kimura, J.-I., 2007. Formation of distinct granitic magma batches by partial melting of hybrid lower crust in the Izu arc collision zone, Central Japan. J. Petrol. 48: 1761-1791.

Sisson, T.W., Grove, T.L., 1993. Experimental investigations of the role of H_2O in calc-alkaline differentiation and subduction zone magmatism. Contrib Mineral and Petr, 113: 143-166.

Sparks, R.S.J., Pinkerton, H., 1978. Effect of degassing on rheology of basaltic lava. Nature, 276: 385−386.

Tamura, Y., Ishizuka, O., Aoike, K., Kawate, S., Kawabata, H. Chang, Q., Saito, S. Tatsumi, Y., Arima, M. Takahashi, M. Kanamaru, T., Kodaira, S.. and Fiske, R., 2010. Missing Oligocene crust of the Izu-Bonin Arc: Consumed or rejuvenated during collision? J. Petrol. 51: 823-846.

Tatsumi, Y., Shukuno, H., Tani, K., Takahashi, N., Kodaira, S., Kogiso, T., 2008. Structure and growth of the Izu-Bonin-Mariana arc crust: 2. Role of crust-mantle transformation and the transparent Moho in arc crust evolution. J. Geophys. Res. 113: B02203, doi:10.1029/2007JB005121.

Taylor, R.S., McLennan, S.M., 1995. The Geochemical Evolution of the Continental Crust. Reviews of Geophysics, 33(2): 241-265.

Tollstrup, D. et al., 2010. Across-arc geochemical trends in the Izu-Bonin arc: Contributions from the subducting slab, revisited. Geochemistry Geophysics Geosystems, 11(1): 27.

Yogodzinski, G.M., Arndt, S., Turka, J., Kelemen, P.B., Vervoordt, J.D., Portnyagin, M., Bindeman, I., 2011. Nature and Significance of the High-Sr Aleutian Lavas. Eos − AGU Fall Meeting, V32C-02

Zimmer, M.M. et al., 2010. The role of water in generating the calc-alkaline trend: New volatile data for Aleutian magmas and a new tholeiitic index. Journal of Petrology, 51(12): 2411-2444.

Santa Barbara Basin: A Key Global Climate Reference Site and Ultra-High-Resolution Quaternary Archive

Richard J. Behl[1], Craig Nicholson[2] and James P. Kennett[2]

[1]California State University-Long Beach, USA, and [2]University of California-Santa Barbara, USA

[Keywords] paleoclimate, sub-decadal resolution, continuous mid-latitude Quaternary record

Orbital through submillennial-scale climate variability during the Quaternary, including abrupt global warming, was driven by processes yet unexplained. The existence of large and rapid change suggests that internal feedback mechanisms play a crucial role in setting the sensitivity of the climate system and creating or amplifying major change at all time scales. Hypotheses proposed to account for millennial-scale cycles during the last 150 kyrs are numerous but include: (1) changes in deep and intermediate thermohaline circulation related to Northern Hemisphere ice sheet instabilities; (2) changes in tropical heat distribution; and (3) increase in greenhouse gas concentrations in the atmosphere from reservoirs of CO_2 and CH_4. Development of high quality, well-dated, climate reference sites spanning a broad and continuous range of climate conditions is an essential prerequisite for testing these hypotheses and developing new ones and is one of the highest priority research themes of the *IODP Science Plan*. This is why Santa Barbara Basin (SBB) is so important. Its unique geologic and oceanographic setting is highly sensitive to changes in global climate, ocean circulation, and the oxygen minimum zone. ODP Site 893 in SBB provided one of the highest-resolution climate archives of the late Quaternary available from the world's oceans (Fig.1a). Oxygen isotopic, sedimentologic and microfossil results reveal a remarkable correlation of climate change between SBB and the Greenland Ice Sheet during the last 70 kyr (Fig.1A). Site 893 was safely drilled in 1992 to ~200 mbsf as a hole-of-opportunity, and although it has provided data crucial to understanding climate behavior since ~160 ka, this continuous basin record has not yet been extended with deeper drilling. It is now feasible to extend this remarkable ultra-high-resolution global climate record with the riser capabilities of the *Chikyu*. Existing subsurface data and recent sampling prove that SBB can provide a high-fidelity, continuous paleoclimatic and sedimentary geochemical marine record back to ~1.5 Ma at millennial to sub-decadal time scales (Fig.1C) with deeper drilling. This record offers unprecedented resolution to evaluate abrupt climate and ocean variability within the context of the Quaternary evolution of the global climate system, including the mid-Pleistocene climate transition when Earth entered the ~100-kyr glacial-cycle regime. Previously, a highly ranked IODP proposal (705-full2) was approved by SPC and submitted to OTF for potential riserless drilling. Deeper drilling using riser capability has always been included in the strategy of the proposed science plan to address any possible safety considerations with riserless penetration. By coring 1500–1800 mbsf in SBB, the *Chikyu* can rapidly recover what will likely be the world's highest-resolution, continuous paleoclimate and paleoceanographic record extending back to ~1.2-1.5 Ma. The unique qualities of the SBB record are both extensive and compelling. They include: (1) Unusually high and remarkably constant rates of sedimentation (>120 cm/kyr) unaffected by changes in global climate; (2) An abundance of planktonic and benthic microfossils sensitive to changes in surface and intermediate water masses originating in both subpolar and tropical regions of the Pacific. High biogenic productivity prevents detrimental dilution by terrigenous sediment; (3) Seasonal variation in sediment composition form annual laminations or varves (Fig.1B), with similar laminations found even in Pliocene-age sediments in SBB; (4) Low oxygen concentrations of basinal bottom waters minimize bioturbation and alteration of carbonate and organic matter, thus preserving varved laminations and microfossils; (5) A mid-latitude location proven to be highly sensitive to abrupt changes in ocean and atmospheric circulation and temperature; (6) A long term record of changes in the oxygen minimum zone in the north Pacific; (7) Abundant pollen, providing high-resolution marine and terrigenous climatic records from the same core; (8) A sufficiently preserved paleomagnetic signal to provide a complete record of magnetic secular variation; and (9) A well understood site suitable for geochemical and microbiological evaluation of subsurface fluid flow, diagenesis and evolution of the subseafloor biosphere. For all these reasons, Santa Barbara Basin can provide continuous, ultra-high-resolution paleoclimate and paleoceanographic records back to ~1.5 Ma at millennial to centennial to decadal and perhaps even annual time scales for potential correlation around the circum-Pacific and beyond. Such records would provide unprecedented insight into the evolution and operation of Earth's climate system and climate variability, and the processes driving abrupt global climate change.

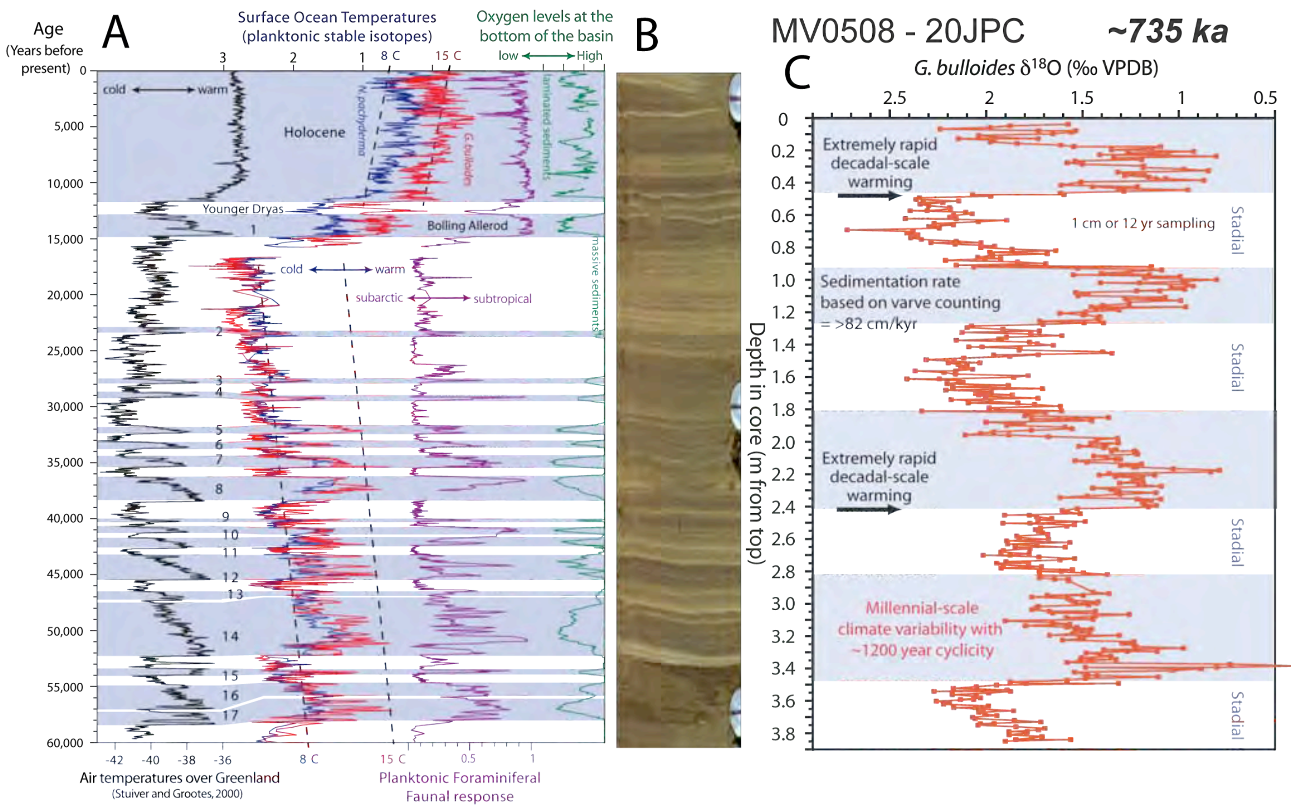


Figure 1. (a) Comparison of $\delta^{18}O$, planktonic assemblages, and laminations from ODP Site 893 in Santa Barbara Basin with air temperature over Greenland; (b) Section of Core MV0508-7 (~300 ka) showing annual (varved) laminations; (c) isotopic record from Core MV0508-20 (~735 ka) showing a distinct 1200-yr stadial-interstadial oscillation that had not been previously recognized owing to a previous lack of paleoclimate data of comparable age and resolution.

Cretaceous-Cenozoic sedimentary basins of New Zealand: insights into global ocean and climate change and regional tectonics

Greg Browne and Chris Hollis
GNS Science, New Zealand
Keywords sedimentary drilling, climate change, New Zealand

New Zealand lies at the interface between Antarctic and Tropical drivers of climate change, as it has done through much of the Cenozoic. In early Cenozoic and Cretaceous time, the Zealandia landmass was situated closer to the Antarctic margin. From the mid-Cretaceous to Early Miocene, thermal relaxation across a vast passive margin led to accumulation of a thick sedimentary succession of largely transgressive sediments extending over ~30° of latitude, from the Campbell Plateau and Great South Basin in the south to the Lord Howe Rise and North Slope Basin in the north.

Whilst the onshore and shallower offshore basins have been subject to many years of geological study, knowledge of the deep offshore basins is based almost exclusively on seismic surveys. Scientific drilling and petroleum wells are limited to a few isolated areas. Targeted drilling of Cretaceous-Cenozoic successions in selected basins will greatly advance our understanding of the depositional and tectonic history of these basins. It will provide new insights both of the local geology and of the broader Southwest Pacific region, and provide an unparalleled history of ocean and climate change over the past 100 million years.

Because of the thickness of sediments and the potential for hydrocarbons, the riser drilling capability of the Chikyu is ideally suited to exploring these basins. We highlight several areas that might form the basis of future drilling proposals, namely in the southeast and northwest margin of the country. Key science questions and challenges for each prospective drilling region are discussed.

Deep-sea Record of Mediterranean Messinian events (DREAM)

Camerlenghi, A.[1], Lofi, J.[2], deLange, G.[3], Flecker, R.[4], Garcia-Castellanos, D.[5], Hübscher, C.[6], Krijgsman, W.[3], Lugli, S.[7], Manzi, V.[8], McGenity, T.[9], Panieri, G.[10], Rabineau, M.[11], Roveri, M.[7], and Sierro, F.J.[12]

[1] OGS National Institute of Oceanography and Applied Geophysics Trieste Italy, [2] Géosciences Montpellier – UMR5343 Université de Montpellier 2 Montpellier France, [3] Faculty of Geosciences University of Utrecht Utrecht The Netherlands, [4] School of Geographical Sciences Bristol University United Kingdom, [5] Institute of Earth Science Jaume Almera – CSIC Barcelona Spain, [6] Institute for Geophysics, University of Hamburg Hamburg Germany, [7] Department of Physics and Earth Sciences Università di Parma, Italy, [8] Department of Earth Sciences, University of Modena and Reggio Emilia Modena, Italy, [9] School of Biological Sciences, University of Essex United Kingdom, [10] ISMAR Institute of Marine Sciences CNR Bologna Italy, [11] CNRS, Institut Universitaire Européen de la Mer (IUEM) de Plouzané Brest, France, [12] Department of Geology, University of Salamanca Salamanca, Spain

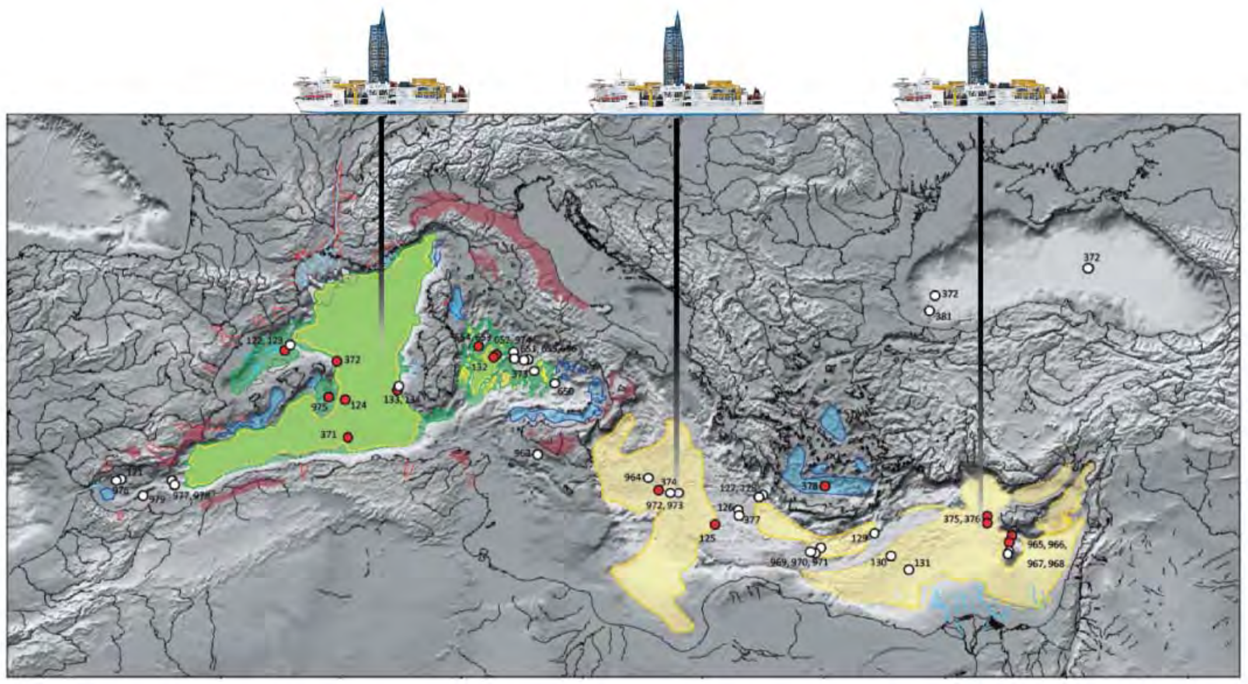
[Keywords] Mediterranean, Messinian, evaporites, salinity crisis, riser-drilling

The scope of this white paper is to promote multi-site riser-drilling in the Mediterranean Sea designed to solve enduring questions concerning the causes, processes, timing and regional and global consequences of an extreme environmental event in recent Earth history: the Messinian salinity crisis (MSC). The DREAM initiative draws on recent activity by various research groups and aims to identify potential sites to perform deep-sea research drilling in the Mediterranean Sea across the deep Messinian sedimentary record.

About 6 million years ago the Mediterranean Sea was transformed into a giant saline basin, one of the largest in the Earth's history and demonstrably the youngest. This event, commonly referred to as the MSC, changed the chemistry of the global ocean and had a permanent impact on both the terrestrial and marine ecosystems of peri-Mediterranean regions. The first fascinating and successful MSC scenario derived from DSDP Leg XIII in 1970. This hypothesis described an almost desiccated, deep Mediterranean basin with a dramatic ~1,500 m drop in sea level; deeply incised river canyons extending onto the exposed continental margins; and a final catastrophic flooding event when the Mediterranean-Atlantic connection was re-established in the earliest Pliocene, 5.33 Ma. During the ensuing 42 years, more than 1800 scientific publications concerning the MSC have been produced, about 900 in the last 10 years alone, demonstrating the enduring scientific interest and importance of this event. Analysis of marginal outcrop data and sparse DSDP and ODP samples, in parallel with the interpretation of the deep basin's seismic record and substantial climate, chemical and geophysical modelling have failed to provide a unified and coherent understanding of the Messinian event. This is mainly because previous DSDP and ODP expeditions in the Mediterranean basin, were able to drill only the topmost part (generally <80 m) of the deep basin MSC succession, commonly with low core recovery. Since the total thickness of the offshore MSC series exceeds 2,000 m, we are lacking lithologic and stratigraphic control on 95% of the MSC succession effectively preventing onshore-offshore correlation and basin-wide model development. The Chikyu riser-drilling technology now offers the opportunity to address this fundamental problem.

In this context, three generations of scientists (those who participated in the discovery, those who are at present actively involved in research, and the next generation) will meet in Italy, in May 2013 as part of the ECORD MagellanPlus Workshop Series Programme. Setting aside enduring controversies, this team will work together to identify the best locations for multi-site drilling to address the key MSC questions. Using existing seismic data sets and the present operational capability of IODP vessels, the workshop will deliver a structured experimental design comprising site characterization, riser-less and riser drilling, sampling, measurements, and down-hole experiments that will be the basis of at least one compelling and feasible multiple phase drilling proposal. Particular focus at the workshop will be given to reviewing existing seismic site survey data available from different research groups at a pan-Mediterranean basin scale, and identifying the need for additional site survey activity including 3D seismics.

"95% of the offshore MSC deposits are still unexplored"



This initiative is envisaged as the beginning of the largest co-ordinated research on the Messinian Event since its discovery over forty years ago. DREAM aims to result in the submission of at least one IODP drilling proposal to drill the MSC deposits; to promote additional seismic surveys to identify new drilling sites; and to engage new communities and existing science projects with this vision of future drilling (e.g. IODP Exp. 339, MEDGATE project, DS^{3}F Project, industry). The DREAM initiative complements the GOLD initiatives where the objective is deep drilling down to Western Mediterranean Basin basement, since multiple-site drilling is mandatory for resolving the enduring questions concerning the MSC.

UNDERSTANDING WARM CLIMATE DYNAMICS BY DRILLING WESTERN PACIFIC MUD DRIFTS

Min-Te Chen[1],Shengfa Liu[2], Xuefa Shi[2]

[1]Institute of Applied Geosciences, National Taiwan Ocean University, Keelung, Taiwan and [2] First Institute of Oceanography, State Oceanic Administration, Qingdao, China

Interglacial, Kuroshio, ENSO, Western Pacific, Mud drift, Hydrological cycle

Understanding the climate dynamics of past warm climate periods is essential in unraveling why and how the present warm climate has been persisted for ~10,000 years. Reconstructing the full spectrum of warm climate dynamics is required, in particular, to predict how the Earth's climate will evolve naturally with unprecedented anthropogenic influences by the increased greenhouse gases. The marine sediments preserved in western Pacific marginal seas (e.g. East China Sea, Yellow Sea, Bohai Sea) provide such natural archives for reconstructing and understanding past warm climate (interglacials). Marine transgressions caused by glacio-eustatics during past warm climate in the past 2-3 Myr help deposit high sedimentation rate mud drifts. The mud drifts contains multiple paleoclimatic proxies, and under the best, newly advanced age constraint methods (geomagnetisms, biostratigraphy, and radiogenic dating), will be able to use as high-resolution marine climate records of orbital, millennial/centennial to multi-decadal time scale. New IODP riser drilling down to few hundred meters into the mud drifts, where natural oil and gas are also possibly formed, will help obtain new marine climate records from the mud drift areas. The mud drift records from the western Pacific marginal seas are proposed here to drill and could be used to evaluate what roles, for example, the Kuroshio, PDO, and ENSO had been played in interacting or impacting the warm global climate since early Quaternary.

MESOZOIC GLOBAL ENVIRONMENTS

Millard F Coffin[1]

[1]Institute for Marine and Antarctic Studies, University of Tasmania, Private Bag 129, Hobart, Tasmania 7001, Australia

Keywords: paleoceanography, paleoclimate, greenhouse Earth, large igneous provinces, oceanic anoxic events, Mesozoic

Old oceans have disappeared and new oceans have been created repeatedly in Earth history. Associated changes in continental distribution, oceanic circulation, and episodic magmatism (large igneous provinces) have been implicated in altering paleoclimate, paleoceanography, and sea level, as well as in forcing biological changes. In Cretaceous time, the two major oceans—Tethys and the Pacific—differed enormously. Prior to Aptian time, Tethys was characterized by massive carbonate deposition, whereas radiolarian clays dominated the Pacific. In mid-Cretaceous time, Tethyan waters contained little oxygen, as recorded by black shales, whereas deep Pacific waters were well oxygenated. We seek to understand why these oceans differed in Mesozoic time, as well as more generally to determine the climatic process(es) that operated in Cretaceous time, the mechanism(s) that sustained the extremely warm Greenhouse Earth, and the process or event that terminated the Greenhouse climatic pattern (eg, cessation of global circum-equatorial circulation). Specific goals in studying the Mesozoic sedimentary record in the ocean are to investigate: the dominant Milankovitch frequencies during the Greenhouse; the operation of and variation in biogeochemical cycles; the effects of evolution, radiations, and extinctions on carbonate cycling; the variation in locus of carbonate cycling and budgets between continental shelves and the open ocean; the variation of the carbonate compensation depth (CCD); the balance between oceanic and continental chemical fluxes; and the history of and processes affecting oxygenation, in particular oceanic anoxic events (OAEs). Drilling is the only means of obtaining the detailed Mesozoic sedimentary sections necessary to understand Mesozoic global environments, and environmental changes and their causes. Optimal site selection for attaining the scientific objectives of drilling Mesozoic sedimentary sections will require extensive regional 2D and local 3D multichannel and wide-angle seismic control of a quality and scale currently typical only in areas of intensive hydrocarbon exploration.

Unlocking the Secrets of Subsalt Sedimentary Environments

Hugh Daigle[1] and Brandon Dugan[2]

[1]Department of Petroleum and Geosystems Engineering, University of Texas at Austin, Austin, Texas, USA

[2]Department of Earth Science, Rice University, Houston, Texas, USA

Keywords: subsalt, pressure, stress, sediment

Subsalt sedimentary environments represent a frontier in ocean drilling as they have recently become a target for oil and gas exploration. There are many unknowns about the deposition and evolution of subsalt sedimentary units, what controls their physical properties, and how fluid, energy, and chemicals move through these systems. Riser drilling with *Chikyu* will help advance our understanding of these systems. Specific questions to answer are: What controls do sedimentary depositional processes have on rock properties? What are typical physical properties of these sediments? How heterogeneous are these sedimentary units? What controls pressure and stress in these systems? How do fluids, energy, and chemicals move through these systems? How are deposition and evolution affected by changes in eustatic sea level?

Deepwater depositional systems are spatially heterogeneous due to differences in source (turbidites, distal fans), accommodation (restricted to location of slope basins), and complex relationships between sediment supply and sea level. Subsalt environments are further complicated by stresses imparted by the mobile salt, thermal anomalies, elevated pore pressures, and chemical cycling associated with salt. Previous studies on sediment-salt interactions have largely focused on salt tectonics. Salt-related geophysical data, laboratory experiments, and numerical models have studied tectonics (Hudec and Jackson, 2007), earthquakes (Berberian, 1981), and impacts of salt deformation on deposition and deformation of overlying strata (Davis and Engelder, 1985; Maxwell, 2009). Sampling, which can better define and calibrate these earlier studies, has historically been quite limited. Another pertinent aspect that has been neglected is the interaction between sub-salt sediments and salt. Geophysical imaging provides some insight into subsalt environments, yet often lacks fidelity and samples. Detailed drilling, logging, and sampling with the D/V *Chikyu* will provide access to this frontier sedimentary environment such that we can understand its origin, evolution, and physical, thermal, and chemical properties. From this we can calibrate geophysical interpretations, and correlate differences in fluid motion and storage between sub- and supra-salt sedimentary environments. While unlocking these sediment secrets, we also constrain deep fluid, energy, and chemical fluxes which, provide clues to past deep marine environments and influence the deep Earth biosphere.

Chikyu drilling would focus on deep sites that have the potential for significant overpressure, therefore requiring a riser. This will allow for safe drilling through salt, and logging and coring operations in subsalt sediments. Drilling will focus on sites with known or suspected sands to allow for characterization of sand bodies and surrounding sediments. Potential drilling locations include but are not limited to the deepwater Gulf of Mexico, the South Atlantic Brazilian basins, and the Nova Scotia Shelf (Fig. 1). Many drilling strategies could evolve, but a primary objective would be to select offset sites that provide sampling beneath one salt sheet, but at different thickness, thus providing a range of sediment-salt interaction and potential thickness of the inferred stratigraphic section that may occur in these environments (Fig. 2).

Subsalt drilling is an ambitious venture, but also provides numerous opportunities for international collaboration between academics and industry. Many subsalt environments are being explored for their hydrocarbon potential, yet industry has basic questions that remain unresolved and parallel our scientific objectives. Therefore there could be multiple avenues for collaboration such as access to seismic data, monetary support to complete or extend objectives, or insights on drilling and sampling strategies. Subsalt drilling therefore has the potential to be fruitful both for the IODP and the scientific community at large.

Fig. 1. Locations of potential subsalt drilling locations. Basins marked are those referred to in text. NSS, Nova Scotia Shelf; DWG, deepwater Gulf of Mexico; SAB, South Atlantic Brazilian basins.

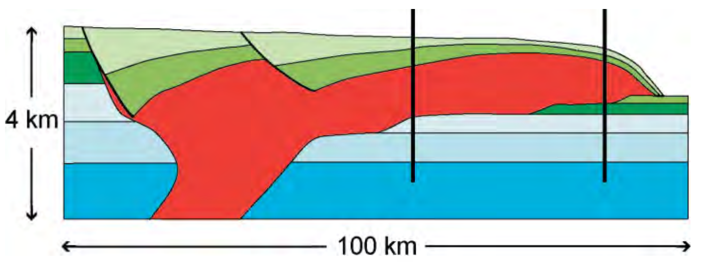


Fig. 2. Example drilling strategy for sampling of subsalt sediments. Drill sites are marked by black vertical lines. Green and blue layers are supra- and subsalt sediments; red is salt body. Example system dimensions are given. Modified from Hudec and Jackson (2006).

References

Berberian, M., 1981. Active faulting and tectonics of Iran, *Geodynamics Series*, 3, 33-69.

Davis, D.M., Engelder, T., 1985, The role of salt in fold-and-thrust belts, *Tectonophysics*, 119(1-4), 67-88.

Hudec M.R., Jackson, M.P.A., 2007, Terra infirma: understanding salt tectonics, *Earth-Science Reviews*, 82, 1-28.

Hudec, M.R., Jackson, M.P.A., 2006, Advance of allochthonous salt sheets in passive margins and orogens, *AAPG Bulletin*, 90(10), 1535-1564.

Maxwell, S.A., 2009. *Deformation Styles of Allochthonous Salt Sheets During Differential Loading Conditions: Insights from Discrete Element Models*, MS Thesis, Rice University, Houston, Texas.

THE LORD HOWE RISE REGION, SOUTHWEST PACIFIC: DRILLING TO UNLOCK CONTINENT AND OCEAN BASIN EVOLUTION AND RESOURCE POTENTIAL

Takehiko (Riko) Hashimoto, Andrew Heap and Clinton Foster
Geoscience Australia, GPO Box 378, Canberra ACT 2601 Australia
Keywords: Lord Howe Rise, Cretaceous, magmatic rift, continental breakup, petroleum potential

The Lord Howe Rise region is one of the world's largest remaining offshore frontiers for scientific research and resource exploration outside the polar regions. The submerged continental landmass covers an area of over 1,500,000 km^2 (Figure 1) and its geological history is poorly known, despite the fact that the region holds the key to global-scale plate tectonic events and environmental change during the Mesozoic and Cenozoic.

Figure 1. Location of the Lord Howe Rise region, southwest Pacific Ocean

Whilst Australian, New Zealand, and French science agencies have acquired geophysical data (largely seismic) from the area, the lack of deep stratigraphic drilling is a major roadblock to furthering our geologic knowledge of the Lord Howe Rise region. Deep stratigraphic drilling into the pre-Late Cretaceous succession will provide essential information to unlock the geological history of the region by targeting basins with the most regionally representative and complete stratigraphy, as identified from the latest studies. The stratigraphic record will reveal the evolution of a large, asymmetric continental rift and marginal ocean basins, and the associated magmatic history, and environmental change. The results will refine our understanding of crustal evolution during the major Cretaceous–Cenozoic plate tectonic re-organisation of the greater Pacific region, as well as changes in ocean circulation and biogeography arising from continental breakup, microcontinent submergence, and ocean basin formation. The stratigraphic record has the potential to provide insights into the geologic drivers and biospheric effects of the Cretaceous and Cenozoic 'Super-Greenhouse' conditions. It will also identify any potential petroleum system elements, i.e. source, reservoir and seal rocks, providing baseline information for petroleum prospectivity assessments.

Initial investigations between the 1960s and early 1980s established the baseline tectonic and stratigraphic framework of the region. Drilling by the Deep Sea Drilling Project (DSDP) in 1971 (Burns et al. 1973) and 1982 (Kennett et al. 1986) provided a stratigraphic benchmark for the post-Late Cretaceous succession in all subsequent studies undertaken in the region. In addition, petroleum industry reconnaissance during the 1970s, encouraged by the rising global energy demand and major hydrocarbon discoveries in the nearby Taranaki and Gippsland basins, resulted in the acquisition of reconnaissance seismic reflection transects. During the 1990s and early 2000s, the governments of Australia, New Zealand and France (New Caledonia) commenced data acquisition and interpretation to support maritime territorial claims under the United Nations Convention on the Law of the Sea 1982 (UNCLOS). A series of marine surveys, several undertaken collaboratively by the governments of the region, helped to build up a geoscientific data set of regional-scale reflection seismic, potential field and bathymetric data, limited rock and sediment samples, and associated geologic interpretations (e.g. Stagg et al., 2002). Interpretation of these data sets has contributed to a resurgence in scientific and petroleum exploration interest in the region since the 2000s, resulting in several government data acquisition initiatives, e.g. Australian government's New Petroleum (2003–2006) and Offshore Energy Security (2006–2011) programmes. Most recently, the Tasman Frontier project, an ongoing regional collaboration led by GNS Science, Geoscience Australia and Service Géologique de Nouvelle-

Calédonie, was initiated to facilitate the synthesis of scientific results and data access across the Australian, New Zealand and New Caledonian jurisdictions. The project released the Tasman Frontier Database in 2012, a first-ever, cross-jurisdictional compilation of open-file seismic reflection data (Sutherland et al., 2012), as an initial step to further encourage scientific and resource exploration interest in the region.

The latest phase of assessments has improved our understanding of the geologic evolution the Lord Howe Rise region, which is now believed to have evolved as a magmatic, asymmetric continental rift from the Late Jurassic or Early Cretaceous until the opening of the Tasman Sea ocean basin during the Late Cretaceous to Paleogene (e.g. Norvick et al., 2008; Collot et al., 2009; Colwell et al., 2010).. The studies have also indicated that some basins are likely to host petroleum systems and are capable of generating oil or gas. But despite these studies, the major barrier to further scientific understanding and promoting industry interest has been the complete lack of pre-Late Cretaceous stratigraphic control, which would confirm the timing of tectonic events and the composition of stratigraphic successions currently inferred from tectonic reconstructions and basin analogues. The DSDP sites 206–208 and 587–592 provide the only existing drilling data sets in the region, but the oldest section penetrated is Late Maastrichtian (i.e. latest Cretaceous). Moreover, the DSDP sites tended to target structural highs, where the stratigraphic successions were incomplete. As such, most of the Late Cretaceous, as well as the older successions, remain untested over the entire Lord Howe Rise region.

Recently acquired reflection seismic data indicate several locations within the Lord Howe Rise region where the pre-Late Cretaceous succession onlaps structural highs at depths of less than 3000 m from the seafloor. Some of these locations are constrained by two or more recent high-quality reflection seismic lines, reducing the scope of pre-drilling site surveys.

The Lord Howe Rise is a region where deep ocean drilling, using the vessel *Chikyu*, could bring about significant scientific breakthroughs in this vast and significant frontier area with no deep stratigraphic control. In addition, drilling could potentially generate economic benefits through identification of petroleum and other natural resources. A possible mechanism for such drilling is through intergovernmental collaboration between Japanese, Australian and other regional partners. Data will be made publicly available to enable access by the global geoscience research community and offshore petroleum industry.

References

Burns, R.E., Andrews, J.E., et al., 1973. Initial Reports of the Deep Sea Drilling Project 21, US Government Printing Office, Washington.

Collot, J., Herzer, R., Lafoy, Y. & Géli, L., 2009. Mesozoic history of the Fairway–Aotea Basin: implications for the early stages of Gondwana fragmentation. Geochemistry Geophysics Geosystems, 10 (2), Q12019, doi:10.1029/2009GC002612.

Colwell, J.B., Hashimoto, T., Rollet, N., Higgins, K., Bernardel, G. & McGiveron, S., 2010. Interpretation of Seismic Data, Capel and Faust Basins, Australia's Remote Offshore Eastern Frontier. Geoscience Australia Record, 2010/06, Canberra.

Kennett, J.P., von der Borsch, C.C., et al., 1986. Initial Reports of the Deep Sea Drilling Project 90, US Government Printing Office, Washington.

Norvick, M.S., Langford, R.P., Rollet, N., Hashimoto, T., Higgins, K.L. & Morse, M.P., 2008. New insights into the evolution of the Lord Howe Rise (Capel and Faust basins), offshore eastern Australia, from terrane and geophysical data analysis. In: Blevin, J.E., Bradshaw, B. E. and Uruski, C. (Eds), Eastern Australasian Basins Symposium III: Energy security for the 21st century. Petroleum Exploration Society of Australia Special Publication, 291–310.

Stagg, H. M. J., Alcock, M., Borissova, I. & Moore, A. 2002. Geological framework of the southern Lord Howe Rise and adjacent areas. Geoscience Australia Record, 2002/25, Canberra.

Sutherland, R., Viskovic, P., Bache, F., Stagpoole, V., Collot, J., Rouillard, P., Hashimoto, T., Hackney, R., Higgins, K., Rollet, N., Patriat, M. & Roest, W.R., 2012. Compilation of seismic reflection data from the Tasman Frontier region, southwest Pacific. GNS Science Report, 2012/01, Lower Hutt.

PHYSICAL PROPERTY PREDICTION USING SEISMIC MULTI-ATTRIBUTES

Senay Horozal[1], Deniz Cukur[2], Gil Young Kim[1]

[1]Korea Institute of Geoscience and Mineral Resources, Daejeon, Korea

[2]GEOMAR | Helmholtz Centre for Ocean Research Kiel, Kiel, Germany

Nankai Trough, seismic post-stack inversion, seismic multi-attribute, sediment physical property

Seismic multi-attribute analysis is primarily based on the use of linear or nonlinear correlations between seismic and well-log data for predicting the sediment physical properties in the subsurface. Post-stack seismic inversion is the procedure for extracting underlying models of the quantitative physical characteristics of rocks and fluids by combining seismic and well-log data such as density, sonic velocity, porosity, Gamma Ray and resistivity measurements. This is conceptually achieved in two steps: inversion of the seismic signal to produce a measurement of an underlying elastic property (such as impedance, velocity, density, or Poisson's Ratio), and conversion of the measured elastic property using rock physics to a geologic property (lithology, porosity, saturation). A study of physical property prediction was performed using the borehole log data of the Nankai Trough IODP Expedition 319 at Site C0009A in the Kumano forearc basin by integrating with a 2-D seismic reflection section that traverses the drilling site across the Nankai subduction zone. Using the dataset consisting primarily of digital logs and seismic data, correlations can be made between seismic attributes and physical properties (porosity, density, p- and s-wave velocity and Vp/Vs), and those relationships can be exploited to predict the distribution of the property of interest in two dimensions (Fig. 1). T-D correlations with synthetic seismograms are crucial for tying well logs to the seismic data. Because a correct seismic-to-well tie is needed to perform the following multi-attribute analysis. The multi-attribute physical property prediction can lead insights to the seismogenic behavior of the sediment properties and the evolution of the forearc basin and accretionary prism. Model-based inversion can employ three different prediction techniques; linear multiattribute regression, probabilistic neural network (PNN), and multi-layer feed network (MLFN) can be performed to generate physical properties correlating well-logs and seismic attributes. It can be concluded that probabilistic neural network analysis gives the best correlations in predicting sediment properties based on the case study results. Seismic multi-attribute analysis can be used to predict physical property volumes using 3-D reflection data with high well control. 3-D post-stack seismic inversion using 3-D seismic reflection and IODP drilling data of the Nankai Trough can be suggested for a detailed and comprehensive study of the sediments of seismogenic zone.

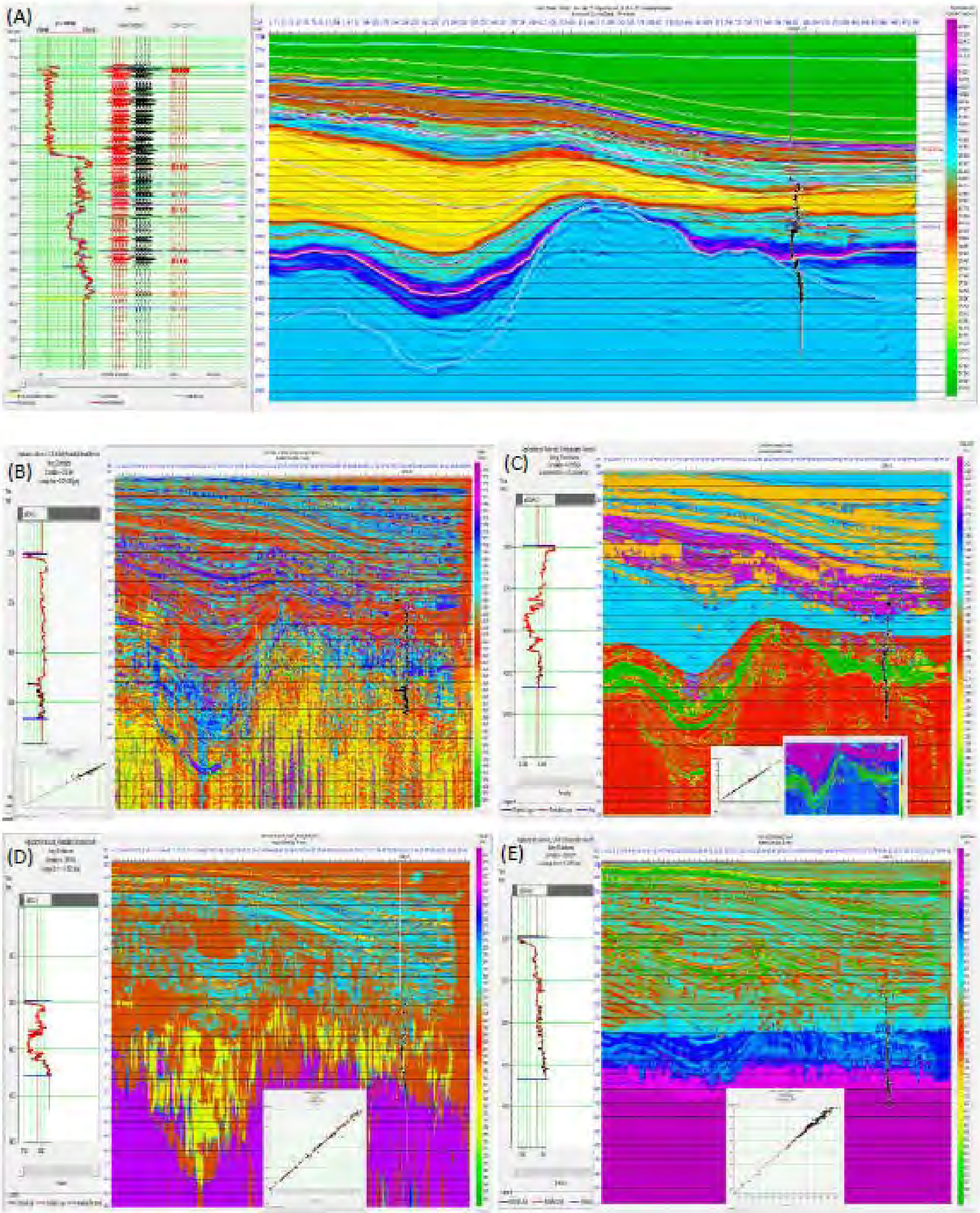


Figure 1. (A) Model-based inversion of acoustic p-impedance. (B) Density prediction converted from pimpedance. (C) Porosity prediction. (D) P-wave prediction. (E) S-wave prediction.

CHANGES IN THERMAL PROPERTIES WITH LITHIFICATION

Young-Gyun Kim[1]

[1]Seoul National University

geothermal gradient, thermal conductivity, lithification, physical properties

Lithification of sediments into rocks is common geological processes but, in general, is not considered when estimating temperature within sediment despite of its large effect on thermal regime. Conventionally, temperature within the top several hundred-meter sediments is estimated based on a linear geothermal gradient which stems from either a few measured points at deep drilling and/or results of surface measurement. This way is preferred by its cost-effectiveness because an assumption that change of physical properties, especially in thermal conductivity, with depth is not significant is applicable to depth interval above which lithification occurs. In general thermal conductivity change with depth can be approximated by porosity change which is also an important parameter reflecting extent of lithification. Abrupt increase in thermal conductivity during lithification may lead to decrease of geothermal gradient. That is, temperature estimate below the depth interval where lithification occurs shows large disparity from actual temperature without careful consideration of characteristics of lithification. Such feature is clearly shown from results at Site U1352 (IODP Exp. 317) as shown Figures 1 and 2. When not considering thermal conductivity variation during lithification occurred at depth interval of 600-800mbsf, bottom-hole temperature at ~2 km below the seafloor is significantly overestimated by ~40 °C. This finding cannot be unraveled if we did not retrieve unparalleled long sedimentary core to such a deep level. It is noted that there is few natural dataset from other continental margins and the reason for it is that there is no way to get deep cores except using D/V Joides Resolution and D/V Chikyu. Because of the same reason, lithification significantly affecting thermal regime within sediments column have been studied under laboratory experiments with respect to restricted conditions. The future activity of D/V Chikyu about a deep drilling up to more than 1 km below the seafloor at various environments, especially passive continental margin, is highly expected to increase our understanding of thermal properties change with lithification.

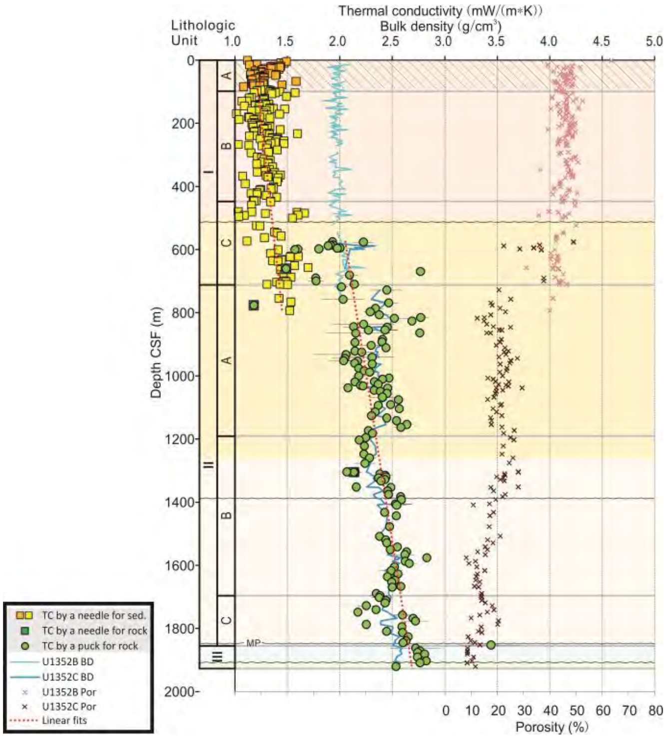


Figure 1. Summary of thermal conductivity, bulk density, and porosity measurements at Site U1352.

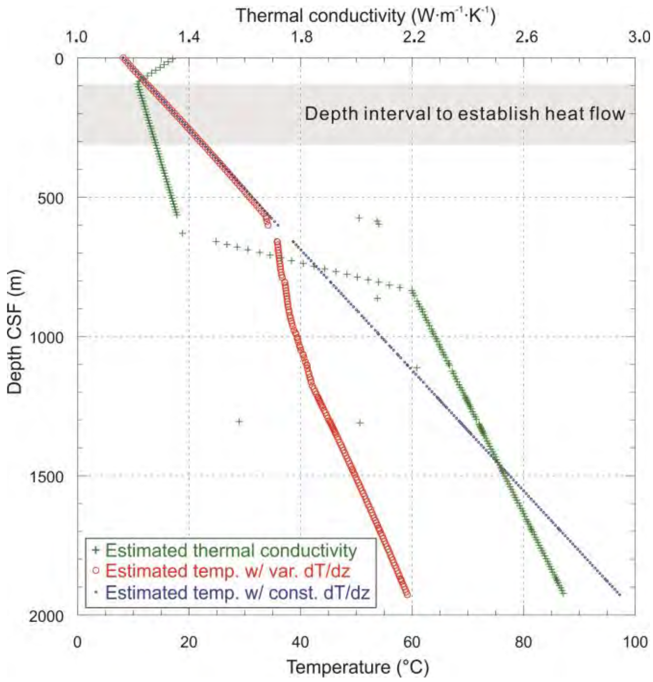


Figure 2. Predicted temperature profiles at Site U1352 based on the geothermal gradinet established in uppermost hole (dots) and based on variable thermal conductivity with depth (circles). Crosses show three thermal conducitvity trend vs. depth as well as some odd values beyond the trend. At 661 mbsf the temperature gradient (dT/dz) is decreased by about half compared to above depth interval for sediments. The predicted bottom hole temperature at Hole U1352 is ~60 °C, which less by ~40 °C than that based on constant geothermal gradient of 46 °C/km measured at shaded depth interval.

HIGH-RECOVERY DRILLING THROUGH THE CRETACEOUS GUYOT LIMESTONES –DECODING HIGH-RESOLUTION MARINE ENVIRONMENTAL CHANGES IN THE GREENHOUSE WORLD

Junichiro Kuroda[1] and Nao Ohkouchi[1]

[1]Japan Agency for Marine-Earth Science and Technology (JAMSTEC)

Mid-Cretaceous, Oceanic Anoxic Event, Guyot Limestone

Cretaceous period is particularly characterized by enhanced intra-plate volcanism which resulted in formations of large igneous provinces (LIPs) such as Ontong Java, Manihiki and Caribbean Plateaus. The Cretaceous warm climate has thus been attributed to the enhanced rate of volcanic CO_2 degassing. The mid Cretaceous is also characterized by episodic and contemporaneous deposition of organic-rich black shales that produces abundant petroleum and mineral resources today. The depositional episodes of black shales in a wide range of marine environments are termed Oceanic Anoxic Events (OAEs), one of the major global events in the Phanerozoic era. Based on sedimentary geochemical records, geoscientists have been demonstrating that Cretaceous OAEs occurred almost simultaneously with massive volcanic events associated with the LIP formations (Kuroda et al., 2007, 2011, Turgeon and Creaser, 2008, Tejada et al., 2009, Bottini et al., 2012). Although the simultaneousness between OAEs and LIP formations is widely accepted, their causal linkages i.e., how the massive eruption affected global ocean-atmosphere system and resulted in the OAEs, are still speculative. For the next step, we need to understand how the ocean-atmosphere system has changed after the onset of massive eruption. Now we look for sedimentary successions suitable to investigate this.

In this white paper we propose a drilling with Chikyu through a thick Cretaceous limestone succession on Pacific Guyots (Figure 1), which is characterized by extremely high sedimentation rate. Such high sedimentation rates have a great potential to reconstruct details of environmental changes in the Cretaceous period. In the previous scientific expeditions, the D/V JOIDES Resolution tried to drill Cretaceous limestone sequences at Site 866A on the Resolution Guyot (21°19.953'N, 174°18.844'E) at the present bathymetry of ~1,362 m (Figure 1). In this site, Post-Cretaceous sediments cover only less than 10 m on the Cretaceous limestone, which enables us to reach to the Cretaceous sediments with shallow subfloor depth (Figure 2). The main part of the sedimentary succession (~1,600 m thick) is composed of shallow sea limestones such as packstone, wackestone, and grainstone (Figure 2) ranging from Hauterivian to Albian stages (128-99 Ma, Wilson et al., 1998). Average sedimentation rate of the Cretaceous section at this site is 50-60 m/my. Great achievements have been developed with the sediment cores from Site 866A such as strontium ($^{87}Sr/^{86}Sr$) and inorganic carbon isotopic records ($\delta^{13}C_{carb}$) etc. (Wilson et al., 1998, Jenkyns and Wilson, 1998). These results demonstrate the presence of Early Aptian OAE (OAE-1a), and there is a thin layer of organic carbon-rich sediments which may correspond to OAE-1a. However, very low core recovery hampered detail geological/geochemical investigations (Figure 2). Full recovery of the Cretaceous limestone may help scientists to reconstruct environmental changes in great detail. Recent developments of drilling technologies achieved by D/V Chikyu have a great potential to improve core recoveries of such limestones.

A marine osmium isotopic record reconstructed from Early Aptian sediments illustrates a clear depletion in $^{187}Os/^{188}Os$ values immediately before the onset of OAE-1a (Tejada et al., 2009). This indicates that supply rate of non-radiogenic Os from the mantle source suddenly increased just before the OAE-1a, which would be associated with the emplacement of Ontong Java Plateau. We speculate that huge amount of CO_2 was released by the volcanic event, which may have caused 1) ocean acidification, 2) global warming, and 3) decrease in marine $\delta^{13}C$ values. The global warming might have accelerated rate of continental weathering, resulting in an increase supply of nutrients from continents which led to enhanced marine productivity and eventually oceanic anoxia (Misumi et al. 2009; Ozaki et al., 2011). In the same time the elevated sea surface temperature would cause stagnation of vertical circulation, preventing O_2 supply to the deep oceans. We believe that the extremely high-resolution record of marine carbonate rocks from Pacific Guyots greatly advances our understanding about the connection between the onset of eruption of Ontong Java Plateau (start of decrease in marine $^{187}Os/^{188}Os$ values) and the onset of climatic/oceanic changes (start of the OAE-1a black shale deposition).

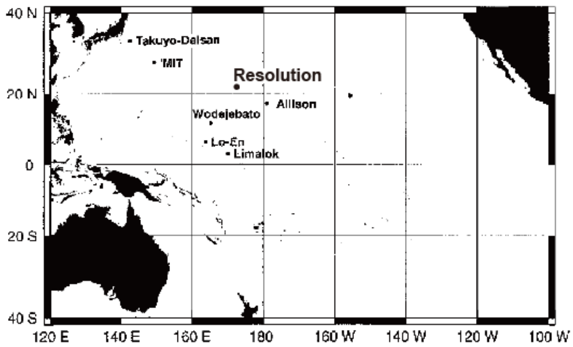


Figure 1. Pacific Guyots drilled during ODP Legs 143/144 (Wilson et al., 1998).

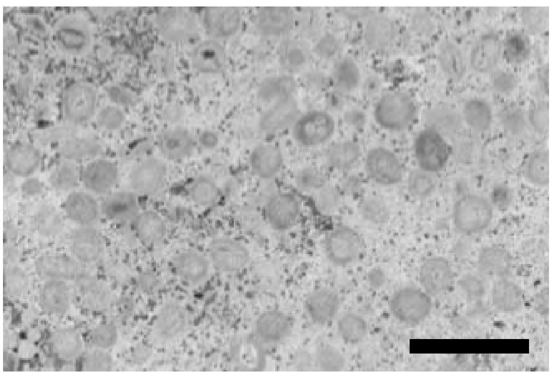


Figure 3. An oolitic-peloidal grainstone of Barremian age (Sager et al., 1993), 143-866A-156R-2, 38-49 cm. Scale bar is 1 cm.

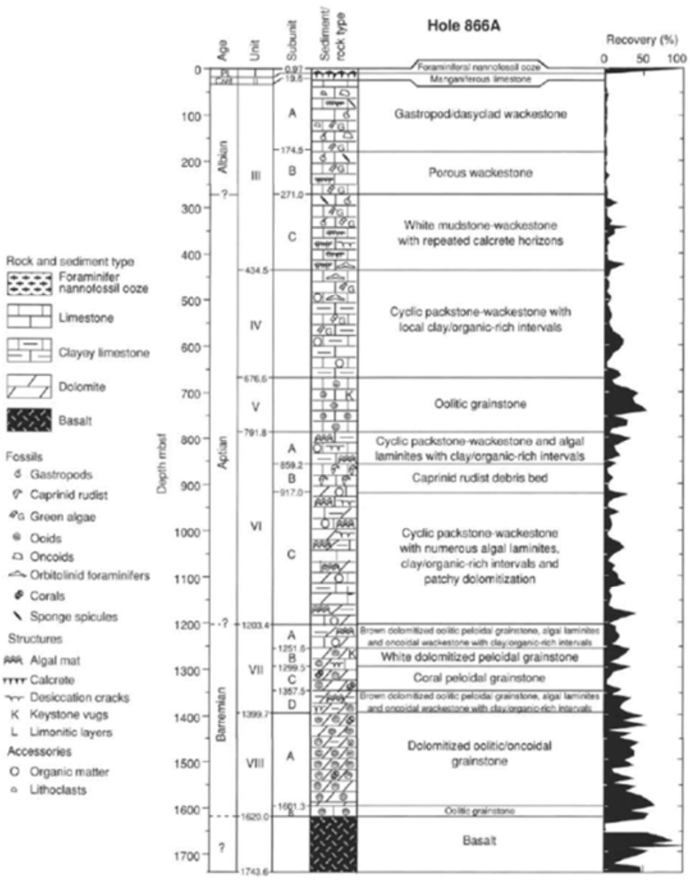


Figure 2. Lithologic column and core recovery of sediments fromSite 866A (Sager et al., 1993).

References: Bottini, C. *et al.* (2012) *Geology* 40, 583-586. Jenkyns, H.C. and Wilson, P.A. (1999) *Am. J. Sci.* 299, 341-392. Kuroda, J. *et al.* (2007) *Earth Planet. Sci. Lett.* 256, 211-223. Kuroda, J. *et al.* (2011) *Earth Planet. Sci. Lett.* 307, 126-134. Misumi, K. *et al.* (2009) *Earth Planet. Sci. Lett.* 286, 316-323. Ozaki K. *et al.* (2011) *Earth Planet. Sci. Lett.* 304, 270-279. Sager, W.W. *et al.* (1993) *Proc. ODP, Init. Rep.* 143. Tedaja, M.L.G. *et al.* (2009) *Geology* 37, 855-858. Turgeon, S.C. and Creaser, R.A. (2008) *Nature* 454, 323-326. Wilson, P.A. *et al.* (1998) *Nature* 392, 889-894.

Targeting Submarine Landslides Generated by Layer-Parallel Slip

Author: Sumito Morita
GREEN, Geological Survey of Japan, AIST

Introduction

When a submarine landslide occurs, a formation of a slip plane should trigger the main mass movement above the plane. However, where and how the slip plane forms is not fully understood, so it is not easy to raise an appropriate model to determine "Submarine Landslide Mechanism", that is one of the subjects on the IODP new science plan for 2013 and beyond. Historically, "circular slip" has been treated as a general landslide style, but this is not suitable for approaching a simple mechanistic model due to the complexities in morphology and lithology in the slip plane (Fig. 1a). On the other hand, "layer-parallel slip" is a simple style of landslide, where the mass movement occurs along on a sedimentary layer in parallel to the seafloor (Fig. 1b). In that case, it is much easier to find the feature of the slip plane and to understand the materials related to the slip plane than in the case of the circular slip. Thus, the layer-parallel slip may have the key to open the way for the subject "submarine landslide mechanism". As a good target for the scientific drilling on this subject, this white paper raises a swarm of large slump deposits in north Sanriku-oki Basin off Shimokita Peninsula, NE Japan.

Slump deposits in north Sanriku-oki Basin

By structural analysis in a 3D seismic data, a great number of large slump deposits have been identified in the Pliocene and younger formations in the north Sanriku-oki Basin (Morita et al., 2011). The slumping was generated primarily by layer-parallel slip on a very gentle continental slope. Each slump deposits show imbrication structure which is formed by repetition of the regular thrusting in the bottom layer (Fig. 2). Dewatering structure is observed as widespread parallel dikes of which distribution is strongly dependent on the imbrication structure. The dewatering structure seems to have occurred from the base of the slumping, i.e. the slip plane, and vertically intruded the main body of the slump deposits (Fig. 2). By tracing seismic layers, slip planes of the slumps proved to be generally characterized as low-amplitude layers having some thickness (Fig. 2), and some of the slip planes exhibit flattened features under the slump units of the imbrication structure accompanied by parallel dikes. This implies that excess fluid in the slip plane was drained through the parallel dikes during the slumping, and that the excess fluid in the slip plane caused the lubrication to enhance the slumping. Typical seismic features and some other previous studies imply that the formation fluid in this survey area is strongly related to natural gas.

The points of the slump as targets for IODP scientific drilling

The purpose of the scientific drilling this white paper proposes is to clarify a submarine landslide mechanism from the change by the slumping. For achievement of this project, a comparison between slump-related portion and –unrelated portion is necessary by arranging at least two drill sites, one for penetrating the slump units and the other for penetrating normal formation in lateral extension of the slump units as reference site. The targets of the penetrations are main bodies of "slump units" and "slip planes" of the slumping.

Since the body of the slump units are basically composed of the imbrication, the structure is much more regular than that of general landslide deposits. It is a very appropriate target to clarify the deformation processes during the slumping. The slip plane is clear as the basal plane of a layer-parallel slip unit, so the layer corresponding to the slip plane can be traced even to the area where the mass movement has not reached. As mentioned before, the layer correspond to the slip plane typically indicates low amplitude so that the layer is very clear as a target horizon. This comparison in the slip plane layer makes it possible to approach the initiation of slip plane.

Various core experiments and analyses, and well-arranged down-hole loggings will reach new findings, and those results would serve useful data for numerical simulations of slip plane initiation and deformation processes of slump bodies. Long term monitoring in a drill hole would be also useful for the future submarine landslide mitigation.

Reference

Morita, S., Nakajima, T. and Hanamura, Y. (2011) Possible ground instability factor implied by slumping and dewatering structures in high-methane-flux continental slope. Eds. by Yamada et al., *Advances in Natural and Technological Hazard Researches*, Springer, 311-320.

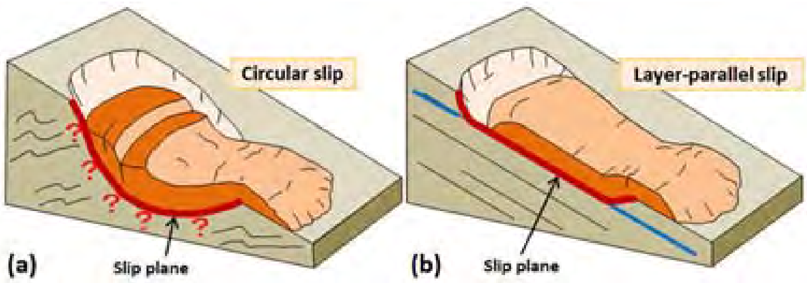


Fig.1 Schematics of general landslide styles. a) "Circular slip" has the complexities in morphology and lithology in slip plane. The slip plane cannot be anticipated before the slipping. b) "Layer-parallel slip" on a flat slope is simple and easy to recognize the figure of the slip plane. The layer correspond to the slip plane is horizontally traceable.

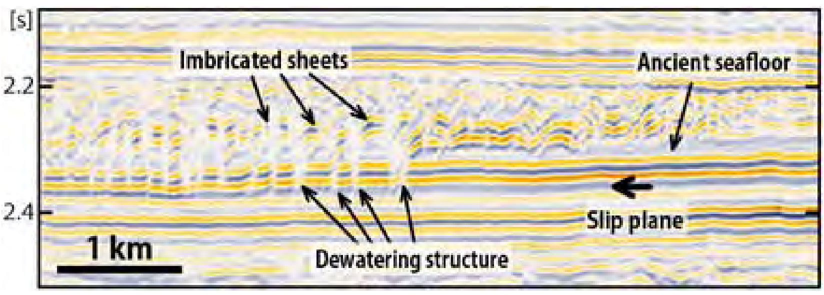


Fig.2 Typical slump sheets in north Sanriku-oki Basin, which is generated by layer-parallel slip. Slump unit is characterized by imbricated thrust sheets and dewatering structure. The layer correspond to a slip plane typically shows low-amplitude layer having some thickness.

DECODING MESOZOIC EXTREME ENVIRONMENTS FROM DEEP PACIFIC BASIN SEDIMENT

Naohiko Ohkouchi[1] and Junichiro Kuroda[1]

[1]Japan Agency for Marine-Earth Science and Technology

Cretaceous, deep Pacific, Black shale, OAE

Mid-Cretaceous time is characterized by extraordinarily warm climates. The warm climate has been attributed to elevated atmospheric pCO_2, associated with elevated rates of volcanic CO_2 degassing (Larson, 1991; Coffin and Eldholm, 2001). Furthermore, mid-Cretaceous time is also characterized by episodic and contemporaneous deposition of dark-colored muddy laminated sediment enriched in organic carbon (black shale) in a wide range of marine settings. Depositional events of black shale have been referred to as “Oceanic Anoxic Events” (OAEs). Among them, OAE-1a at 121 Ma and OAE-2 at 94 Ma have been most intensively investigated, mainly due to their world wide distribution (Fig. 1).

Over the last four decades, DSDP/ODP/IODP have drilled Mesozoic sediment at many sites in the western Pacific Ocean. Despite these efforts, core recovery of mid-Cretaceous sediment from deep basins in the western Pacific has been very low (generally <10%), which contrasts strongly with recovery from the Atlantic Ocean. Such low core-recovery is attributable mainly to the fact that the sediment deposited beneath the CCD consists of chert and shale successions: that combination of hard and soft sequences has proven difficult to recover with the drilling technologies of *Glomar Challenger* and *JOIDES Resolution*.

Due to these circumstances, the spatiotemporal distribution of mid-Cretaceous black shale in the Pacific basin is far less understood than those of the Atlantic and western Tethys. So far, mid-Cretaceous black shale from the Pacific Ocean has been successfully recovered from only five sites. Except for the Mariana Basin (Premoli Silva and Sliter, 1986), the black shale has been recovered from flanks of structural highs at paleodepths shallower than 2 km. Furthermore, at most sites, they were recovered in fragments or sections far from optimal, *e.g.*, drilling breccias, reworked beds, and sediment with poor chronology. These impediments mean that understanding of mid-Cretaceous paleoceanography in the Pacific region lags far behind that of the Atlantic.

Currently, some evidence indicates that black shales formed in the deep Pacific basins (paleodepth ≈ 5700 m) during the OAEs. One, a 2-cm-thick laminated black shale associated with OAE-2 was recovered at DSDP site 585 (in Mariana Basin). Although it was suggested that the sediment may have been reworked from other locations, convincing evidence for reworking is lacking. Two, laminated brown-colored sediment deposited during mid-Cretaceous time was recovered at ODP site 1149 (in Izu-Mariana Margin), suggesting that bottom water was anaerobic when the sediment was deposited.

Here we propose to recover sections deposited during the mid-Cretaceous OAEs from the deep basins of the western Pacific through application of new drilling technologies of D/V *Chikyu*. This proposal addresses several initiatives of the “Climate and Ocean Change” themes, including “How does Earth’s climate system respond to elevated levels of atmospheric CO_2?” of the IODP New Science Plan.

1) Distribution of black shale during Oceanic Anoxic Events in the deep Pacific basins

The distribution of organic-rich sediment in the Pacific Ocean is critical to understanding the nature and causal mechanism(s) of OAEs. Schlanger and Jenkyns (1976) originally postulated that mid-Cretaceous black shale in the Pacific was deposited only at intermediate water depths (0.3-2 km below sea level) where the seafloor was directly overlain by a water mass depleted in dissolved oxygen. However, as mentioned earlier, this notion is based on sparse and fragmentary evidence obtained mainly from the flanks of bathymetric highs; hence, the distribution of black shale in the Pacific Ocean remains to be critically evaluated.

2) Causal mechanism(s) of Cretaceous OAEs

It has been proposed that either massive dissociation of gas hydrate, enhanced recycling rates of nutrient-rich intermediate water, or formation of large igneous provinces (LIPs) was an ultimate trigger for OAEs. The gas hydrate hypothesis is based on observations that OAE-1a sediment is commonly associated with a negative isotopic shift of sedimentary carbon corresponding to the onset of the OAE-1a. Some believe that the enhanced recycling rates of nutrient-rich intermediate water brought about by changes in ocean productivity. Others think that emplacement of LIPs trigger OAEs based on the timing their emplacement and geochemical evidence from some black shale suggesting simultaneous massive volcanic events (*e.g.*, Castillo et al., 1994; Storey et al., 1997; Tejada et al., 2004; Snow et al., 2005; Kuroda et al., 2007). In any case, to reveal the causal mechanism(s) for OAEs, it is essential to investigate geological records in deep-sea sequences that cover more than 90% of the Pacific basin. Since sedimentation rates of chert sequences are expected to be at most 10 m myr^{-1}, ultra-high-resolution studies (Kuroda et al., 2005) of laminated black shale and adjacent chert/shale sequences are required for understanding temporal relationships between OAE formation and potential causal events. Therefore, high core-recovery is essential for our proposed work.

Figure 2. Distribution of black shales deposited during OAE-2 (Kuroda and Ohkouchi, 2006). Filled symbols indicate dark-colored sediment with TOC contents higher than 2%, whereas open symbols indicates TOC lower than 2%. Numbers indicate drill site of DSDP (in italics) and ODP.

THE DEEP WESTERN MEDITERRANEAN SEDIMENTARY BASIN (GEODYNAMICS, PALEO-ENVIRONMENT AND DEEP BIOSPHERE ARCHIVES): PROPOSAL FOR A DRILLING IN THE GULF OF LIONS (GOLD)

Rabineau, M.[1], Kuroda, J.[3], McGenity, T.[4], Aslanian, D.[2], Droxler, A.[5], Sierro, F.[6], Karine A.[1], Gorini, C.[8], Haq, B.[8], Eguchi, N.[3], Lofi, J.[9], Lirer, F.[10], Jimenez-Espejo, F.[11], Roure, F.[12], Pezard, P.[9] and the GOLD Working Group (Dos Reis, T.[13], Constantin, M.[14], Praeg, D.[22], Sprovieri, M.[23], Ohkouchi, N.[3], Takai, K.[3], Tatsuhiko, H.[3], Cloetingh, S.[25], Bache, F.[26], Huismans, R.[27], Afilhado, A.[28], Moulin, M.[2], Ercilla, G.[30], Hernandez-Molina, J.[31], McKenzie, J.[32], Flecker, R[29]., Phipps-Morgan, J.[33], Perez-Gussinye, M.[34], Amend, J.[35], Deino, A.[36], Giosan, L.[37], Scott, G.[37], Waldmann, N.[38], Burov, E.[15], Dennielou, B.[2], Gardien, V.[16], Jolivet, L.[17], Klingelhoefer, F.[2], Lucazeau, F.[18], Popescu, S.[8], Bassetti, M-A.[19], Rouxel, O.[2], Schnürle, P.[2], Suc, J-P.[8], Thouveny, N.[21])

[1]CNRS Brest, [2]IFREMER, [3]JAMSTEC, [4]Univ. of Essex, [5]Rice Univ., [6]Univ. of Salamanca, [8]Univ. of Pierre and Marie Curie, [9]Univ. of Montpellier, [10]CNR Napoli, [11]Univ. of Granada, [12]Institut Français du Pétrole, [13]UERJ, [14]Univ. of Laval, [16]Univ. of Lyon, [17]Univ. Orléans, [18]IGPG, [19]Univ. of Perpignan, [21]CEREGE, [22]OGS, [23]Univ. degli Studi di Palermo, [25]Utrecht, [26]GNS Science, [27]Univ. of Bergen, [28]Univ. Lisboa, [29] Univ. Bristol, [30]Institut de Ciències del Mar - CSIC, [31]Univ. de Vigo, [32]ETH, [33]Univ. of Cambridge, [34]Univ. of London, [35]Washington Univ., [36]Univ. of Berkeley, [37]WHOI, [38]Univ. of Haifa

[Keywords] Mediterranean, Geodynamics, Rifting, Messinian Salt, pre-salt, Deep Biosphere

Quantitative understanding of the Earth has made significant strides in the last few decades. In part this has been driven by advances in seismological and seismic methods used to decipher the 3D structure of the mantle, lithosphere and crust, coupled with growing potential of sedimentary basin analyses to connect temporal and spatial scales of natural change. Quantitative understanding of mass transfers by surface erosion and deposition, as well as their feedbacks to crustal and subcrustal dynamics, has been recognized as a new frontier in Earth sciences by the international community (e.g. Topo-Europe, GeoPRISMS, TerMex). In addition there is increasing awareness that the Earth harbors a vast number of unknown life forms in a deep biosphere that may play an important role in climate change and evolution. Progress in these fields has been hampered by the scarcity of data from sedimentary archives encompassing the full history of continental margins. The Mediterranean Sea represents an ideal venue to take a step forward.

This white paper outlines an ambitious drilling project aiming to fully recover the last 25 Ma history of the Gulf of Lion continental margin, with specific focus on margin formation, global climate changes and sea-level fluctuations (including the Messinian Salinity Crisis (MSC) when the Mediterranean Sea experienced a major desiccation), and their implications for the deep biosphere. The objectives fit into three topics of equal importance:

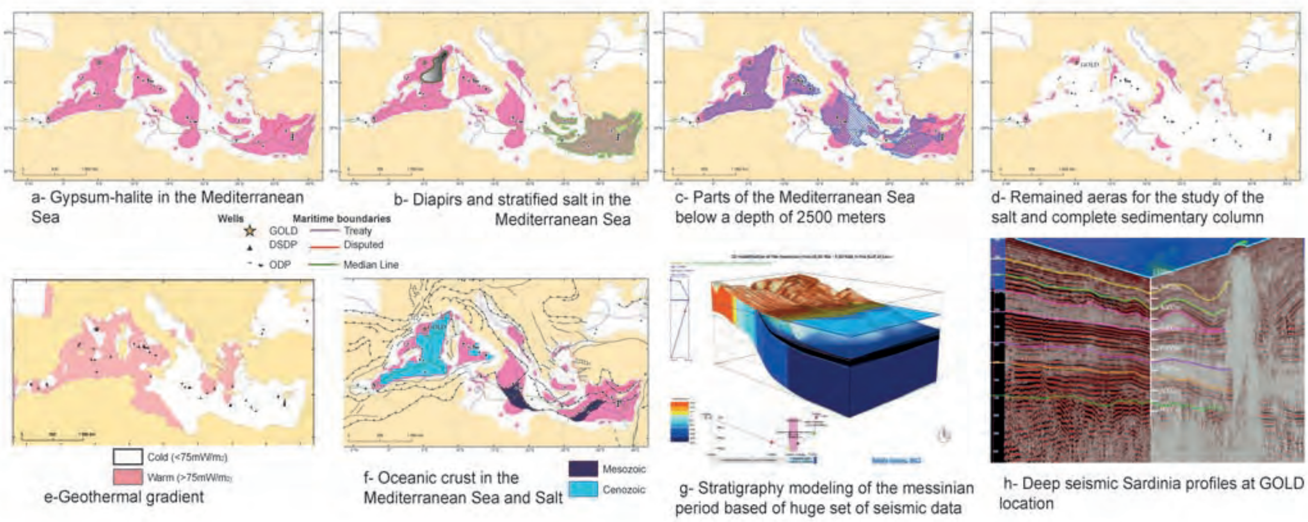
1) **Understand the formation of continental margins**: Seismic reflection-refraction data clearly image, at the toe of continental slope, the boundary between continental crust and transitional substratum where highly reflective lower crust visible below the shelf abruptly disappears seaward and the upper continental crust thins to less than 5 km. Several different hypotheses have been proposed alluding to different nature for this crust (thinned or intruded continental crust/exhumed mantle/lower crust). Drilling would provide crucial information about the lithology of this crust to test such models, while the recognition of paleo-environments and dating the

sedimentary column overlying the crust will provide the first necessary paleobathymetric markers to reconstruct subsidence and thermal history of the margin.

2) **Explore climate-driven change and environmental crises**: Drilling will allow us to date and characterize deep basin sedimentary deposits, recently quantified and modelled from geophysical data (Figure 1g), in order to establish detailed budgets of land/sea transfers drive by 25 Ma of changing climate. These changes are punctuated by the Messinian event, a unique sedimentological, hydrological, oceanographic, biological and climatological crisis in Earth history, which provides an opportunity to study the impact of >1000 m sea-level drop on the vertical evolution of the margin (isostatic rebound), sediment erosion/deposition, and the associated biotic crisis. Our current knowledge of this event is based on a meager sampling of only the upper veneer of the evaporitic section, which has generated intense discussion and controversies in the academic community, and raised more questions than answers.

3) **Investigate life in an extreme environment**: Drilling will provide a unique opportunity to study the interplay between temperature, pressure and salinity on microbial communities, to understand life's limits and to assess the importance of extremophile activity in altering the geochemistry. In addition, the presence of isolated impermeable layers subject to multiple extreme conditions would make this site particularly relevant to address questions related to evolution and adaptation of life to one of Earth's extreme environments that are fundamental to evolutionary biology and ecology.

Our scientific goals place significant constraints on the location of a potential drill site. We wish to sample a complete sedimentary succession without faults, major erosional hiatuses nor sedimentary lacunae, the saline series (preferably homogeneous and without diapirs) and reach the transitional crust (with an additional 600m of drilling). Besides, the geothermal gradient should be low enough to permit the survival and preservation of micro-organisms. A number of technological constraints (bathymetry < 2500 m; bottom hole maximum depth 9 km) further reduces potential sites (Figure 1d). The Gulf of Lion, with its extensive data and accumulated knowledge is a very suitable site.



Industry scientists have expressed keen interest in the potential of new insights into the pre-salt history of the western Mediterranean Basin. The GOLD initiative has a strong connection with the more recent DREAM initiative which aims to promote multiple riser-drilling sites specifically focused on the Messinian Salinity Crisis.

USING SCIENTIFIC OCEAN DRILLING TO UNDERSTAND THE AGE AND ORIGIN OF THE ALEUTIAN BASIN, BERING SEA

Robert J Stern[1], Dave Scholl[2, 3], Dan Scheirer[3], Ginger Barth[3]
[1]U Texas at Dallas, [2]U Alaska Fairbanks, [3]USGS Menlo Park
Keywords: Aleutian Arc, Aleutian Basin, Marginal Basin, Backarc Basin

Circum-Pacific marginal basins are natural targets for scientific ocean drilling, including three behind the Aleutian Arc: the older, larger Aleutian Basin and the younger Komandorsky Basin in the west and Bowers Basin in the south. Scientific drilling in the Aleutian Basin could reveal a lot about the tectonic and climate history of the Pacific sub-Arctic. The Aleutian basin is generally thought to have formed in place when the long-active Alaskan subduction zone propagated west, capturing part of the Mesozoic Kula, Izanagi, or Resurrection plates to form the Aleutian subduction zone. This shut down the Beringian arc along the outer edge of the Beringian shelf at the same time that subduction beneath the Aleutian Arc began. Collision of the Olyutorsky arc with Kamchatka may have also been important. This could be summarized as the “Captured Kula/Izanagi/Resurrection” (left panels in Fig. 1). Alternatively, the Aleutian Basin may have opened as a Paleogene backarc basin. We call this the “Bering BAB” hypothesis (Right panels in Fig. 1). It should be possible to solve this controversy via drilling to basement in the Aleutian Basin.

Opening geometry of the Aleutian Basin has a clear N-S magnetic spreading-like fabric. These stripes have been interpreted as M1 to M13 (~130-140 Ma), aging westward, but it is also possible that this fabric is much younger. This is also suggested by rifting of the Beringian arc ~50 Ma and carving of the ‘Red Unconformity’ on the Bering Shelf about this time. Heatflow through the Aleutian back is also consistent with an age ~45 Ma, but backarc basins are often sites of high heatflow. Some heat may also be produced accompanying conversion of opal-A to opal-CT, This conversion will evolve fluids that help to advect methane via VAMP structures through the sediments to the seafloor, which may also contribute to heatflow. Basement topography is rugged, with fault scarps that show 500 m to 2 km offset that formed in association with opening of extensional basins. We can drill to basement to determine its age and recover a complete sedimentary record of a high-latitude basin, at least back through Oligocene time.

We need to drill in the Aleutian Basin to recover a complete record of overlying sediments as well as good penetration (>200m) into magnetic basement. We plan to drill on the Vitus Arch, which traverses the region that shows good spreading-like magnetic anomalies. The Vitus Arch is a NE-SW trending, 100-to 200-km-wide seamount-crested uplift, comprising six linear basement ridges, each 30 to 140 km long. Aleutian Basin crust is blanketed by >4 km of sediments over most of the basin, but there are some places along the Vitus Arch where sedimentary sections are 1-2 km thick. There are several places where local buried basement highs extend to within a few hundred meters of the seafloor. Regardless, the upper section of drilled sediments should be like those penetrated at DSDP Site 190 on the east flank of the Komandorsky Ridge. Site 190 penetrated Holocene to middle Miocene diatomaceous sediment with variable amounts of silt and clay. This 615 m thick upper sediments contain well-preserved diatoms. 15m below this (to the bottom of the hole) consists of porcelaneous mudstone and claystone containing only scattered and severely corroded diatoms as old as middle Miocene. This boundary at ~615 m is Opal-A-Opal C/T diagenetic front

There are several places on the 6 Vitus Arch ridges that should be considered for drilling, and there are lots of MCS lines that cross these ridges, which we will carefully examine for the best places to drill. The core that we should recover should allow us to choose between the two competing models, as outlined in Fig. 2, and thus lead to a better understanding of the tectonic evolution of the Aleutian convergent margin and surrounding regions

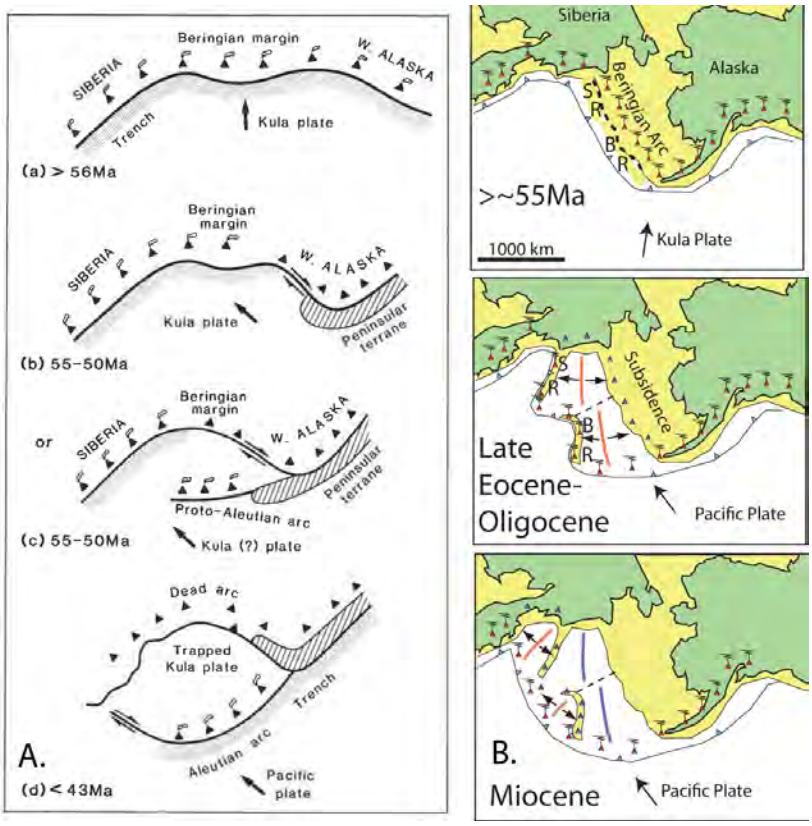


FIG. 1 Competing hypotheses for origin of Aleutian Arc and flanking oceanic basins in the Bering Sea. A: Captured Kula Plate hypothesis (a) Before about 56 Ma, northward-directed motion of the Kula plate resulted in a more or less continuous subduction zone extending from Siberia into proto-Alaska. (b) Between 55 and 50 Ma, Kula plate motion changed to more westerly and the Beringian arc died. (c) Alternatively, the rocks may have erupted in a "proto" Aleutian arc, which may have been continuous with the Peninsular terrane. The arc and terrane became accreted to the continental margin when subduction shifted to the Aleutian arc. (d) Between 50 and 40 Ma, the Aleutian arc began and older arc fragments and portion of the Kula plate were trapped behind the arc. (Davis et al., 1989.) B: Possible scenario for opening of the Aleutian Basin as a backarc basin behind the rifted Beringian margin; in this scenario, Aleutian basin opens in Eocene-Oligocene time. Green areas = present land; yellow = shelf; SR = Shirshov Ridge; BR = Bowers Ridge; Red = active volcanism and spreading; Blue = extinct volcanism and spreading.

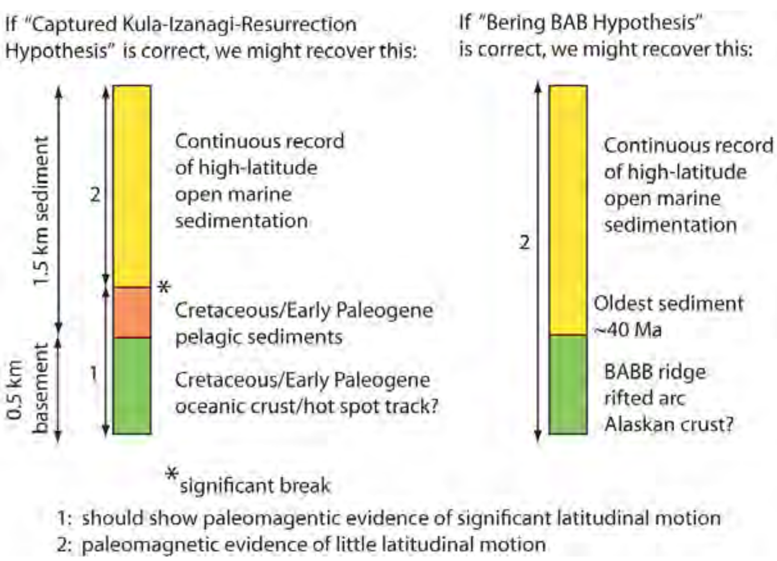


Fig. 2: What drilling in the Aleutian Basin is likely to yield, depending on whether the “Captured Kula” or “Bering BAB” hypothesis outlined in text and Fig. 1 is correct.

Evolution of the East Antarctic Ice Sheet and Southern Ocean at Dronning Maud Land, Antarctica

Yusuke Suganuma[1], Minoru Ikehara[2], Gerhard Kuhn[3], Masao Iwai[2], Hisashi Oiwane[1], Hideki Miura[1], Wilfried Jokat[3], Yoshifumi Nogi[1]
[1]National Institute of Polar Research, [2]Kochi University, and [3]Alfred Wegener Institute

Keywords: East Antarctic Ice Sheet, Dronning Maud Land, Rillser-Larsen Sea, Weddel Gyre, Cenozoic, Continental Breakup

The Antarctic cryosphere is a key component of the Earth's climate system. Climatic models (e.g., DeConto and Pollard, 2003; Huber et al., 2004; Pollard and DeConto, 2009) suggest that the main triggering mechanism for the Antarctic ice sheet stability is the CO_2 concentration in the atmosphere. However, complex interactions between the Antarctic cryosphere and global climate system and their response to future climate change in a high-CO_2 world remain uncertain (IPCC, 2007). Marine sediments from Antarctica's margin contain a detailed archive of past ice sheet behavior; therefore, it can be used to assess the accuracy of global climate models and to better predict future climate change in response to increasing atmospheric CO_2 levels. Since the 1960s, number of scientific drilling campaigns have sampled marine sediments from Antarctica's margin and the Southern Ocean (by i.e., DSDP, ODP, IODP, and ANDRILL) and have contributed significantly to knowledge of the development and evolution of the Antarctic ice sheets, their influence on global sea levels, and paleoceanographic and biotic changes. For example, the recent successful drilling of the ANDRILL program in the Ross Sea identified significant variability and vulnerability in the West Antarctic ice sheet during the early Pliocene warm climate (e.g., Naish et al. 2009). However, only few sectors of Antarctica's margin have been sampled by these geological drilling; therefore, the evolution and dynamics of Antarctica's ice sheets, particularly the large East Antarctic Ice sheet (EAIS), are not yet well understood. In addition, these historical drilling projects on Antarctica's margins, especially by drilling vessels, have been hampered by the technological challenges associated with achieving adequate core recovery in inhomogeneous glacial marine sedimentary sequences (Shevenell and Bohaty, 2012) in very strong consolidated sediments such as porcellanites (Site 1094) or diamictites intercalated with highly porous biosiliceous ones. Therefore, further scientific drillings with more stable platforms against the rough southern seas and more developed drilling technology, for example, the Chikyu riser drilling vessel, for excellent core recovery and a better understanding of the dynamics of the EAIS and its future stability are urgently needed from both a scientific and societal point of view.

The EAIS at Dronning Maud Land, which overlies continental terrains that are largely above sea level, is considered more stable than the WAIS and other parts of the EAIS, for example, the Wilkes Basin (Escutia et al., 2005). Based on the climate modeling by DeConto and Pollard (2003a), this region of the EAIS has started to grow during the very early stage of climatic change corresponding the Greenhouse to the Icehouse world transition during the Cenozoic. Because atmospheric CO_2 levels may reach those of the Greenhouse world (900 ppm) in 2100 (IPCC2007), it is very important to quantify the physical boundary conditions for the advance/retreat of the EAIS based on direct geological records from Antarctica's margin at Dronning Maud Land. The effects of the behavior of the EAIS on the Antarctic Circumpolar Current (ACC) and Southern Ocean gyres, such as the Weddel Gyre (WG), can also be addressed by these geological records.

Here, we propose new drilling sites in Antarctica's margin at Dronning Maud Land (Fig. 1). The key scientific issues surrounding these sites are (1) the history and behavior of the East Antarctic ice sheet at Dronning Maud land, (2) the responses of the ACC and WG to the evolution of the EAIS, and (3) tectonic influences on climatic changes.

Drilling along Antarctica's margins on the continental slope sediment drift allows for the revelation of age control points for seismostratigraphic interpretations of data from the Riiser-Larsen Sea (Fig. 1). These data will recover Antarctic geological records back 30 to 50 million years ago, when Earth's atmospheric CO_2 level was 2 to 4 times higher than the present level. Drilling on Astrid Ridge, Gunnerus Ridge, and Kainan Maru Seamount is also important in providing constraints for the long-term advance/retreat history of the EAIS. The detailed history of the evolution of the ACC and WG will be given by riser redrilling of the historical ODP Site 1094 and Maud Rise sites (690, 691).

The tectonic evolution of the Southern Ocean associated with the Gondwana breakup affects long-term climate change, but the initial opening history around Dronning Maud Land remains unclear. The nature of aseismic ridges and rises around the East Antarctic margin, such as the Gunnerus Ridge and the Astrid Ridge, is vital to understanding the initial Gondwana breakup process, and direct samplings of the basement are required to elucidate the origin and evolution of these ridges and rises. The drilling of the aseismic ridges and rises around the East Antarctic margin will greatly advance the comprehension of the Gondwana reconstruction, the opening of the circum-Antarctic gateways, paleogeography, and paleobathymetry.

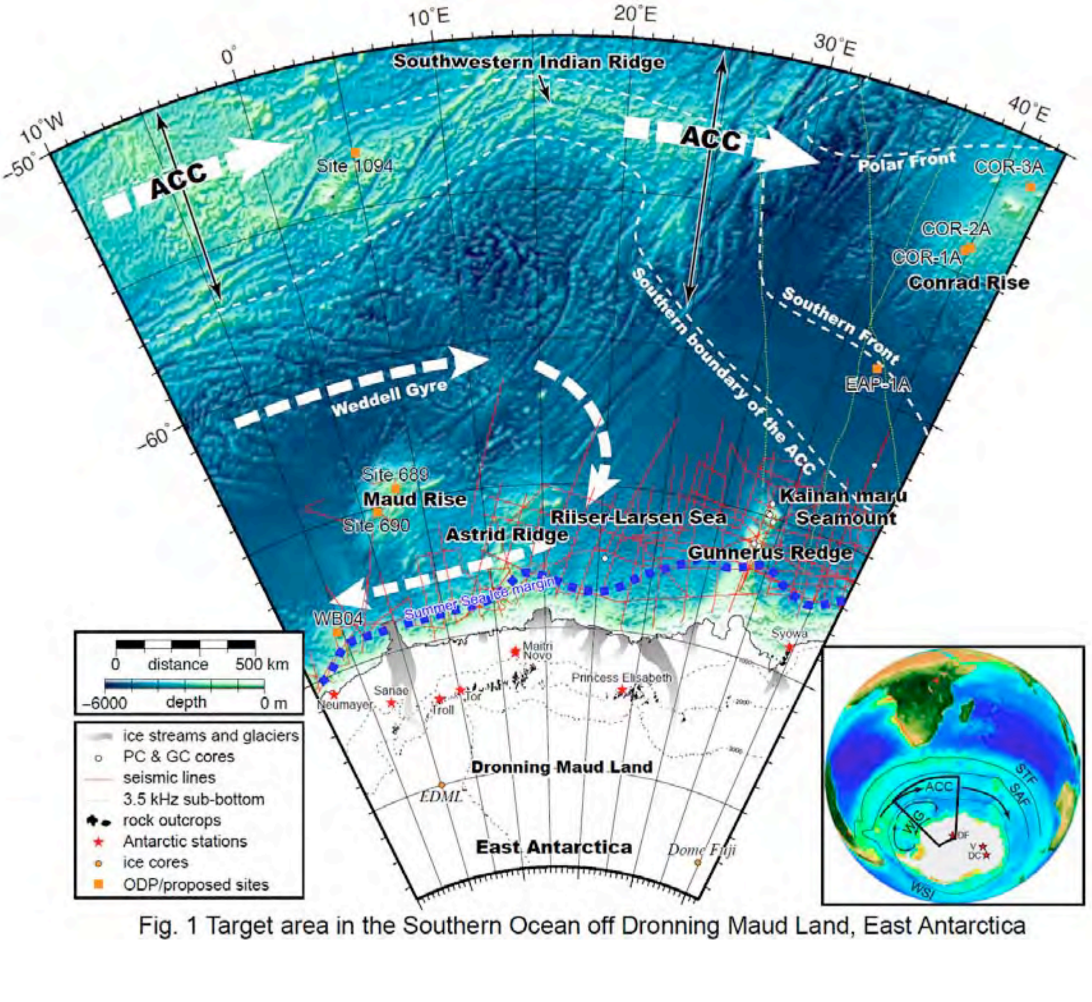


Fig. 1 Target area in the Southern Ocean off Dronning Maud Land, East Antarctica

RIFTED MARGINS EVOLUTION UNVEILED BY DEEP SEISMIC SURVEYS: AN INCOMPLETE SCENARIO THAT REQUIRES FURTHER INVESTIGATION

Adriano R. Viana[1], Mario Neto C. de Araujo[1], Luciano Magnavita[1], Renato O. Kowsmann[1], Peter Szatmari[1], the BrasilMargens Research Group[2], Gianreto Manatschal[3], Daniel Aslanian4, Nicholas W. Hayman[5], Laurent Geoffroy[6], Luc Lavier[5], Maryline Moulin[4]

1- Petrobras – Petróleo Brasileiro S.A., Brasil

2- CNPq – Conselho Nacional de Pesquisas, Brasil

3- Univ. Strasbourg, France

4- IFREMER- Institut Français pour la Recherche de la Mer, France

5- Univ. Texas Austin, USA

6- Univ. Bretagne Occidentale, France

Keywords: Continental rifted margins, deep seismic, South Atlantic, breakup, Gondwana

Intense offshore activity related to oil and gas exploration since the 1970’s along the rifted margins and the need to explore continuously towards ultra deep water settings provided significant new information that helped to advance further in the understanding of the processes related to continental margin evolution, and to shed some light on the intricate relationship between tectonics, sedimentation, palaeoceanography and palaeoclimate.

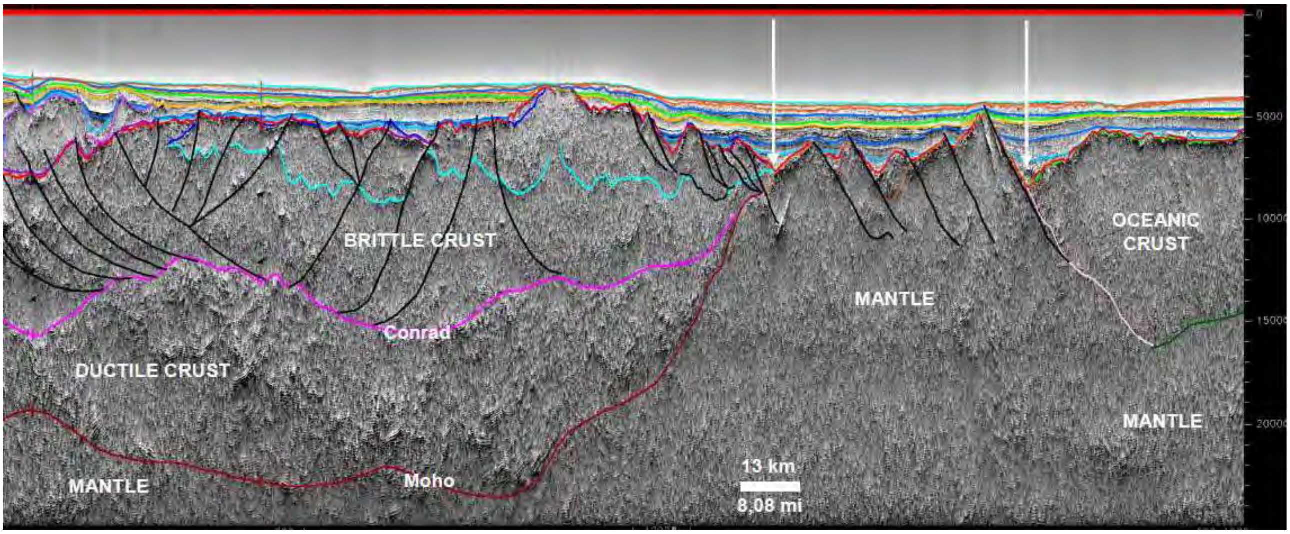
Despite all these activities and large data set collected over time, fundamental processes related to rifting, breakup and subsequent divergence of continental margins remain poorly understood. Most of the industry activity was done relatively close to the coastal setting because of technological and costs limitation. Studies performed from the beginning of this millennium along the deep Iberian Margin and its conjugate counterpart Newfoundland margin including deep reflection and refraction surveys coupled with ODP coring produced a set of new data that coupled with large oil discoveries in the distal margins offshore Brazil, Gulf of Mexico and Africa motivated reevaluations of classical models of rifted margins.

Extensive deep seismic reflection surveys punctually supported by refraction experiments evidence the large heterogeneity of deep margin structure along the oceans. The last 10 years of deep seismic imaging in the South Atlantic highlighted the importance of further understanding of the rifted margins behavior through geological time. Lithospheric stretching and thinning processes that led to continental margin extension and eventually to breakup can locally involve a complex interaction of lower crust, mantle exhumation and different episodes of magmatism. Continental rafted blocks physically separated from their original land mass have been observed and witness the complexity of the different processes that led to continent fragmentation. Margin topography readjustment, thermal and density effects of mantle exhumation and serpentinization, diachronism in rifting and sagging are still debatable. Deep and wide sag basins, formed on the roof of rifted continental crust preceding the continental breakup show relative absence of faults suggesting that most subsidence occurred landward of the continent-ocean boundary but after cessation of major basement-involved extensional episodes affecting the continental crust. Geological conditions responsible for the development of a wide salt basin in the central South Atlantic during late Aptian are still under debate.

Recently acquired deep seismic data indicate several potential scientific targets to be drilled in order to better constrain the early phases of South Atlantic opening, oceanic crust formation and palaeoecology of the magnetically quiet Aptian-Albian transition when a wide stressed microbial-rich lacustrine shallow water carbonate environment evolved to a very thick salt basin. Complex numerical models are being developed aiming to test scenarios and identify thermal and fluids history related to margins evolution. However, geological data fundamental to calibrate and validate the models are still missing.

Deep marine sedimentation processes that took part after Gondwana breakup and the newly formed Atlantic Ocean were strongly controlled by physiographic readjustment of the adjacent margins, palaeoclimate and shallow to deep ocean circulation changes. Strong bottom currents that controlled the distribution of large sedimentary bodies are observed along the whole southwestern margin of the Atlantic Ocean since the late Cretaceous, a glacial-free period, suggesting a triggering mechanism for deep oceanic currents different from a glacial dependent source. Such deposits must record these important palaeoceanographic changes.

The South Atlantic has also recorded different periods of accumulation of organic carbon-rich strata, from late lower Cretaceous to Neogene which reflect oceanic circulation and climate changes. Of these the older events are poorly documented in the western part of the ocean. Interaction between gravity-driven, upper margin derived sedimentation processes and those processes related to deep ocean circulation constitute extremely interesting targets to be drilled and are well identified in the new vintage seismic data.



Dip seismic section (depth) in the Santos Basin displaying the dual nature of the continental crust (upper brittle and lower ductile crusts), the exhumation of the mantle (between arrows) and the passage to oceanic crust. Visualization of seismic section in tecVA_RFASE (Petrobras patented in-house technique). Seismic line provided by ION-GXT (Fig from Zalán et al., 2011)

Studies on paleomagnetism and cosmogenic nuclide using sediment cores in the West Caroline Basin: Possible connection among the geomagnetic field, Earth's orbit, and climate

Toshitsugu Yamazaki[1], Yusuke Yokoyama[1], Toshiya Kanamatsu[2], Yusuke Suganuma[3], and Yuhji Yamamoto[4]

[1]Atmosphere and Ocean Research Institute, University of Tokyo, [2]Japan Agency for Marine-Earth Science and Technology, [3]National Institute of Polar Research, [4]Kochi Core Center, Kochi University

Keywords: paleomagnetism, cosmogenic nuclide, orbital forcing, paleoclimate

The possibility of orbital modulation of the geomagnetic field has been a matter of debate for more than ten years (e.g., Channell et al., 1998; Yamazaki, 1999; Yamazaki and Oda, 2002; Thouveny et al., 2008; Yokoyama et al., 2010; Valet et al., 2011). If this is true, it has fundamental implications for the geomagnetism because it means that an energy source of the geodynamo resides outside the Earth's core. The current points of the arguments are a possibility of lithological contamination to paleointensity records and statistical significance. Orbital frequencies found in paleomagnetic records may have caused by variations of sediment properties induced by climate changes. To settle the problem, it is required to obtain high quality paleomagnetic records (both paleointensity and direction) during the last ca. 10 m.y. with new strategies.

The effect of lithological contamination to sedimentary paleointensity records can be evaluated by comparing paleointensity records from sediments that were responded differently (i.e. with different phases) to climate changes. For this purpose, sediments in the West Caroline Basin (WCB), north of New Guinea, are considered to be suitable. It was well known that for sediments in the Pacific Ocean carbonate contents increased in glacial periods and thus magnetic susceptibility of sediments shallower than the CCD decreased in glacials by a dilution effect. However, it was revealed recently that this was the opposite before about 1.1 Ma; carbonate content decreased in glacials (Sexton and Barker, 2012). Carbonate contents reflect ocean productivity and then control magnetic properties of sediments including mineralogical changes associated with differences in oxic-redox conditions and production of biogenic magnetites. Sediments in the WCB are known to have preserved stable remanent magnetization favorable for paleointensity studies (e.g. Yamazaki and Oda, 2005). In the basin floor of the WCB near the New Guinea, where the water depths are deeper than the CCD, it is known that magnetic susceptibility variations mimic the pattern of oxygen isotope ratios. This is controlled by variations in the flux of terrigenous magnetic minerals caused by climate changes, and the phase shift at ~1.1 Ma did not occur (Yamazaki and Oda, 2005). On the other hand, at topographical highs east and north of the WCB, where the water depths are shallower than the CCD and terrigenous flux from the New Guinea is minor, the phase shift at ~1.1 Ma is expected to have occurred. If we compare relative paleointensity records of cores from the basin floor and topographical highs, we will be able to separate a true geomagnetic component and a lithological contamination component; the latter will show a phase shift at ~1.1 Ma, whereas the former will not.

Another strategy to evaluate the reliability of sedimentary paleointensity records is to obtain a paleointensity record back to several million years using a cosmogenic nuclide ^{10}Be. Production of ^{10}Be is controlled by the strength of the geomagnetic field, and thus a paleointensity record can be derived, which is independent to the records using conventional paleomagnetic methods and hence enables us to evaluate the effect of lithological contamination. By comparing with a ^{10}Be-based paleointensity record we will also be able to confirm/discard the possibility of a polarity bias in paleointensity; some paleointensity records show lower intensities during the Matuyama Chron compared with the Brunhes (Valet et al., 2005), but others are not (Channell et al., 2009). Another important issue to be addressed using ^{10}Be is a possible connection between paleoclimate and the geomagnetic field, which has a long history of debate. Recently, a possible connection between influx of galactic cosmic rays and climate has been argued (e.g., Svensmark and Friis-Christensen, 1997). If this is true, the geomagnetic field might affect climate because the strength and shape of the geomagnetic field control influx of galactic cosmic rays. It is important to study both cosmogenic nuclides and paleomagnetism using the same sediment cores.

The objectives mentioned above can be achieved by coring triple holes of ~200 m deep at least two sites in the WCB with non-riser HPCS system of D/V Chikyu.

References

Channell, J.E.T., Hodell, D.A., McManus, J., & Lehman, B. (1998) Nature, 394, 464-468.

Channell, J.E.T., Xuan, C., & Hodell, D.A. (2009) EPSL, 283, 14-23.

Sexton, P.F., & Barker, S. (2012) EPSL, 321/322, 81-94.

Svensmark, H., & Friis-Christensen, E. (1997) J. Atmos. Solar-Terrestrial Phys., 59, 1225-1232.

Thouveny, N., Bourles, D.L., Saracco, G. et al. (2008) EPSL, 275, 269-284.

Valet, J.-P., Meynadier, L., & Guyodo, Y. (2005) Nature, 435, 802-805.

Valet, J.-P., Moreno, E., Bassinot, F. et al. (2011) G-cubed, 12, Q08012.

Yamazaki, T. (1999) EPSL, 169, 23-35.

Yamazaki, T., & Oda, H. (2002) Science, 295, 2435-2438.

Yamazaki, T., & Oda, H. (2005) G-cubed, 6, Q11H20.

Yokoyama, Y., Yamazaki, T., & Oda, H. (2010) GRL, 37, L11302.

Scientific drilling by Chikyu to unravel the opening history of the South China Sea and its implications for Southeast Asian tectonics, climates, and deep mantle processes since the Late Mesozoic

Xixi Zhao[1] and Chun-Feng Li[2]
University of California Santa Cruz, USA[1] and [2] State Key Laboratory of Marine Geology, Tongji University, Shanghai 200092, China

Keywords: Tectonics, Climate, Marginal seas

A primary goal of the scientific ocean drilling in the new IODP is to distinguish and quantify cause and effects relationships between tectonics and climate, particularly in areas of rapid sedimentation where the potential resolution of events is greatest. One clear way to evaluate the relationship between tectonic uplift and climate is to measure the resulting changes in marginal sea strata. The South China Sea (SCS) is geologically unique (Fig. 1): the SCS is a classical representative of western Pacific marginal seas that developed from continental margin rifting and is floored with oceanic crust; they are located at the junction of the Eurasian, Pacific, and Indo-Australian plates, and thereby sensitive to their tectonic and climatic changes; the relatively small size of the SCS facilitates easy tectonic comparisons between the two conjugate continental margins, accessible through one single IODP leg. The SCS has been at the center stage of many first-order tectonic and paleoclimatic events since the Mesozoic. Mesozoic subduction of the Paleo-Pacific plate, a fragment of which developed roughly along the present-day northern SCS continental margin (Jahn et al., 1976; Li et al., 2008), gradually dispelled the Paleo-Tethys and built a massive orogen in Southeast Asia that have very pronounced effects on regional climates, magmatism, and sedimentation. However, during the transition from the Early to Late Cretaceous, all supportive evidences of a subduction zone mysteriously disappeared, and regional extension started to prevail and eventually triggered the Cenozoic opening of the SCS, via continental margin break-up and ultimately seafloor spreading from ~32 Ma to ~16 Ma (Taylor & Hayes, 1983; Briais et al., 1993).

Given the unique characteristics of the SCS, a dedicated drilling program with Chikyu will fill in important gaps in our understanding of the regional formation of western Pacific marginal seas, and of global continental margin rifting and basin formation in places such as the Gulf of California, the Japan Sea, and the Andaman Sea. Increases in sedimentation accumulation rates, driven by increased topographic relief and erosion, can be directly tied to a chronostratigraphy and to the proxy indicators of climate and unroofing history contained in the complete marginal sea strata. Rapid sedimentation throughout the past 32 m.y. in South China Sea has produced an unexplored but potentially extremely high-resolution (cm/yr; meters/kyr) sedimentary record of Western Pacific environmental change over the range of time scales of interest to IODP: tectonic (longer than about 0.5 m.y.), orbital (20 kyr to 400 kyr), oceanic (hundreds to a few thousand years), and seasonal-to-centennial time scales. Interesting targets in the region include pre-rifting and syn-rifting sequences, ocean ridges, and basement basalts (Fig. 2).

To sum up, new scientific drilling of the SCS area can identify and refine both regional questions related to East Asian geology and fundamental issues regarding continental breakup and basin formation. Reconstruction of the tectonic evolution of the SCS, especially the start and end of the spreading events that led to the formation of the different SCS sub-basins and the nature of the continent-ocean transition can be linked to several IODP science themes, such as Challenge 9: “How are seafloor spreading and mantle melting linked to ocean crustal architecture?”, Theme 4: “Earth connections: deep processes and their impact on Earth’s surface Environment “, and Theme 2: “Climate and Ocean Change”.

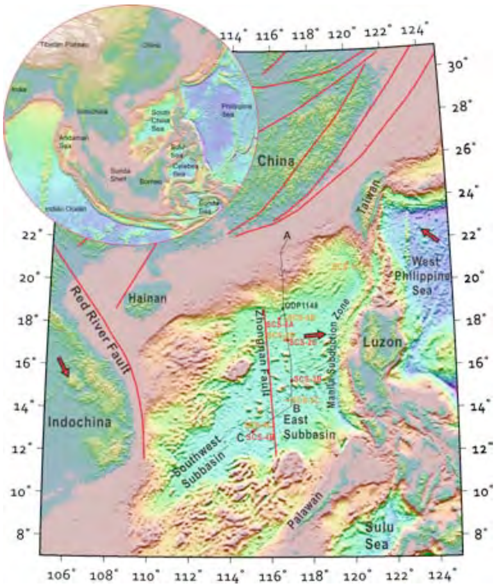


Fig. 1 Regional topography and geodynamic framework of Southeast Asia (modified from Smith and Sandwell, 1997).

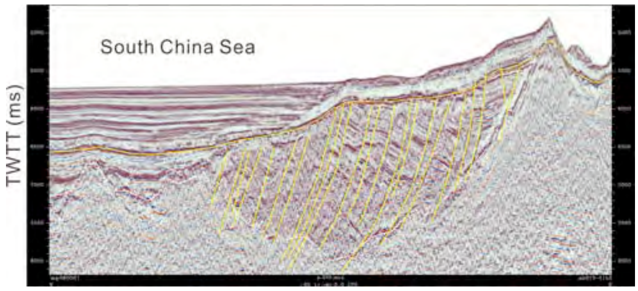


Fig. 2 Syn-rifting sequences found on the basin margins form an interesting drilling target for understanding early rifting events.

References cited:

Briais, A., Patriat, P., Tapponnier, P., 1993. Updated interpretation of magnetic anomalies and seafloor spreading stages in the South China Sea: implications for the Tertiary tectonics of Southeast Asia. J. Geophys. Res. 98, 6299–6328.

Jahn, B. M., Chen, P. Y., Yen, T. P., 1976. Rb–Sr ages of granitic rocks in southeastern China and their tectonic significance. Bull. Geol. Soc. Am. 86, 763–776.

Li, C.-F., Zhou, Z., Hao, H., Chen, H., Wang, J., Chen, B., Wu, J., 2008b. Late Mesozoic tectonic structure and evolution along the present-day northeast South China Sea continental margin. J. Asian Earth Sci. 31,546–561.

Smith, W. H. F., D. T. Sandwell, 1997. Global seafloor topography from satellite altimetry and ship depth soundings, Science, v. 277, p. 1957-1962, 26 Sept.

Taylor, B., Hayes, D.E., 1983. Origin and history of the South China Sea basin. In: Hayes, D.E. (Ed.), The Tectonic and Geologic Evolution of South Eastern Asian Seas and Islands, II. Am. Geophys. Union, Geophys. Monogr., Washington, D.C., 27, 23–56.

Monitoring state of stress in the earthquake fault system in the Nankai Trough

Eiichiro Araki[1], Shuichi Kodaira[1], Koshun Yamaoka[2], Demian Saffer[3], and Masataka Kinoshita[1].

[1]Japan Agency for Marine Earth Science and Technology, [2]Nagoya University [3], Penn State University.

[Keywords] Nankai Trough, seismic velocity, stress, earthquake, long-term borehole observatory, submarine cable network

In understanding the mechanism of seismogenesis in subducting oceanic plate, we consider it is necessary to define status and dynamics of the seismogenic fault in the vicinity. The key parameters defining the status and the dynamics include chemical and physical composition and structure, thermal, stress, pore-fluid pressure, and deformation (or strain change) of the media.

In this decade, it becomes widely known that episodic slow slip occur near the subducting plate boundary. The nature of such event is still very much unknown where the events occur in a precision to be associated with any known structure of the system of plate subduction, as well as the physical and chemical condition to make such type event happen, which is almost similar to our level of understanding the "regular" earthquakes.

How the status and the condition of seismogenic (including of slow slip events) fault system change as the event occurs? How such change (if any) propagate and trigger other events? What makes difference between slow slip and regular earthquakes. These problems are tackled by numerical simulation based on the model of seismogenesis from knowledge through laboratory experiments. We need to set "real" parameter from observation and see if our numerical model behaves similarly to the real nature.

In the IODP NantroSEIZE scientific drilling in the seismogenic Nankai Trough subduction system, we have successfully collected a fault sample with historical record of slip. We have also established a long-term observatory above the seismogenic fault of large earthquake monitoring seismic signal, strain (tilt), pore-fluid pressure, and thermal structure at approximately 1 km beneath the seafloor, approaching less than 3 km to the mega-splay fault at depth and 6 km the seismogenic plate boundary. We expect the observatory is sensitive to a small change of the condition of such seismogenic system, but still leaves at a distance from the fault itself to define pore-fluid and thermal condition at the fault. We need to reach the faults to establish observation at the fault system itself with deep riser drilling technology.

Although we expect a lot from a borehole observation in the vicinity of the seismogenic fault, we also know the slip of large earthquake occur in wide area, and our observation at the borehole is a point sampling. It is necessary to devise ways to connect knowledge at the point into areal behavior of the fault system.

We propose to conduct continuous and long-term data analysis on the seismic waves that has effect from propagation in the seismogenic fault to monitor the change of status in the fault.

Experience on the vertical seismic profiling in the NantroSEIZE experiment suggests that seismic anisotropy observed can be a powerful tool to infer stess state of the subduction system. We try further expanding this into depth to the seismogenic fault to profile and monitor stress (or pore-fluid pressure) state of the fault system.

An example implementation of the monitoring could be continuous long-term seismic monitoring in the borehole from controlled seismic sources at fixed locations (Figure 1). This is a concept similar to borehole seismic logging to obtain seismic property of media around the borehole, but we propose to do this continuously in long-term for temporal change detection, and to target much wider area than the seismic logging which is widely practiced in the present scientific drilling.

To implement such seismic observation in practice, we need to install a network of seismic "transmitters" and "receivers" at each fixed location. Preferably, both the seismic receiver and transmitter are installed beneath the seafloor, to escape effects from oceanographic and near surface disturbance to the seismic wave to sample effects near the fault at depth. In the Nankai Trough, we started establishing a network of seafloor and borehole seismic "receivers" (to date, 20 seafloor observatories and a borehole observatory are in operation in the DONET submarine cable observatory (Fig. 2)). The concept will be first evaluated using an airgun "transmitter" from ship and the network of seafloor and borehole "receivers", but the plan includes steps towards near surface borehole controlled seismic "transmitter" and the deep array "receivers" near the seismogenic fault at depth.

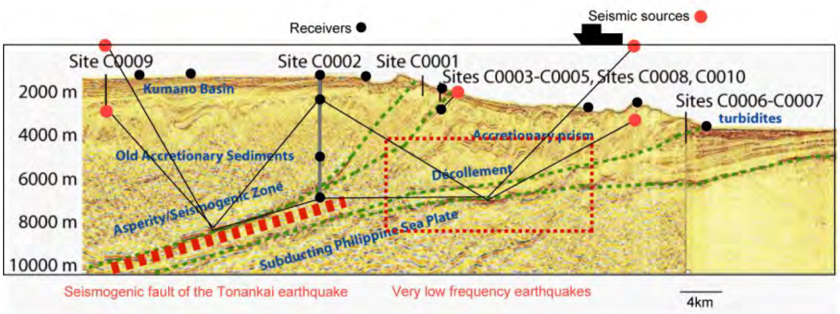


Figure 1. Conceptual long-term continuous seismic profiling in the Nankai Trough. Seismic source and receivers are indicated by red and black circles. Target area of the profiling includes area of very low frequency earthquake occurrence, near surface splay fault, and the seismogenic fault at depth.

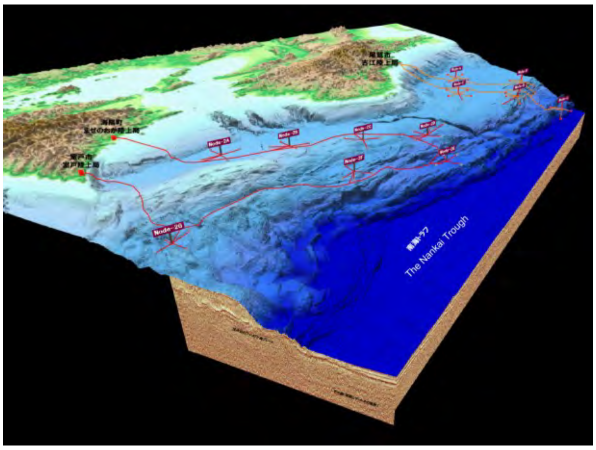


Figure 2. The DONET Submarine cable network plan viewed from south-west of the Nankai Trough. Eastern segment of the network corresponds to the target area of the present NantroSEIZE experiments and is operational since 2010 with 20 seafloor seismic observatories and one borehole observatory. The western segment is planned to start deployment in 2013.

Formation pressure as a proxy for volumetric strain: Holes in understanding subduction seismogenic zones need new holes for monitoring

Earl Davis, Pacific Geoscience Centre, Geological Survey of Canada
Keir Becker, Rosenstiel School of Marine and Atmospheric Science, University of Miami
Masataka Kinoshita, JAMSTEC and Kochi Core Repository, Japan
Key Words: formation pressure, crustal strain, subduction seismogenesis

The primary goals of early ODP "CORK" hydrologic observatory efforts were to determine the natural thermal state and driving forces for fluid flow through oceanic crust and subduction-zone accretionary prisms, and to obtain pristine pore-water samples in the absence of drilling and open-hole perturbations. Some installations have been operational continuously for over 16 years, and the long records have provided a variety of additional "fringe benefits". For example, the formation response to variable loads imposed on the seafloor over a broad frequency range by seasonal ocean dynamics, tides, tsunamis, and wind-generated ocean waves have provided constraints on elastic and hydrologic properties (compressibility, shear modulus, permeability, storage compressibility), with inferred properties being representative over spatial scales much greater than covered by standard borehole or laboratory measurements.

Another originally unanticipated application of CORK hydrologic monitoring has been the use of formation pressure as a proxy for crustal strain. Pressure changes have been observed at the times of many discrete episodes of seafloor spreading and fault slip along the Juan de Fuca Ridge and adjacent transform faults, and at the times of seismogenic and aseismic slip along the Nankai, Mariana, and Middle America (Costa Rica) subduction zones. In each case, quantitative estimates of strain have been made with the elastic properties estimated from seafloor loading response. Post-slip pressure transients have also been observed, as well as secular interseismic strain accumulation at Costa Rica and Nankai.

Various improvements to CORK hardware since the first deployments in 1991 now provide a means for monitoring pressure at multiple isolated formation levels, and for including other sensors such as seismometers and strain meters. Improvements to pressure monitoring electronics allow high resolution (e.g., 10 ppb full-scale pressure, or 0.4 Pa at 4000 m) reaching up to seismic frequencies (1 Hz). The combination of this measurement capability and the sensitivity of pressure to strain in low-porosity (≤40%) sediment and igneous oceanic crust - typically 5 kPa/μstrain - makes this observational technique viable and valuable for geodynamic studies. The most versatile hole completion scheme for geodynamic studies is the so-called "Advanced CORK", in which formation pressures are transmitted from large-surface-area screens wrapped around the outside of solid steel casing via robust hydraulic tubing to ROV-servicable sensors and electronics at the seafloor, where temperatures are stable and cool. The inside of the casing can be plugged or grouted to prevent leakage, and other sensors can be mounted inside the casing or imbedded into the formation below. This simple configuration is possible for any final section of casing; it is only critical that all sections of casing be sealed to one another to prevent any thermally induced or direct perturbations from up- or down-hole flow.

Admittedly, the full capabilities of the Chikyu are not esssential for installing such systems or reaching depths (c. 1 km) where formational rigidity and hydrologic isolation allow reliable long-term measurments of pressure, and the ACORK technology is no longer "advanced". Nevertheless, the need for an expanded distribution of geodynamic observatory sites in subduction zone settings, particularly at Nankai, is great and should not be ignored when developing future plans, nor should the utility of simple pressure monitoring for watching tectonics in action. The value of pressure has been made abundantly clear with records from the first ACORKs installed at Nankai, and from modified ACORKs installed at Costa Rica (e.g., Figs. 1 and 2). Data from the incoming Philippine Sea plate at Nankai have revealed a steady increase of pressure believed to reflect contractional interseismic strain; contractional and dilatational anomalies caused by regional co-seismic and post-seismic strain produced by distant large earthquakes; and other anomalies related to episodes of slow slip on the nearby subduction thrust (all dilational). In contrast, anomalies seen in the toes of the subduction prisms at both Nankai and Costa Rica consistently indicate contraction, with leading edges that lag other indicators of strain further landward, including the initiation of VLFE activity in the Nankai prism (Fig. 3) and ETS downdip from the prism at Costa Rica (Fig. 2). These observations tell a fairly clear story about the nature of interseismic subduction thrust slip, but the geographic isolation of the sites is frustrating. Companion sites are badly needed to establish such things as the rate of slip propagation, and the locus and magnitude of slip responsible for the anomalies. Establishing additional sites (Fig. 3) should be a key part of any effort to study a subduction zone like Nankai.

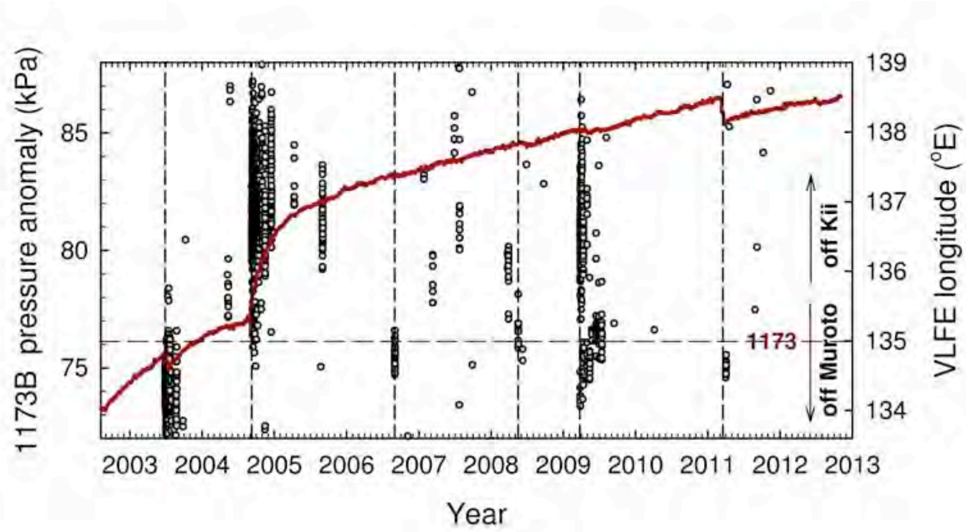


Fig. 1. Pressure at 880 m depth in IODP Hole 1173B in the subducting Philippine Sea plate, Nankai subduction zone,, and local VLFE activity (see Fig. 2) (after Davis, Becker, Wang, and Kinoshita, Earth Planets Space, 61, 649-657, 2009 and EPSL, in review).

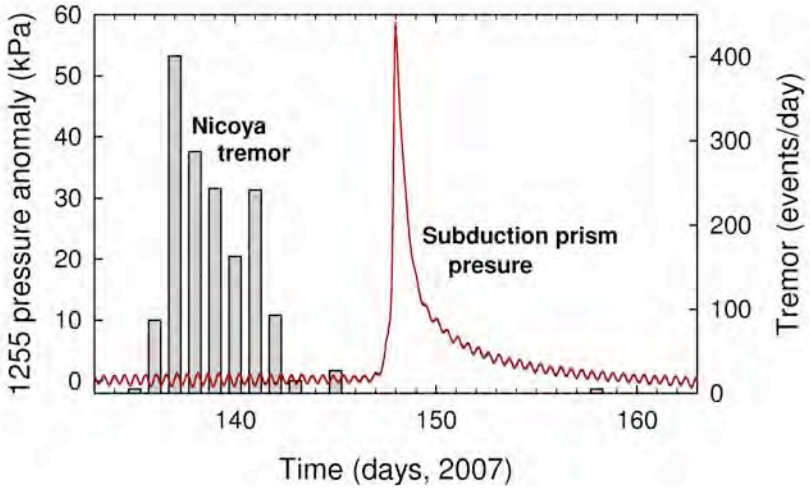
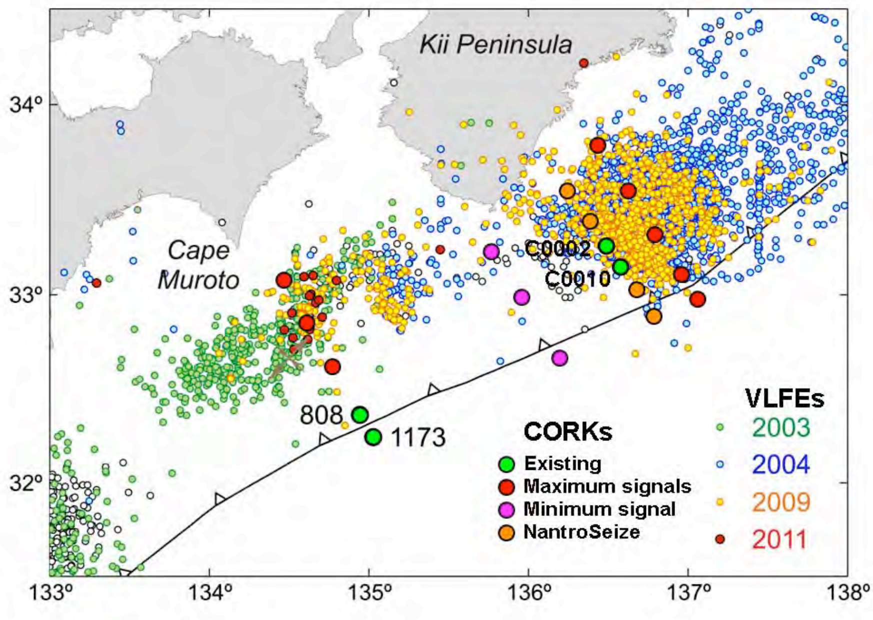


Fig. 2. Pressure at 130 m depth in Hole 1255A in the Costa Rica subduction prism at the time of a tremor and slip event landward of the prism beneath the Nicoya Peninsula (after Davis, Heesemann, and Wang, EPSL, 306, 299-305, 2011).

Fig. 3 Map of the Nankai Trough showing locations of very low frequency earthquakes, and a proposed array of existing and new borehole observatories that would allow slip events in this region to be characterized properly (after Davis, Kinoshita, Becker, Wang, Asano, and Ito, EPSL, in review).



Outer rise drilling transect to study structural evolution of the oceanic plate prior to subduction

Gou Fujie[1], Koichiro Obana[1], and Shuichi Kodaira[1]
[1] Japan Agency for Marine-Earth Science and Technology (JAMSTEC)
outer rise, bending-related faulting, water penetration, mantle hydration, oceanic lithosphere

Dehydration processes and the expulsion of the water from the subducting oceanic plate affect various subduction-zone processes, including arc volcanism and generation of earthquakes. This means that the amount of water subducting within the oceanic plate is a key to understand these subduction zone processes.

Recent seismic structure studies in several subduction zones suggest that P-wave velocity (Vp) within the incoming oceanic plate systematically decreases toward the trench, probably owing to bending and fracturing of the incoming plate under a tensional stress regime before the subduction [e.g. Ranero et al., 2003, *Nature*; Contreras-Reyes et al., 2008, *J. Geophys. Res.*]. In addition, Fujie et al. [2013, *Geophys. Res. Lett.*] successfully modeled S-wave velocity (Vs) structure in the trench-outer rise region of Kuril trench and showed that the Vp/Vs ratio increases toward trench, suggesting the water percolation into oceanic crust (Figure 1). These seismic structure studies confirm that plate bending and fracturing of the incoming oceanic plate in the trench-outer rise region play an important role in the water supply to the subduction zones.

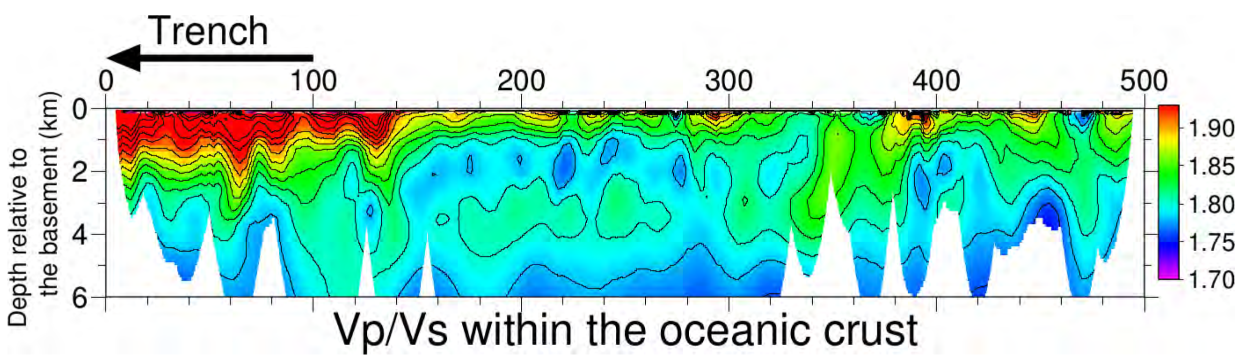


Figure 1. In the trench-outer rise region of Kuril trench, Vp/Vs ratio within the uppermost oceanic crust increases toward the oceanic trench, suggesting the seawater percolation into the oceanic plate. The horizontal axis represents the distance along the seismic profile in km and the trench axis is located at around -10 km [Fujie et al., 2013, *Geophys. Res. Lett.*].

As seismic velocities and the Vp/Vs ratio depend on various parameters, such as lithology, porosity, pore geometry (aspect ratio of the pore), and presence of fluid, it is difficult to estimate the actual amount of the water contained within the oceanic plate by remote sensing approaches like the seismic structure study. Therefore, we propose a drilling transect from the deep sea basin to the trench through the outer rise to reveal the essential information to quantitatively explain the systematic structural evolution of the incoming oceanic plate before its subduction.

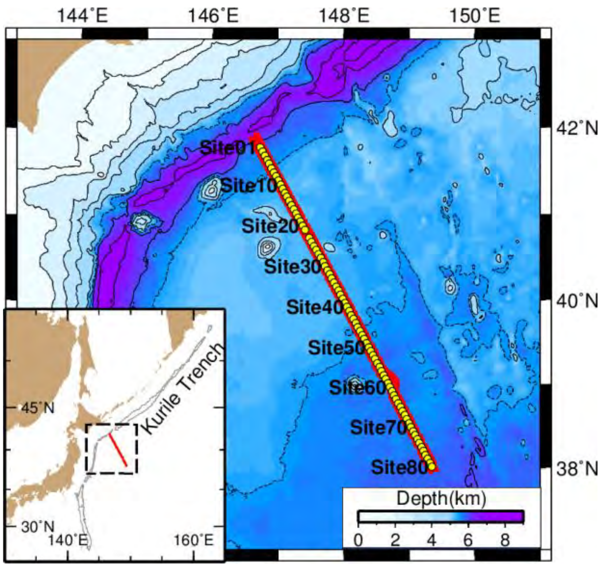


Figure 2. Bathymetric map around the seismic profile of Figure 1. The yellow circles represent OBSs and the red line is the air-gun shot line.

One of the best places to study is the trench-outer rise region of the Kuril trench because the detailed structural evolution including the changes in Vp/Vs ratio has been resolved there (Figure 2). Besides, this region is suited for examining the effect of the plate curvature upon the oceanic plate because the relative elevation of this outer rise is the world's largest class.

To reveal the mechanism of the structural changes and the amount of water, and to reveal the variation in the stress state along the subduction direction, a transect consisting of several drill sites are required from a normal oceanic crust area (around x=250km in Figure 1) to a heavily-fractured/altered area (around x=50km). At most drill holes, the depth of 2km below the sediment is enough because the structural changes are confined to the upper crust until the onset of horst-and-graben structure (x<80km). However, at least one drill hole should be deeper to investigate the stress state variation with depth. Earthquake focal mechanisms show a depth dependent variation of the stress within the incoming oceanic plate related to the mantle hydration [e.g., Lefeldt et al., 2012, *Geochem. Geophys. Geosyst.*]. The tensional stress within the incoming oceanic plate is usually limited at shallower depths of the oceanic plate, but it extends down to depths of about 40 km, which correspond to the depths of the lower plane of the double seismic zone, beneath the outer slope of the Japan Trench after the 2011 Tohoku-oki earthquake [Obana et al., 2012, *Geophys. Res. Lett.*]. The depth dependence of the stress state would be critical information to simulate water penetration and hydration deep into the oceanic plate prior to the subduction.

Bending-related faulting, hydrothermal convection, and slab hydration on the oceanic plate seaward of the trench

Xiang Gao and Shiguo Wu

Key Laboratory of Marine Geology and Environment, Institute of Oceanology, Chinese Academy of Sciences

Bending-related faulting, hydrothermal convection, slab hydration, oceanic plate

Bending-related faulting is pervasive across most of the ocean trench slope and can be clearly identified through the observation of multibeam bathymetry. It can cut across the oceanic crust and even penetrate deep into the mantle, which allows the sea water to penetrate into the cold crust and upper mantle. Hydrothermal convection in the lithosphere may occur if the faults are sufficient to form fluid channels by connecting with each other. Meanwhile slab hydration like serpentinization of peridotites can happen on the fault surface. Due to episodic tectonic activity and crack propagation, high rates of hydration may occur and plenty of heat will be released. Recently, high heat flow anomalies on an old oceanic plate were observed seaward of the Japan Trench. Does this caused by the heat released from hydrothermal convection or slab hydration? And which one is the main factor? The along-strike length and depth of penetration of these faults are thought to be similar to the dimensions of rupture area of intermediate-depth earthquakes at the Middle America trench. Is there any relationship between them? To answer these questions, the seismic data and rock samples of the oceanic plate seaside of the trench are much more valuable.

Fluid pressure in seismogenic subduction zones

Yoshitaka Hashimoto[1]

[1]Department of Applied Science, Faculty of Science, Kochi University

seismogenic zone, subduction zone, fluid pressure, elastic properties

One of the most significant targets for ocean drilling science is seismogenesis in subduction zones. We have been conducted researches to understand mechanisms of seismognesis in subduction zones, such as NanTroSEIZE, CRISP and J-FAST. Although those cruises have provided some big and new discoveries, and many on-going science on those cruise will make further progress in the near future, those are insufficient because we have only reached at shallow depth. We need to drill into seismogenic plate boundaries. In addition to that, the comparison between accretionary margin and erosional margin is also important to understand the seismogenesis in subduction zones more generally. CRISP Deep is one of a reliable cruise to conduct such comparison to Nankai.

In this paper, I focus on fluid pressure in subduction zones. Fluid pressure affects on sediments strength and shear strength on faults significantly. Fluid itself has a role on transportations of heat and materials. Fluid is not only the result of mechanical compaction and chemical reaction, but also the medium for chemical reaction such as cementation which also changes sediment's strength. Those sediment's strength within wedge and shear strength on decollement control wedge architecture, seismogenic behavior, stress distribution within wedge and along decollemenet. Consequently, distribution of fluid pressure in subduction zone is strongly connected to dynamics of subduction zones.

There are some methods to estimate fluid pressure.

1) Using porosity-effective pressure relationship at input site under an assumption of normal consolidation of sediments at input site, effective pressure can be estimated from porosity in wedges where fluid pressure is not hydrostatic. Compaction test for sediments in input site by laboratory measurements can also provide porosity-effective pressure relationship. Porosity is obtained by 1-1) direct measurement from core samples on-board, 1-2) by logging, 1-3) velocity from seismic profiles using empirical relationship between velocity and porosity.
2) Using velocity-effective pressure relationship obtained from on-board measurement, logging and laboratory measurements, velocity distribution form seismic profile can be converted to effective pressure.
3) Using Vp-effective pressure and Vs-effective pressure relationships in hanging-wall and footwall, respectively, at a reflector such as decollement or mega-splay fault, parameters of amplitude variations

with offset (AVO) at the reflector can be calculated. Laboratory measurements are needed to obtain Vp-effective pressure and Vs-effective pressure relationships. AVO parameters are also estimated from seismic profiles at the reflector. Comparison between AVO parameters from laboratory measurement and from seismic profile, effective pressures both in hanging-wall and footwall are estimated at the reflector.

4) Direct measurement by packer-test and hydrofracturing test in borehole.

Most of methods mentioned above require getting core samples by drilling. To understand deep seismogenic zone, we need samples collected there. Furthermore, those methods are based on core-log seismic integration. Therefore, high resolution and powerful 3D seismic profiles and logging while drilling are also essential. Because boreholes in subduction zones are unstable, wire-line logging is not practical in most cases. Because fluid pressure may built up transiently or intermittently, long-term monitoring in borehole with Do-net system is also interesting to examine a change in fluid pressure with time or event.

To understand the effect of fluid pressure in subduction zone on seismogenesis widely and generally, we need to investigate as many subduction zones as possible including accretionary margins and erosional margins, and also as deep as possible.

FLUIDS AND SEISMOGENESIS IN INTRA-OCEANIC DEFORMATION

Pierre Henry[1], Christian Hensen[2], Marianne Nuzzo[3,4], João Duarte[3,5], Filipe Rosas[3], Luis Matias[3], Luis Pinheiro[6], Pedro Terrinha[3,4], Matthias Delescluse[7], Eulàlia Gràcia[8], Valentí Sallarès[8], Rafael Bartolomé[8] and Cesar R. Ranero[8]

[1]CEREGE, Aix-Marseille University and CNRS, Marseille (France) (henry@cerege.fr); [2]GEOMAR - Helmholz Centre for Ocean Research, Kiel (Germany); [3]Dom Luiz Institute, University of Lisbon (Portugal); [4]Portuguese Institute for the Sea and Atmosphere (IPMA), Lisbon (Portugal); [5]School of Geosciences, Monash University, Melbourne (Australia); [6]CESAM & Department of Geosciences, University of Aveiro (Portugal), [7]Laboratoire de Géologie de l'Ecole Normale Supérieure, Paris (France) and [8]Institut de Ciències del Mar, CSIC, Barcelona (Spain)

Seismogenesis, Serpentinization, Oceanic Lithosphere, Fluids, Mega-earthquakes

According to current paradigm, fracturing of oceanic lithosphere favors fluid circulation and serpentinization, which in turn results in aseismic mantle behavior in deformation zones. Oceanic transform faults connecting spreading centers do have low seismic moment release rates (relative to their length and slip rate) and generally produce earthquakes of Mw < 8. Intra-oceanic deformation is also thought to be largely aseismic, however, major faults in old oceanic lithosphere have occasionally caused (Mw > 8) mega-earthquakes. The 1933 Sanriku earthquake is one example of large (Mw 8.4) normal fault earthquake in old oceanic lithosphere bent near a subduction trench. Also in a near subduction context, strike-slip earthquakes off Sumatra April 11, 2012 (Mw 8.6 and 8.2) surprised earth scientists, showing that reactivated oceanic transform faults can generate strike-slip earthquakes with exceptionally large rupture lengths [1]. This event also reactivated an old European debate on the source of the devastating 1755 Lisbon Earthquake (estimated Mw between 8.5-9.0), which is thought to have nucleated along the Azores Gibraltar Fracture Zone (AGFZ) at its intersection with the Gibraltar subduction zone [2,3,4]. More recently, a Ms=8.4 earthquake (25/11/1941) was registered along the AGFZ implying a rupture of 250-300km and evidence for active strike-slip faults in the Horseshoe Abyssal Plain (HAP) associated with upper mantle (40-60 km) transpressive seismicity [5]. The interaction observed between trusts and strike-slip faults in the western part of the AGFZ is hypothetically linked to the oceanwards propagation of the Gibraltar subduction zone [6].

Moreover, it was recognized after the 2004 Sumatra and 2011 Tohoku earthquakes that subduction mega-earthquake rupture can extend, and even nucleate, below a partly serpentinized forearc mantle wedge [7,8]. The heterogeneity of mantle composition and serpentinization in subduction mantle wedges, along oceanic transforms, and generally in all intra-oceanic deformation zones thus appears as a possible factor controlling seismicity. In the HAP, recent investigations demonstrated that sediments overlay directly serpentinite rock exhumed from the mantle, which displays important lateral variations (from 2 to 12 km) of serpentinized layer thickness [9]. On the other hand, mud volcanoes linked to strike-slip faults are known from the Gulf of Cadiz to the east where deeply sourced fluids indicate leaching of oceanic crust underneath [10]. More recently, sites of active fluid migration were also discovered along these strike-slip faults in and adjacent to the HAP. The discovery of this novel type of seeps, which is intermediate between sedimented margins cold seeps and hydrothermal vents at mid-ocean ridges, implies that deep fluid circulations take place even in up to 140 My old [11] oceanic lithosphere. The seeps appear close to earthquake epicenter clusters, suggesting the existence of a link between deep fluid circulation and seismic activity. Fluid flow in old oceanic lithosphere is largely unconstrained and favored by the presence of seamounts and rugged basement topography [12].

Performing a fluid injection test in an oceanic transform to trigger a moderate earthquake has been proposed as a fundamental seismology experiment [13]. Even though such endeavor might seem unrealistic, it is possible to characterize the fluid-mantle interaction in an intra-oceanic deformation zone accessible by drilling and to determine the composition and properties of a major seismogenic fault zone in this context. Monitoring and active experiments could be envisioned on the longer term but, apparently, such settings have not been addressed by drilling since DSDP Leg 13 on Gorringe Bank. This white paper spawned from a European networking proposal "FLOWS" that aims to study the “Impact of Fluid circulation in old oceanic Lithosphere on the seismicity of transfOrm-type plate boundaries: neW solutions for early seismic monitoring of major European Seismogenic zones” (COST proposal oc-2012-2-13444). The AGFZ constitutes a possible intra-oceanic deformation setting to investigate the role of deep fluid circulation and upper lithospheric structure in stress cycling and seismic activity. We propose at the 2013 Chikyu+10 meeting to open a debate on the best strategies and locations worldwide to address seismogenesis within old oceanic lithosphere and upper mantle.

References:

[1] Delescluse, M. et al., 2012, Nature 490, 240–244, doi:10.1038/nature11520; [2] Rosas, F.M. et al., 2012, Tectonophysics, 548-549, 1 – 21; [3] Duarte, J.C. et al., 2011, Marine Geology 289, 135–149; [4] Gutscher et al., 2012, Tectonophysics, 574-575: 72-91; [5] Bartolome, R., et al., Geology 40, 495-498; [6] Duarte J., et al., Geology (in press); [7] Dessa, J.-X. et al., 2009, Geology, 37, 659-662, doi: 10.1130/G25653A.1; [8] Yamamoto, Y. et al., 2011, J Geophys. Res., 116, B10310, doi: 10.1029/2011JB008470; [9] Sallarès V. et al., 2013, Earth Planet. Sci. Lett., 365, 120-131; [10] Scholz F. et al., 2009, Geochim. Cosmochim. Acta, 73, 5444-5459; [11] Sallarès V. et al., 2011, Earth Planet. Sci. Lett., 311(1–2), 112-123; [12] VonHerzen R.P., 2004, in: Hydrogeology of the oceanic lithosphere, E.E. Davis and H. Elderfield, eds., pp. 414-447, Cambridge University Press, Cambridge; [13] Mori, J.K. et al., 2009, INVEST workshop Bremen, http://www.marum.de/Binaries/ Binary42250/Mori_TransformFaults.pdf.

Drilling into shallow interplate thrust zone for long-term monitoring of fault motion

Ryota Hino

Graduate School of Science, Tohoku University

Keywords:

The occurrence of the 2011 Tohoku-Oki earthquake (M9.0) showed that an interplate earthquake which ruptures up to the front end of the subduction interface, a trench axis, can occur, although it has been conceived that the shallowest portion of the megathrust fault is completely aseismic. Along the shallowest margin, anomalous tsunami earthquakes sporadically happen to cause disproportionally large tsunami as compared to the radiated seismic energy, and the same kind of process occurred during the 2011 Tohoku-Oki earthquake. JFAST (Expedition 343 in April and May 2012) tried to shed lights on the frictional process of the shallow portion of the plate boundary fault zone and provides us with invaluable information which contributes to clarify how and why the shallowest zone can break to cause tsunami earthquakes or gigantic earthquakes. However, it remains unknown if the fault was locked and strain was accumulated prior to the occurrence of the massive earthquake. As to the rupture zone of the Tohoku-Oki earthquake, it is very difficult to estimate slip rate at the fault before the mainshock rupture but afterslip measurement will put large constraint on the fault motion prior to the earthquake. There is no room for argument regarding the importance of in-situ measurement of the fault slip in other shallow thrust faults including the northern and southern parts of Tohoku margin remained unruptured by the 2011 earthquake.

I propose here to make long-term geodetic monitoring in the boreholes drilled into the shallowest portion of the megathrust fault to clarify how deform this area in the interseismic as well as postseismic periods. Due to the complexity of the fault zone structure, as revealed by JFAST, we may not assume that the long-term deformation is in a form of slip along the single fault as in the normal earthquakes. Therefore, building a dense vertical array across the fault zone is particularly important. The deformation data obtained by this array observation will reveal rate of deformation indispensable to interpret the sample oriented study.

These downhole measurements have to be made in tight collaboration with large scale survey to construct an earth model on which computer simulations are made. Both gigantic earthquakes and tsunami earthquakes are rare phenomena, simulation studies are inevitable for understanding the generation mechanisms of these anomalous earthquakes. The multiple borehole observatories have to be built. Deployment of ocean bottom geodetic network, i.e. GPS/A for horizontal motions, pressure gauges for vertical movements, covering the downhole sites is essential as well as network of seismic observations to detect microseismicity, which may be involved in deformation of the fault zone.

The most preferable site for this drilling research is Japan Trench subduction zone, including the source areas of the 2011 Tohoku-Oki and 1986 Sanriku tsunami earthquakes. In the area, dense ocean-bottom seismological and geodetic observation networks are planned to be deployed. Other source areas of past tsunami earthquakes whose spatial slip patterns have been well studied, e.g. the 1992 Nicaragua earthquake, the 2006 Java earthquake, the 2010 Mentawai earthquakes can also be good candidates for comparative study to generalized the idea obtained in Japan Trench.

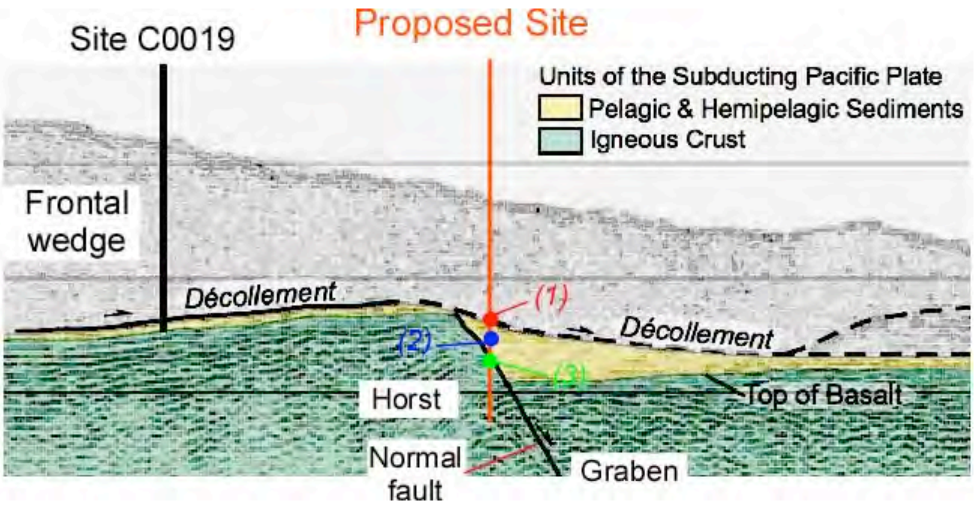
Active Processes around Subduction Trenches (J-FAST revisited)

Takehiro Hirose[1]

[1]Kochi Institute for Core Sample Research, JAMSTEC

Keywords: Japan Trench, earthquake, fault, outer rise, tsunami,

Earthquake faulting near subduction trenches and subsequent deformation of trench sediments potentially cause destructive tsunamis. To reveal mechanisms of the faulting and the tsunami generation are essential to understand what happened at depth during great subduction earthquakes (i.e. the 2011 Tohoku earthquake). We'd like to propose the following subjects and potential sites:



A potential drilling site to research above scientific subjects (modified from Preliminary Report of Expedition 343).

1. The 2011 Tohoku Earthquake fault(s)

What mechanisms cause large slip near the trench at 2011 Tohoku earthquake?

It is necessary to identify the physico-chemical processes in the shallow portion plate boundary fault (decollement) during the Tohoku earthquake to understand great subduction earthquakes and subsequent tsunami generations worldwide. To do this, *continuous core samples across the potential slip zones* of the Tohoku earthquake are needed.

2. Sediment features in Graben

Do a part of oceanic sediments erode at horst and redeposit at graben?

~400 m thickness of oceanic sediments on the Pacific plate at Site 436 (Leg. 56) reduces to only ~20 m observed at Site C0019 (Exp. 343) which locates only 5 km landwards from the trench. A question arises where the sediments move away. Likely answers include the accretion to the wedge and/or the redeposition in the graben. Such phenomenon is a key to understanding the geological processes at erosional margins. However probably no one has known/observed the sediment features of active graben so far.

3. A possible fault for outer rise earthquakes

Can seismic normal faulting reach near ocean bottom?

Outer-rise normal faults forming horst-graben structures develop towards subduction trenches. Outer-rise earthquakes are thought to result from such normal faulting and often become active after plate-boundary earthquakes. To reveal whether these faults are seismic or not and whether earthquake rupture propagated to near ocean bottom in the past if these are seismic are essential to assess the tsunami hazard. Style of faulting also may affect the sediment strictures in graven. The issue can be accessed by recent structural and chemical analyses of fault core materials. Drilling through proto-decollement and outer-rise normal faults *at the incoming Pacific plate* can also help to better understand active geological and hydrological processes at the Japan Trench by comparing two sites.

PORE PRESSURE IN ACCREIONARY SEDIMENTARY PRISMS AND ITS CONSEQUENCES: Chikyu+10 Workshop

R.D. Hyndman
Pacific Geoscience Centre, Geological Survey of Canada
and SEOS, University of Victoria

Introduction

The notes below are intended as discussion points for examining some of the consequences of high pore pressures in large accretionary sedimentary prisms, and how deep drilling and measurement can be used to provide model testing. The aim is: how can we increase our understanding of sediment deformation processes and the role of pore pressure variations? High pore pressure in sedimentary fold and thrust belts as an explanation of common shallow thrust dips has been much discussed since the seminal papers of Hubbert and Rubey (1959) (several examples: Davis et al., 1983, critical taper theory; Kumura et al., 2007, landward changes). High pore pressures also are commonly given explanation of the inferred low stress drops and very small frictional heating of great thrust earthquakes (although there are several other good possible explanations). The IODP SEIZE drilling and measurements in subduction thrusts off SW Japan and Costa Rica are acquiring some of the critical test data for the different explanations. As well as great subduction earthquakes, there is much more to be done to address the role of high pore pressure in the large scale deformation of subduction accretionary prisms, and by inference the deformation mechanisms of now inactive land fold and thrust belts. I focus on the role of pore pressure on deformation, but fluid migration driven by pressure gradients are also very important for fluid migration and chemistry and for some hydrocarbon and mineral distributions, especially in land fold and thrust belts. I note that there is an interesting possibility of complementary drilling and measurement for pore pressures and stresses in currently active land fold and thrust belts such as the eastern Andes and Yukon Mackenzie Mountains frontal thrusts, such as by the International Continental Drilling Program (ICDP).

Accretionary Prism Deformation and Pore Pressure

Accretionary sedimentary prisms appear to deform in two principal modes (although can be very complex), (1) frontal thrusts and folds, including some out-of-sequence thrusts, (2) bulk incoherent deformation where the incoming sedimentary layering as seen in seismic sections is completely lost (often “scaly fabric” in cores). I give examples from northern Cascadia below. We have indirect estimators of pore pressure within prisms primarily from seismic velocities and inferred porosities (velocity-porosity relations need calibration for this environment), and we have numerical deformation models explaining why porosities in some areas are higher than those for normal compaction with depth. Normal consolidation with depth is retarded by high pore pressures. In turn, the rate with which tectonic high pore pressures are bled off with time is dependent on large scale sediment permeability.

Cascadia Example

I give two examples of tectonics-driven porosity changes from Cascadia (chosen because I am familiar with the work): (1) Frontal thrusts have anomalously low porosities, especially in the hanging wall (relative to normal consolidation), based on seismic velocity data (e.g., Yuan et al., 1994) (in contrast to high porosity high pore pressure underthrust section drilled in SW Japan) and, (2) In the incoherent deformation area further landward, the inferred porosities are

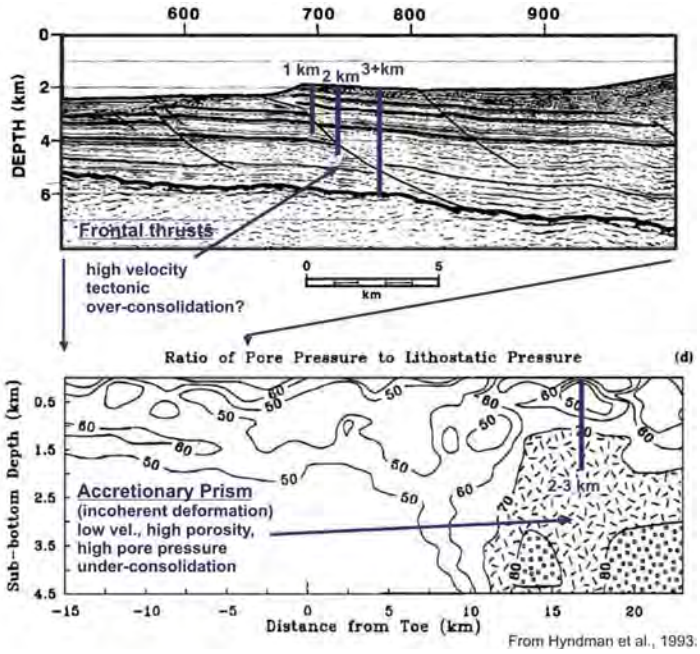


Figure. Top: N. Cascadia frontal thrusts that extend to top of crust and that result in overconsolidation, (Bottom) Pore pressures (%Lithostatic) across the whole accretionary prism.

anomalously low as expected from high pore pressures that retard normal consolidation (e.g., Hyndman et al., 1993). These high pore pressures undoubtedly play an important role in the bulk deformation of the inner prism (the role of landward sediment lithification also needs to be further addressed).

The Cascadia accretionary prism has several advantages over many other areas. First has a large prism of mainly clastic sediments with few if any volcanic horizons that have been altered to weak clay detachment layers that complicate the study, and has the basal detachment commonly right at the base of the sediment section, and second, it has been exceptionally well studied with a wide range of relevant current and planned future studies (e.g., GeoPrisms etc.).

CORK and Related Borehole Systems

The important question is how to test the models for sediment accretion deformation and consolidation. Fortunately we now have the basic tools for measuring formation pore pressures in boreholes i.e., the CORK system (e.g., Davis et al., 1992) that has been a remarkable success. There also has been some success in geotechnical properties. What is needed is very carefully prepared drillhole measurements and long-term recording in appropriate locations to test the models and increase our understanding of the small scale deformation mechanism where it occurs (i.e., scaly fabric) and large scale deformation in faults and folds where that is the primary deformation mechanism.

A few references:

Hubbert, M.K. and W. Rubey, 1959. Role of fluid pressure in mechanics of overthrust faulting: I. Mechanics of fluid-filled porous solids and its application to overthrust faulting, *GSA Bulletin,* 70, 115-166.

Davis, D., J. Suppe, and F.A. Dahlen, 1983. Mechanics of fold-and-thrust belts and accretionary wedges, J. Geophys. Res. 88, 1153-1172.

Kimura, G. et al., 2007. Transition of accretionary wedge structures around the up-dip limit of the seismogenic subduction zone, Earth and Planetary Science Letters, 255, 471–484.

Hyndman, R.D., K. Wang, T. Yuan, and G.D. Spence, 1993. Tectonic Sediment Thickening, Fluid Expulsion, and The Thermal Regime of Subduction Zone Accretionary Prisms: The Cascadia Margin Off Vancouver Island, J. Geophys. Res. 98, 21,865-21,876.

Davis, E.E. and R.D. Hyndman, 1989. Accretion and recent deformation of sediments along the northern Cascadia subduction zone, Geol. Soc. Am. Bull. 101, 1465-1480.

Davis, E. E., M. J., Mottl, A.T. Fisher, et al., 1992. 3. Cork: A Hydrologic Seal and Downhole Observatory for Deep-Ocean Boreholes. Proc. Ocean Drill. Prog., Initial Reports, 139.

Yuan, T., G.D. Spence, and R. D. Hyndman, 1994. Seismicity, velocities and inferred porosities in the accretionary wedge sediments at the Cascadia margin, J. Geophys. Res. 99, 4413-4427.

Turbidite paleoseismology using the trench deposits

[Author] Ken Ikehara[1]

[Institution] [1]Institute of Geology and Geoinformation, Geological Survey of Japan, AIST

[Keywords] turbidite, earthquake, tsunami, geohazard, Japan Trench

Earthquakes and their related tsunamis are typical geohazards. Challenge 12 of the IODP Science Plan for 2013-2023 clearly indicated that “Improving our standing of when, where, and how great earthquakes occur is among the most urgent and challenging tasks facing modern Earth science”. Some observations suggested the significant influence of submarine landslide(s) for tsunami height in the 2011 Tohoku earthquake tsunami. But the ground-truth data has not been obtained yet. We need much knowledge and ground-truth data on the earthquake-related submarine slope failures and their deposits for reducing the damages by the natural hazards. For the purpose, sequential drillings along the Japan Trench lower landward slope where submarine slides/failures are expected from bathymetry, are important.

On the other hand, recent study by shallow coring in the Japan Trench floor near the epicenter of the 2011 Tohoku earthquake suggested the occurrence of clear evidence of the past earthquakes in the Japan Trench. High sedimentation rate and most distal sedimentary setting of the Japan Trench indicates higher preservation potential of the earthquake-related event deposits in the Japan Trench floor than in the shallower forearc basins where the benthos activities are higher than the trench floor. Small basins formed related to the subducted seafloor morphology (horst-graben structures on the Pacific Plate) in the Japan Trench form a series of individual depocenter, which has high probability of local preservation of gravity flow deposits occurred in relation to the submarine slope failures at the nearby slopes. Therefore, sequential corings of the trench floor deposits at each small basin may allow us to reconstruct the temporal-spatial distribution of gravity flow deposits such as turbidites and debrites related to the past large earthquakes along the Japan Trench, and to understand the history and location of past large earthquakes and their related submarine landslides along the Trench. These reconstructions might contribute to “when and where great earthquakes occur”. Simply considered, the larger spatial distribution of a correlative event deposit suggested the wider spatial disturbance by an earthquake suggesting larger magnitude (or larger destructive area) of the earthquake. Of course, there is a possibility that the similar reconstruction might be done by using onshore tsunami deposits. However, due to the eustatic sea-level fluctuation during the Quaternary, onshore tsunami deposits are influenced by the relative location of the past shoreline. More stable trench deposits have much potential to reconstruct the location of the past large earthquakes, especially along the Japan Trench. Furthermore, far-field tsunami might have smaller influence to the deep-sea sediments than onshore and coastal sediments due to their larger water depths, even if the large far-field tsunami got huge damages along the coast. Thus, the deep-sea sediments have much advantage than the onshore tsunami deposits on this point.

Therefore, I recommend to the IODP community, especially to the Japanese community, to drill each small basins along the Japan Trench to understand the past large earthquakes along the Trench. Spatio-temporal distribution of gravity flow deposits such as turbidites and debrites may give us information on the past earthquakes. Furthermore, the deformation of the trench-fill sediments may give us further information on the mode of the faults and behavior of the tectonic movements along the Trench. The Japan Trench is the best place to do such a study because the small basins are bathymetrically clearer than the other trenchs such as the Nankai Trough and Sumatra Trench.

The experience along the Japan Trench might be useful for the application of this method and understanding of the past earthquakes and their related phenomena along the other trenches, even if the response of the slope on the earthquake and its related tsunami might different place by place reflecting sedimentological, geomorphological, seismological and geological settings of the place. Therefore, the earth scientists should do similar works along the other plate boundaries, and gather the local examples to make a global standard to reduce the human damages all over the world.

Slow slip drilling re-defines earthquakes

Yoshihiro Ito (Tohoku University), Arito Sakaguchi, Yuzuru Yamamoto (JAMSTEC), Satoshi Ide (University of Tokyo), Reiji Kobayashi (Kagoshima University)

Keywords: slow slip, earthquake, subduction zone

The risk of earthquakes is apparently different in subduction zones. While large earthquakes occur in limited regions of a subduction zone, slow-slip events (SSE) can be a ubiquitous background process, which governs a wide variation in seismic behaviors in subduction zones. This paper emphasizes the importance of investigating SSEs via deep-ocean drilling projects in the next 10 years and more.

SSEs have been known since 1970s, but the importance of SSEs has only been recognized in this decade. SSEs have been discovered in many subduction zones worldwide, such as Nankai, Boso, Cascadia, Mexico, and Costa Rica. They were originally thought to be typical of young and warm subduction zones. However, they have also been discovered in Hikurangi, New Zealand, and even in a very old subduction zone near the Japan Trench, where an SSE occurred before a very large earthquake. We assume that SSEs occur in every subduction zone. More generally, any parts of a plate interface that do not radiate intense seismic waves can be considered as potential slow slip sources. Unlike ordinary earthquakes, which are elastodynamic ruptures controlled by fracture/friction laws, the governing laws for slow slips are not well understood. The diversity of SSEs is much larger than that of ordinary earthquakes. For example, the duration of an earthquake correlates with the cubic root of the seismic moment. The duration of a slow earthquake is also roughly proportional to the seismic moment, but the scatter of samples is wider than two orders. Because of this large diversity, a comprehensive understanding of slow earthquakes cannot be achieved by detailed investigation of a single subduction zone. Comparative studies of different tectonic settings are required. The difference between physical/material conditions in background plate interfaces, including slow-slip areas, could well help explain the wide variety of seismicity in subduction zones, which used to be interpreted with two end members: Chile and Mariana types.

SSEs are an end member of the slow-earthquake family, which also includes very-low frequency earthquakes, low-frequency earthquakes, and tectonic tremors. The diversity of the slow-earthquake family is attributed to the scale or dominant frequency of the source spectra of the event. While most SSEs are found in deeper portions of subduction zones, several shallow (<20 km depth) SSEs are documented, such as off Boso Peninsula, Japan Trench, Costa Rica, and New Zealand. These shallow slow slip areas are the most suitable drilling targets to obtain information that will help understand the governing laws for slow earthquakes. The other distinct advantage of drilling of shallow slow slip areas is the frequent activity, or short recurrence intervals between events; the recurrence intervals of SSEs with moment magnitude 6.5 off Boso Peninsula, and off the east coast of North Island of New Zealand are 4–6 years and 1–2 years, respectively, whereas that of large earthquakes is >10–20 years.

Multi-phase drilling of a slow slip fault, especially before and after an SSE is our basic strategy. The short recurrence intervals of SSEs give us a high chance of observation of multiple SSEs and enables flexibility in the drilling plan. In the first drilling, core samples and logging would provide information on lithology, seismic velocity (P- and S-wave velocities), density, pore-fluid pressure, and stress in the target area before an SSE. Tiltmeters, strainmeters, and broadband seismometers would then be installed into the borehole.

Following an SSE, the second drilling plan would be adjusted in accordance with the details of the depth, thickness, slip amount of the slow-slip fault plane/zone from the instruments installed in the borehole. Hypocenters of tectonic tremors observed by borehole seismometers as well as ocean-bottom seismometers would also provide constraints to the geometry of slow slip faults, with accurate depth and thickness. Soon after the SSE, branch drilling would re-penetrate the slow-slip fault in the surroundings of the main hole to measure the spatial and temporal variation in stress and physical properties. Vertical seismic profile data along the main borehole is a feasible approach to detect the temporal change of the reflection from the plate boundary.

Coring the inside and outside of a slow-slip zone is the only way to identify what kinds of materials, structures, and *in situ* pressure-temperature conditions characterize slow-slip and non slow-slip zones. In a subduction accretionary complex, a zone of mélange is recognized as a large scaled brittle-plastic deformation zone. Some theories suggest that a mélange-forming process with small effective pressure due to high fluid pressure corresponds to slow-slip fault. Core analysis will validate this prediction by characterizing a slow-slip zone based on accumulated displacement, maximum slip velocity, physical/frictional property distribution, and structural development. Stress estimation using core samples and logging data, combined with fluid pressure measurements, will provide a realistic effective pressure of an SSE. Multi-phase coring with borehole monitoring will reveal variation of the stress state and fluid pressure during an SSE cycle. Given the variation in the rupture processes of SSEs, variations in these aspects in different SSE regions are expected.

We believe that investigation of SSEs via several multi-phase drilling projects will re-define the current understanding of “earthquakes” based on the new knowledge of slow slip mechanisms and lead to a new perspective of subduction processes.

Riser drilling of the Hahajima seamount, Bonin forearc: Ophiolite thrust faults and subduction-initiation magmatism

Akira Ishiwatari (Tohoku Univ.), Yildirim Dilek (Miami Univ.), Tomoaki Morishita (Kanazawa Univ.), Naoto Hirano (Tohoku Univ.), Teruaki Ishii (Fukada Geol. Inst.), Yasufumi Iryu (Tohoku Univ.), Ron Harris (Brigham Young Univ.), and Hirokazu Maekawa (Osaka Pref. Univ.)

Active faults and Earth's mantle are the top two themes of this Chikyu+10 Workshop. Subduction of the Mesozoic oceanic plates caused the two devastating M9 earthquakes in recent years (2004 Sumatra and 2011 Tohoku), and the ruptured faults extended along the subduction zones over 500-1000 km length and 100-200 km depth, penetrating deep into the mantle. Understanding of the active destructive plate boundary is essential for the studies of seismogenic processes, earthquake-tsunami prediction, and hazard mitigation. Ocean drilling of the Hahajima seamount, Bonin forearc may provide a rare opportunity to decipher the subduction zone processes such as hydration and dehydration of the oceanic crust and mantle materials, their deformation in thrust fault zones, scraping and accretion of a subducting oceanic plateau and its limestone cover, and the peculiar Eocene subduction-initiation magmatism with 'mid-ocean ridge basalt' ('MORB'), boninite and adakite.

Hahajima seamount is a fault-bounded, flat-topped (about 1100 m deep), rectangular, table-like topographic high of 60 x 30 km size to the southeast of the Ogasawara (Bonin) Islands. The Hahajima Seamount is about 100 km apart from the Hahajima Island of Ogasawara. The eastern side of the Hahajima seamount is adjacent to the Izu-Mariana trench, which is relatively shallow in this place possibly due to subduction of the buoyant Ogasawara plateau on the Pacific plate. The Hahajima seamount was studied by many dredge hauls, seismic profiling, and submarine diving (e.g. Ishiwatari et al. 2006; Miura et al. 2008).

The Hahajima seamount is situated above the subducting Ogasawara plateau on the Pacific plate, and is interpreted either as a big, composite serpentinite seamount or an uplifted block of the forearc lithosphere (ophiolite) (cf. Ishiwatari et al. 2006). The facts that many dredge sites on the Hahajima seamount are free from serpentinite/peridotite and widespread occurrence of mylonitic, cataclastic and brecciated gabbro/peridotite suggest that the seamount comprises a pile of ophiolitic thrust sheets (*ibid.*). Analogous occurrence of various ophiolitic rocks is reported from the Guatemalan forearc at Cocos-Caribbean plate boundary (DSDP Leg 67 and 84; Geldmacher et al. 2008), where an alternation of serpentinized peridotite and layered gabbros, plagiogranites and basaltic rocks as well as intercalated sediments of Jurassic-Cretaceous ages was drilled. Drilling of the Hahajima seamount may provide important data on emplacement mechanism of forearc thrust slices, helped by fossil dating of the tectonically intercalated limestone films that were peeled off from the subducting Ogasawara plateau.

The Hahajima seamount also bears wide variety of gabbroic and ultramafic rocks. The gabbroic rocks include troctolite, olivine gabbro, (olivine-) gabbronorite, gabbro, norite, hornblende gabbro and their fine-grained varieties. Plagioclase-clinopyroxene mineral chemistry indicates both MORB- and island arc basalt (IAB) magmas for their origin. Ultramafic rocks includes both cumulate and residual mantle types, and the mantle peridotites (mostly harzburgite) shows various degrees of hydration (serpentinization) and metamorphic dehydration (thermal recrystallization) with various degrees of deformation.

Boninite is a high-magnesian andesite that can co-exist with the mantle peridotite, and hence is thought to be one of the primary magmas generated by partial melting of hydrous mantle. Recent discovery of primitive adakite in association with boninite among dredged rock samples from the Hahajima seamount suggests that boninite may be a reaction product between silica-rich adakite magma and mantle peridotite wall (Ishiwatari et al. 2006; Li et al. 2013). We consider that drilling of the Hahajima seamount can provide valuable information about volcanic rock stratigraphy including boninite, adakite, 'MORB', IAB, calc-alkali andesite, dacite and rhyolite. Analogous boninite-adakite assemblage was also reported from Tonga forearc (Falloon et al., 2008), suggesting pervasive distribution of adakite among oceanic forearc areas and its importance in the subduction-initiation magmatism.

The riser drilling system equipped on the D/V Chikyu is the most suitable for penetrating and sampling many thrust fault zones that are expected for "ophiolite drill holes" of the Hahajima seamount that can hardly be drilled by a riserless system. The shallow water depth of the seamount (~1100 m) and enough distance from the Kuroshio current also merit operation of the riser system. The Chikyu drilling of the Hahajima seamount will discover a missing link between the on-land ophiolite and submarine ocean crust, and provide a springboard for advancing subduction zone sciences.

Rererences

Falloon, T., Danyushevsky, L.V., Crawford, A.J. et al. (2008) Boninites and adakites from the northern termination of the Tonga Trench: Implications for Adakite Petrogenesis. *J. Petrol.,* **49**, 697-715.

Geldmacher, J., Hoernle, K., van den Bogaard, P.et al. (2008) Age and geochemistry of the Central American forearc basement (DSDP Leg 67 and 84): Insights into Mesozoic arc volcanism and seamount accretion on the fringe of the Caribbean LIP. *J. Petrol.,* **49**, 1781-1815.

Ishiwatari, A., Yanagida, Y., Li, Y.-B. et al., (2006) Dredge petrology of the boninite- and adakite-bearing Hahajima Seamount of the Ogasawara (Bonin) forearc: An ophiolite or a serpentinite seamount? *Isl. Arc,* **15,** 102-118.

Li, Y.-B. et al. (2013) High-Mg adakite and low-Ca boninite from the Bonin forearc seamounts: Implications for the reaction between the slab melt and depleted mantle. *J. Petrol.* (in press)

Miura, R., Nakamura, Y., Koda, K.et al. (2004) "Rootless" serpentinite seamount on the southern Izu-Bonin forearc: Implications for basal erosion at convergent plate margins. *Geology*, **32**, 541-544

Modes and temporal variation of great earthquakes in the western Nankai Trough

Masao Iwai[1], C. Hans Nelson[2], Yasuhiro Yamada[3], Minoru Ikehara[4], Toshiya Fujiwara[5], et al.

Institutions: [1]Department of Natural Science, Kochi University, [2]Instituto Andaluz de Ciencias de la Tierra, CSIC, [3]Department of Civil and Earth Resources Engineering, Kyoto University, [4]Center for Advanced Marine Core Research (CAMCR), Kochi University, [5]Japan Agency for Marine Earth Science and Technology (JAMSTEC), etc.

Keywords: prehistoric earthquake, great and mega earthquake cycles, Nankai Trough, co-seismic turbidites, active fault.

1. Scientific Objectives
   - To obtain continuous uppermost Quaternary section and to assess the temporal history of historic and prehistoric Nankai Great Earthquakes during last the 200-400kyrs for better understanding of the tempo and mode of subduction earthquakes under different climatic conditions.
2. Background

1) Scientific background

The March 2011 Tohoku earthquake (Mw=9.0) show us that geologic evidence is very important and essential for the risk assessment of low frequency/high impact subduction earthquakes and tsunami hazards. Coseismic turbidites give us an opportunity to reveal tempo and mode of prehistoric great earthquakes (e.g., Nelson et al., 1995; Goldfinger et al., 2003, 2008; 2012; Goldfinger, 2011; Nelson et al., 2000, 2009, 2012). An isolated slope basin is one of the best places to access prehistoric earthquake by using turbidites, and has a potential as a natural recorder of great earthquakes (Iwai, et al., 2004; McHugh et al., 2006; 2011; Beck et al., 2007; 2012; Black et al., 2012; Goldfinger et al., 2012). However, most of the previous studies have been restricted within the Holocene section and there are few studies that show details of temporal change and modes of paleoearthquakes under different climatic condition such as glacial and deglacial stages and Dansgaard-Oeschger climate oscillations (Pouderoux et al., 2012). It is important for better assess of seismic hazard in the climatically unpredictable warming century. Also a deep drilling for a long paleoseismic record has a potential to detect posible superquakes, such as 2011 Tohoku earthquake (e.g. Goldfinger, et al., 2013)

2) Previous studies and related DSDP-ODP-IODP cruises (reference sites)

A total of ~260m thick sediments, Mt2 formation of Minamitosabae Group, fill the Tosabase Basin, a tectonic basin on the landward slope of Nankai Trough (Okamura and Joshima, 1986). Average sedimentation rate of the Holocene section is 0.5-1m/k.y. (Iwai et al., 2004). Recurrence time interval of turbidites obtained from an isolated Tosabae Basin is almost equivalent to those of historic earthquakes, and a total of nine turbidites were directly correlated to historic documents and archaeological records of Nankai Great Earthquakes (Iwai et al., 2004). 2-D seismic profiles show the normal fault in the Tosabae basin has been active through the late Quaternary (Okamura and Joshima, 1986; Iwai et al., 2004)

The accretionary prism of the Nankai Trough off Muroto was drilled during ODP Legs 131 (Taira, Hill, Firth et al., 1991), 190 (Moor, Taira, Klaus et al., 2001), and 196 (Mikada, Becker, Moore, Klaus et al., 2002). Site 1178 of Leg 190 is the closest to the Tosabae Basin, however, it was designed to drill the Miocene-Pliocene accretionary prism and only a few meters of Quaternary section was recovered. Site C0001 of IODP Expedition 315 was drilled at a small bench on the hanging-wall of the megasplay fault and the footwall of the subsidiary fault of Tonankai Great Earthquake source area off Kumano Basin, and recovered ~200m thick Quaternary section, however, turbidites were found from only lower Quaternary section (Ashi, et al., 2008).

3. Overview of Drilling Sites:

(1) Strategy (including Proxies)

<u>Age control</u>: biostratigraphy, magnetointensity stratigraphy, oxygen isotope stratigraphy, AMS ^{14}C, volcanic ash

<u>Detection and characterization of catastrophic events</u>: CT, XRF-scanner, XGT (micro-focus XRF), grain size analysis, geophysical properties (density, magnetic susceptibility), coeval megaturbidite and stacked turbidite directions from sedimentary structures in CT scans

<u>Origin of event sediments</u>: microfossils (Pouderoux et al., 2012), XRD, XRF, Pb-isotope, magnetic properties and micro-fabrics

(2) Plan and design

Area: slope basin of the western Nankai Trough off Muroto Peninsula

Proposed sites:

<u>Site TB1</u> (1650m water depth)

-Triple holes drilling (HPC).

-total penetration depth= A: 4.5m (mudline), B: 200m, C: 205m (5m offset to Hole B)

-site-specific objective: obtain a continuous section from footwall of the normal fault.

-reference site: KR9705P1 (420cm, ~7.3ky)

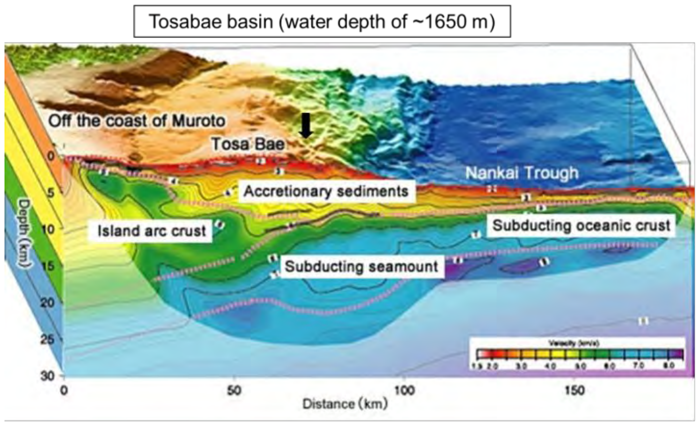
<u>Site TB2</u> (1670m water depth)

-Triple holes drilling (HPC),

-total penetration depth= A: 4.5m (mudline), B: 200m, C: 205m (5m offset to Hole B)

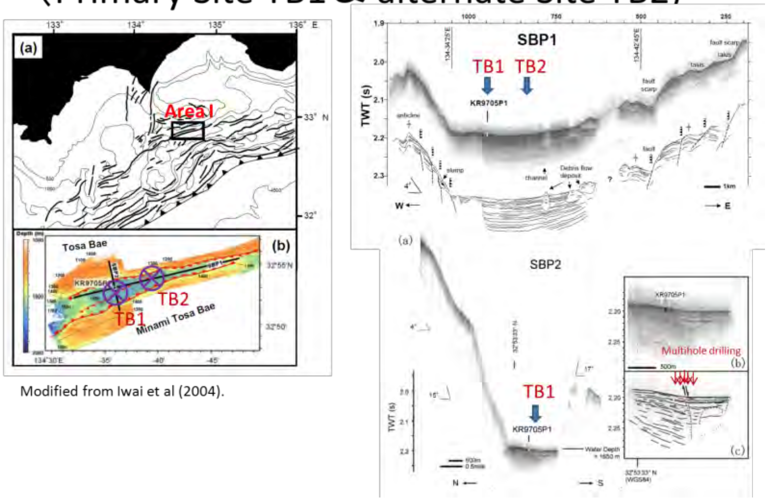
-site-specific objective: obtain a continuous section from hangingwall of the normal fault.

-reference site: KR9911 PC1



3D bathymetry and seismic profile interpretation of Nankai Trough off Muroto Peninsula (Kimura and Kinoshita, 2009) .
Tosabae Basin located on the south of the Tosa Bae is an isolated slope basin on the landward slope of Nankai Trough. A seamount are subducting beneath the Tosabae Basin and strongly affected to the distribution of seismogenic zone of the Nankai Great Earthquakes

Proposed sites
(Primary Site TB1 & alternate Site TB2)



Modified from Iwai et al (2004).

Seismogenic Zone Deep Drilling Off shore Osa Peninsula and Mew Zealand

Miriam Kastner, Scripps Institution of Oceanography, La Jolla, CA 92093, USA

Keywords: Seismogenesis, CRISP, Fluids, Deep-Life, Monitoring

My great interest in participating in the CHIKYU+10 International Workshop in Tokyo, April 21-23, 2013, for the following main reasons:

1. I was one of the original proponents in the planning of drilling offshore Costa Rice, both offshore Nicoya peninsula and more recently offshore Osa Peninsula (CRISP Program). My involvement with the Costa Rica drilling continued as a shipboard scientist on Expeditions 170, 205, and recently on CRISP II Expedition 344. Clearly, I am most interested in being deeply involved in the discussions at this upcoming workshop and if possible in the planning of the next phase of deep drilling to the seismogenic zone offshore Osa Peninsula with CHIKYU.

I was also involved in the planning and in instrumenting the two CORKs for monitoring the role of fluids offshore Nicoya Peninsula (IODP Sites 1253 and 1255); at the workshop I would be able to summarize the results of the monitoring so far. In the fall of 2013 NSF approved 3 days of ROV time to download the latest data and recover the fluids at these two CORKs.

2. Similary, I was one of the proponents of the rather recently approved New Zealand drilling program. At present a proposal to NSF for the monitoring plans is in preparation. This is an exciting drilling program that will as well require the involvement of CHIKYU.I certainly would like to be involved in the discussion of this project at the CHIKYU+10workshop.

3. Finally, If there will be time, discussing the importance of recovering deep volatiles and fluids, that would be possible only with CHIKYU, and the relations to life in extreme environments, would be especially of great interest to the biologists and to the “subducton factory” research community.

The above is a brief summary of my potential contributions to the discussions at the CHIKYU+10 workshop. I am not writing a special white papers on the above topics, because clearly discussion leaders on the basic above topics 1 and 2 must have been chosen already by the organizing committee. I am hoping to contribute during the discussions of these topics.

Regarding topic 3, the deep fluids and biology topic, I will be discussing it with the keynote speaker Ken Nelson on how he could integrate fluid chemistry in his presentation.

In addition to the Active Faults Theme I am most in interested in the Deep Life Theme.

Paleo-seismological record in subduction trench basin

Toshiya Kanamatsu [1]

[1] Japan Agency for Marine-Earth Science and Technology

Earthquake, trench basin, deformation, seismo-turbidaite, diagenessis, faulting

Introduction

The rupture of the 2011 Tohoku earthquake propagated to the trench. Less attention has been paid to this type earthquake, and we have no enough knowledge to understand this event. However geological indications marked by the past earthquakes should be archived in the trench sequence. Coring of sedimentary sequences in the area will provide information for understanding the dynamics of deformation and earthquake recurrence.

Dynamics of trench axis

Fujiwara et al., (2011), and Kodaira et al., (2012) revealed the several ten meters scale displacement of the lower landward slope of Japan Trench occurred co-seismically. Meanwhile an uplifted seafloor appeared in the trench axis, and co-seismic deformation beneath the trench floor reveals thrust imbricated complexes. Such deformation can be studied by coring into the trench wedge, and kinematic analysis on the structure will detail the dynamics of slip at the trench.

Diagenesis process in incoming sequence changes the properties of sediments. The process has no relationship to earthquake, but it changes the property of incoming sediment drastically. In the case of Nankai Trough it causes change of incoming sediment strength (Spinelli et al., 2007), thus inhomogeneity of physical properties of the sediment control where a new fault is formed in the sequence. Such signatures could be helpful to understand a mechanism how a rupture propagates in the trench sequence. So it is also important to monitor physical property of the trench sequence.

Recurrence of earthquake

Recurrence of earthquake can be evaluated using seismo-turbidite accumulated in the trench. Actually paleo seismo-turbidites including 2011 event were observed in the sedimentary sequence in Japan Trench axis. A series of coring in the trench can provide an opportunity to study a long paleo-earthquake history. Describing of temporal and special distribution of seismo-turbidite along trench could document the strongly shaken area: information for location of the epicenter.

Required technologies to implement the study

•Multi-hole coring strategy at one area.

•Precise and detail shallow acoustic image to target the sequence.

•Drilling operation in deep water depth (7000-9000m)

•Non disturbed sampling technique is indispensable to obtain in-situ sequence structure and properties (e.g. maximize HPCS ability such as half penetration strategy).

THE RENEWAL SIGNIFICANCE OF DEEP RISER DRILLING INTO PLATE BOUNDARY THRUST FAULTS
from an exercise of exhumed and fossilized seimogenic plate boundary thrust

Gaku Kimura[1], Saneatsu Saito[2], Asuka Yamaguchi[3], Jun Kameda[1], Mari Hamahashi[1], Rina Fukuchi[4], Yohei Hamada[1], Yoshitaka Hashimoto[5], Koichiro Fujimoto[4], Yujin Kitamura[2], and Hiroko Kitajima[6]
[1]Univ. Tokyo, [2] JAMSTEC, [3]AORI, Univ. Tokyo, [4] Tokyo Gakugei Univ., [5] Kochi Univ., [6] AIST

Recent investigations of exhumed and fossilized plate boundary thrusts and megasplay faults strongly suggest that unraveling the physico-chemical dynamics of fluid-rock interaction and resultant rupture of great earthquake and tsunami is the scientific target of the seimogenic plate boundary processes, which is accessible only by Chikyu-deep riser drilling. The expected result of drilling into the active and living fault in depth will be a great step of science.

Technological advantage of the Chikyu Riser drilling provided us the ability of deep hole coring, logging and observatory installation. A main target of IODP was direct drilling into the seismogenic plate boundary thrust in the Nankai Trough of subduction zone. After the first proposal for the NanTroSEIZE many new discoveries have been reported from subduction zones, e.g. deep low frequency earthquakes, shallow low frequency earthquakes, high velocity slip even along the plate boundary decollement and on-going stress build-up within the hanging wall accretionary prism. However, unfortunately the deep target of IODP has not been reached yet.

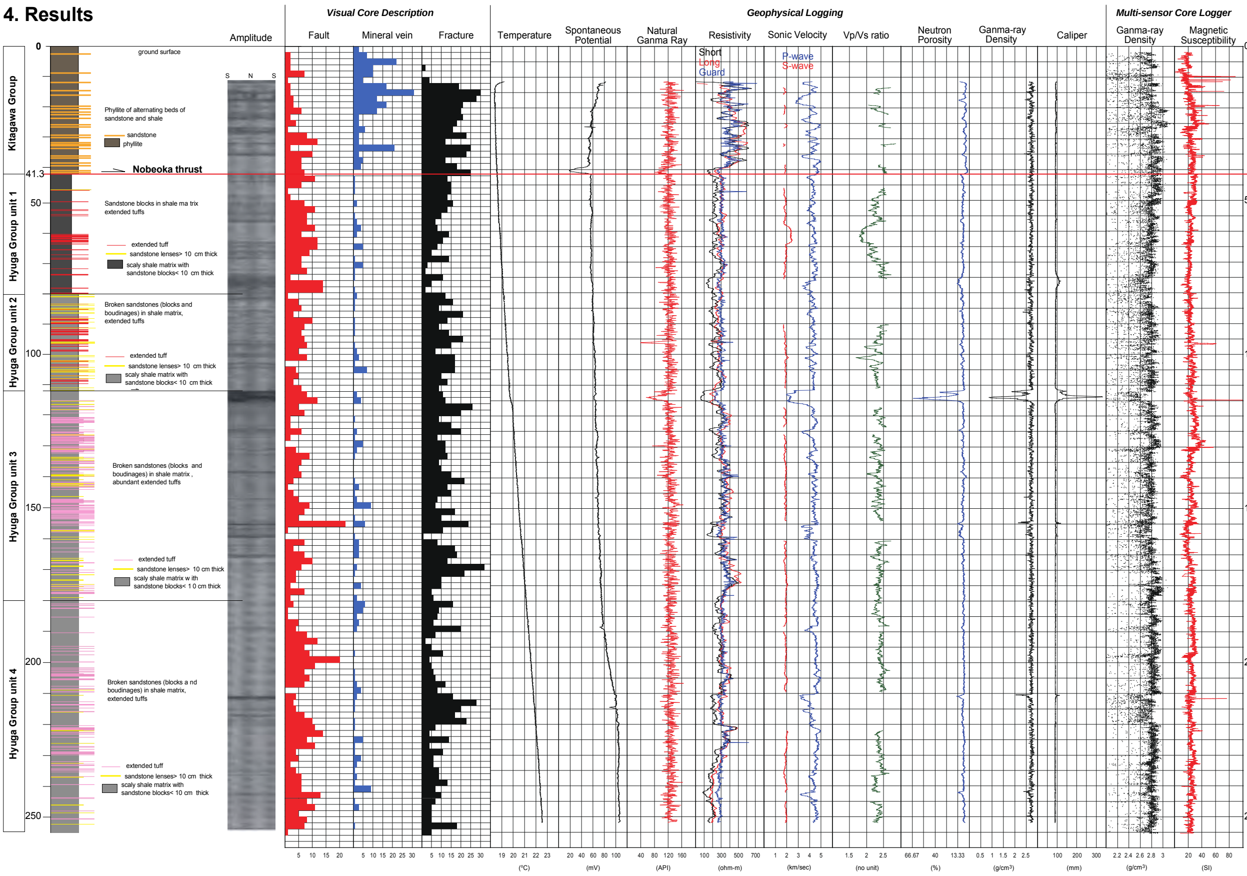
Prior to drilling into the seismogenic deep splay fault and plate boundary thrust, we have conducted investigation of exhumed and fossilized splay fault of the Nobeoka thrust and plate boundary fault rocks recorded as melange in the Shimanto belt, Japan. The Nobeoka thrust was once buried at the depth of more than 10 km in subduction zone. Combining with the inspection of surface exposure, drilling with logging for physical properties and borehole imaging was operated to compare the one dimension data set with the three dimensional occurrences of the fault zone.

In spite of the surface weathering and cracking with exhumation, the results of coring, logging, and borehole imaging present the condition of the fault in the depth of plate boundary. They show porosity less than several percentages with a marked contrast between the hanging wall and footwall, which are well correlated with electric resistivity, and elastic wave velocities of Vp and Vs. These physical properties systematically change with the development of discrete slip zones in the shear zone and define a quantitative damage zone. Abundant mineral precipitation is characteristic in the fault and presents a catalog of fault rocks from friction melt of pseudotachylyte to fluidized fault rock suggesting various fault mechanisms of dynamic weakening.

REE pattern of carbonate vein precipitated along the slip surfaces and extensional cracks suggests that fluid flow along the fault, which might be co-seismic, would be under reductive condition but inter-seismic fluid appear to be oxidized condition. The change in chemical property might be related to rupture-induced fluid-rock interaction along the plate boundary.

Exploration of the fossilized plate boundary to deep living ones is the revolving jump like autopsy to modern open-heart surgery in medical science. The drillin g into various plate boundaries with different subduction parameters is quite essential.

4. Results



Amplitude
Visual Core Description
Fault
Mineral vein
Fracture
Geophysical Logging
Temperature
Spontaneous Potential
Natural Ganma Ray
Resistivity
Short
Long
Guard
Sonic Velocity
P-wave
S-wave
Vp/Vs ratio
Neutron Porosity
Ganma-ray Density
Caliper
Multi-sensor Core Logger
Ganma-ray Density
Magnetic Susceptibility
Kitagawa Group
Hyuga Group unit 1
Hyuga Group unit 2
Hyuga Group unit 3
Hyuga Group unit 4
ground surface
Phyllite of alternating beds of sandstone and shale
sandstone
phyllite
Nobeoka thrust
41.3
Sandstone blocks in shale matrix extended tuffs
extended tuff
sandstone lenses> 10 cm thick
scaly shale matrix with sandstone blocks< 10 cm thick
Broken sandstones (blocks and boudinages) in shale matrix, extended tuffs
Broken sandstones (blocks and boudinages) in shale matrix, abundant extended tuffs
(°C)
(mV)
(API)
(ohm-m)
(km/sec)
(no unit)
(%)
(g/cm³)
(mm)
(SI)

The physics and mechanisms of shallow décollement earthquake nucleation and slip from deep drilling in the Japan Trench

James Kirkpatrick[1], *Matt Ikari*[2], *Kohtaro Ujiie*[3,4]
[1]Colorado State University, USA, [2]MARUM, University of Bremen, Germany, [3]University of Tsukuba, Japan, [4]IFREE, JAMSTEC, Japan

Keywords: Earthquake, Japan Trench, tsunami, shallow slip, seismic cycle

Scientific objectives

Earthquake slip at shallow depths on subduction décollements causes large motion of the seafloor and consequently has a high risk of generating tsunamis. Seismological observations show that slip in the up-dip section of the décollement is characterized by enhanced long period radiated energy compared to deeper subduction zone earthquakes for both great earthquakes that nucleate at depth and propagate up-dip toward the trench, and for 'tsunamigenic' earthquakes that can nucleate at shallow depth (Kanamori, 1972; Fukao and Kanjo, 1980; Polet and Kanamori, 2000; Uchida *et al*., 2004; Lay *et al*., 2011; Lay *et al*. 2012). However, several key aspects of the physics of shallow slip are currently unknown:

1. How efficient is strain energy accumulation and release at shallow depths?
2. What conditions facilitate earthquake nucleation at shallow depths?
3. What physical mechanisms control the coseismic slip shear resistance and radiated energy content?

Answering these questions is critical for better understanding the underlying physics of earthquake slip at shallow depths and therefore the hazard from these devastating events.

Strategy for answering these questions: Deep ocean drilling in the Japan Trench

We propose that these questions can be addressed by deep ocean drilling by the D/V *Chikyu* in the Japan trench, which has a history of tsunamigenic events. Coring the shallow décollement where tsunamigenic slip is known to have occurred can provide samples for direct observation and measurements of the physical properties of the materials in the seismic fault zone. The key questions outlined above can be answered from these observations and measurements in the following ways.

1. Strain energy accumulation in the vicinity of the décollement is a function of the steady-state, low velocity frictional strength of the fault, and the elastic properties of the rock surrounding the fault. Friction measurements on samples recovered from the shallow portions of the Japan and Nankai trenches suggest that the low-velocity frictional behavior of the plate boundary faults is more complex than previously appreciated. In addition, recovery of the plate boundary décollement during IODP Expedition 343 (J-Fast) revealed intense strain localization and a strong foliation in clay-rich material, which are considered to be a major controls on fault slip behavior (Collettini *et al*., 2009). However, recovered material was limited, and experimental friction data for samples with preserved in-situ fabric and microstructure are essential. Additionally, the fault zone-wall rock boundaries, considered important because it is where slip tends to localize, were not recovered. Samples dedicated to friction and physical properties tests would measure the frictional strength of the décollement at plate-convergence rate velocities and the elastic moduli of the surrounding rock.

2. The tendency for slip instability resulting in earthquake nucleation depends on the frictional properties of the décollement, effective stress conditions (and thus, pore pressure), and elastic properties of the wall rocks (Scholz, 1998). Shallow regions of subduction zones are generally assumed to be conditionally stable, with velocity-strengthening frictional behavior and/or low effective stress inhibiting nucleation. However, some events do nucleate at shallow depths (Fukao and Kanjo, 1980; Ito and Obara, 2006), suggesting the transition from conditionally stable to unstable with depth (Marone and Saffer, 2007) is complex. Measurements of the velocity-dependence of friction and wall rock elastic properties (Young's moduls, shear modulus, Poisson's ratio) will show whether the materials in the shallow part of the Japan Trench favor shallow earthquake nucleation and will shed light into the long-term evolution of the fault.

3. Recent results suggest that shallow slip in the stable parts of plate boundary faults may result from dynamic weakening as large earthquakes propagate up-dip to the trench (Noda and Lapusta, 2013). The radiated energy from tsunamigenic slip may also depend on the physical characteristics of the slip zone and processes activated during an earthquake. It is not clear what the exact process are, but identifying them is essential for understanding the conditions that facilitate rupture propagation and the anomalous

radiated energy. We propose that microstructural examination of samples containing the slip zone of the 2011 Tohoku and 1895 Sanriku earthquakes will demonsrate the coseismic processes that enabled large shallow slip. These samples will also be used for physical properties measurements (e.g. porosity, permeability) that control these processes.

Drilling targets and operation

The 2011 M_w9.0 Tohoku-Oki earthquake and the 1896 Meiji-Sanriku earthquake off Iwate both exhibited large, shallow slip (Figure 1; Tanioka and Satake, 1996; Lay *et al.*, 2011) and both caused enormous tsunamis. However, the Sanriku event is considered a tsunami earthquake unlike Tohoku event. These events provide targets for samples that relate directly to shallow seismic slip, facilitate a comparison between tsunamigenic slip and slip propagating from depth, and also, because they are separated by ~115 years, from different stages in the seismic cycle. Furthermore, comparing the frictional properties and coseismic processes associated with areas of very large, moderate and small shallow slip is possible by targeting multiple sites within the 2011 M9 Tohoku rupture, for which slip models are well constrained from teleseismic and GPS data (e.g. Lay *et al.*, 2011; Yue *et al.*, 2011). Therefore, to evaluate the temporal and spatial controls on shallow slip, we propose to visit multiple sites within the area of the 2011 M9 Tohoku rupture, the 1896 Sanriku rupture, and the region south of the Tohoku rupture, which did not rupture in 2011 and may therefore be primed for failure in the near future (Figure 1).

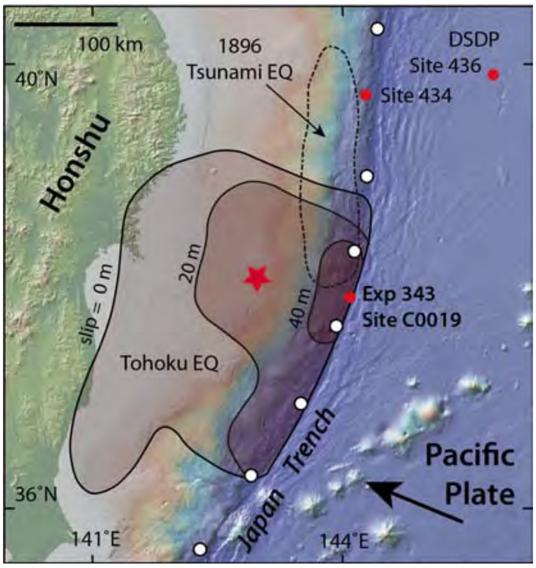


Figure 1. Location of the Mw9.0 Tohoku-Oki and 1896 Meiji-Sanriku earthquake ruptures in comparison to the Japan Trench. Red dots mark the locations of previous ocean drilling expeditions, and white dots represent target sites for the work proposed here. Note we also propose to revisit site C00019 from Expedition 343. Modified from Chester *et al*. (2012).

The deep ocean drilling capabilities of D/V *Chikyu* are essential to the scientific goals outlined here. Ocean bottom depths near the trench in the target regions are 6000-7000 mbsl. Penetrating the décollement at shallow depths (≤1 km) therefore requires coring at a total depth below sea level of ≤8 km. The recent success of Expedition 343 shows that the frontal prism at the Japan Trench is relatively stable for drilling operations (Chester *et al.*, 2012). We suggest that the coring operations required for this proposal can be achieved relatively simply by blind spudding and coring for small intervals (potentially targeted at 100 m intervals). Recovery of the entire width of the plate boundary décollement is an important goal; high velocity slip tends to nucleate at boundaries of mechanical contrast, which most likely occur at the edges of the sheared fault zone.

References

Chester, F.M., Mori, J.J., Toczko, S., Eguchi, N., and the Expedition 343/343T Scientists (2012). IODP Prel. Rpt., 343/343T. doi:10.2204/iodp.pr.343343T.

Collettini, C., Niemeijer, A., Viti, C., & Marone, C. (2009). *Nature*, *462*(7275), 907-910.

Fukao, Y., & Kanjo, K. (1980). *Tectonophysics*, *67*(1), 153-162.

Ito, Y., & Obara, K. (2006). *Geophysical research letters*, *33*(2), L02311.

Kanamori, H. (197. *Physics of the earth and planetary interiors*, *6*(5), 346-359.

Lay, T., Ammon, C. J., Kanamori, H., Xue, L., & Kim, M. J. (2011). *Earth, Planets and Space*, *63*, 687-692.

Lay, T., Kanamori, H., Ammon, C. J., Koper, K. D., Hutko, A. R., Ye, L., ... & Rushing, T. M. (2012).. *Journal of Geophysical Research*, *117*(B4), B04311.

Marone, C., & Saffer, D. M. (2007). *The Seismogenic Zone of Subduction Thrust Faults*, 346-369.

Noda, H., & Lapusta, N. (2013). *Nature*, *493*(7433), 518-521.

Polet, J., & Kanamori, H. (2000). *Geophysical Journal International*, *142*(3), 684-702.

Scholz, C. H. (1998). Earthquakes and friction laws. *Nature*, *391*(6662), 37-42.

Tanioka, Y., & Satake, K. (1996). *Geophysical research letters*, *23*(13), 1549-1552.

Uchida, N., Hasegawa, A., Matsuzawa, T., & Igarashi, T. (2004). *Tectonophysics*, *385*(1), 1-15.

Yue, H., & Lay, T. (2011). *Geophys. Res. Lett*, *38*, L00G09.

Kanto Asperity Project: Geological and Geophysical Characterization of the Source Regions of Great Earthquakes and Slow Slip Events

Reiji Kobayashi (Kagoshima Univ.), Yuzuru Yamamoto (JAMSTEC), Toshinori Sato (Chiba Univ.), Saneatsu Saito, Takehiro Hirose, Hisao Ito (JAMSTEC), and Masanao Shinohara (ERI, Univ. Tokyo)

Keywords: great earthquake, slow slip event, Sagami trough, geohazard, ultra-deep drilling, monitoring

The Kanto region is one of the most densely populated urban areas in the world. Complicated plate configurations are due to T-T-T type triple junction, island arc-island arc collision zone, and very shallow angle between axis of the Sagami trough and subducting direction. Great earthquakes along the Sagami trough have repeatedly occurred. The 1703 Genroku and 1923 (Taisho) Kanto earthquakes caused severe damages in the Tokyo metropolitan area. Intriguingly slow slip events have also repeatedly occurred in an area adjacent to the asperities of the great earthquakes, off Boso peninsula.

In the cases of the Nankai and Cascadia subduction zones, slow slip events occur at deeper levels than the asperity, in a transition zone between the asperity and a region of steady slip. In contrast, slow slip events in the Kanto region have occurred at relatively shallow depths, at the same level as the asperity, raising the possibility of friction controlled by different conditions to those (temperature and pressure) encountered at Nankai and Cascadia.

Kanto Asperity Project focuses on three different types of slip events occurring repeatedly at the almost same depth of the seismogenic zone along the Sagami trough (5–20 km) (Figure).

(1) The 1923 M~7.9 Taisho Kanto earthquake, located in Sagami Bay. Maximum slip is approximately 6 m, the recurrence interval is 200–400 yr, and the coupling rate is 80%–100% ("coupling rate" = "slip amount during earthquakes or SSEs" / ["rate of motion of the Philippine Sea Plate" – "recurrence interval"]).

(2) The 1703 M~8.2 Genroku earthquake, located in Sagami Bay but also extending to the southern part of Boso Peninsula. Maximum slip is 15–20 m, the recurrence interval is ~2000 yr, and the coupling rate at the southern part of Boso Peninsula (i.e., the Genroku asperity) is 10%–30%.

(3) Boso SSEs, located southeast of Boso Peninsula. Maximum slip is 15–20 cm over ~10 days, the recurrence interval is 4–6 yr, and the coupling rate is 70%–100%.

Recent progress in supercomputer technology has enabled numerical simulations of the generation cycles of earthquakes and SSEs, but the parameters are not based on scientific data, and are not sufficiently reliable to assess the hazards associated with future earthquakes. The establishment of a realistic earthquake-generation model is of crucial importance in mitigating the danger posed by earthquake geohazards.

Proposals of the KAP have been submitted to the IODP to investigate the three patches. The scientific objectives are

Objective 1: To understand why the three different types of events occur laterally, at similar depths in the Sagami Trough (i.e., under the same P–T conditions).

Objective 2: To establish realistic earthquake-generation models using data obtained at each step of the generation cycle of natural earthquakes.

This Multi-phase Drilling Project consists of the three programs. Program A proposes ultra-deep drilling to intersect plate boundaries in the Boso SSE region and the Taisho asperity to compare the geological materials at the two sites. Coring and logging at plate boundaries would also yield realistic frictional properties and effective normal stress, as derived from experiments and from measurements of pore pressure, respectively.

In Program B, we plan to perform long-term monitoring using a large borehole-observatory network covering the SSE region off Boso Peninsula. Because of the short recurrence interval of a SSE cycle (relative to the long duration of a great earthquake cycle, ~100 years), crustal deformation associated with 2–3 cycles of SSEs would be recorded during 15 years of monitoring. This program will yield a detailed account of stick–slip behavior in and around the plate boundary. Computer simulations of the earthquake generation cycle can also be applied to the SSE cycle by assigning appropriate values of frictional parameters and pore pressure measured from a fault at depth. It would be possible to establish a physical model of the SSE generation cycle by reproducing the observed SSE behavior.

Program C will propose drilling at four sites to recover input materials from the Philippine Sea Plate. The cores, and the results of frictional experiments using the core materials, will be used to test the hypothesis that the different types of slip arise from different input materials.

Each program alone would provide sufficient results to achieve objectives 1 or 2. Taken together, however, the results of Programs A-C would provide comprehensive knowledge of the fault and allow us to markedly improve models of the earthquake generation cycle.

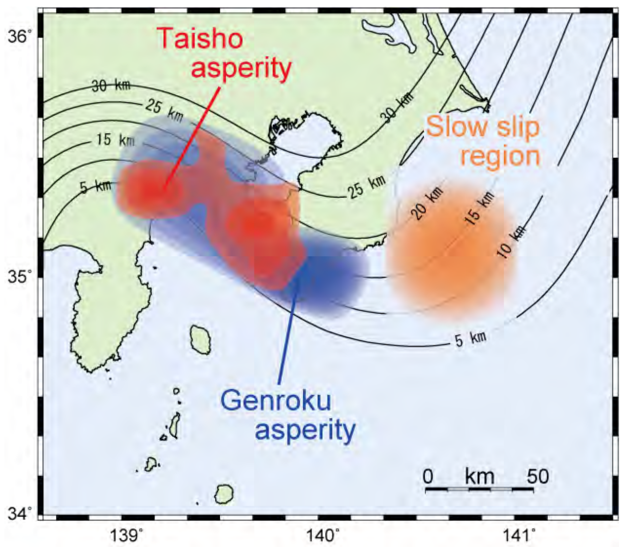


Figure: Slip distributions (for slips > 4.0 m) on the plate boundary during the 1923 Taisho Kanto and 1703 Genroku earthquakes. Orange shading represents a region with slow slip earthquakes off Boso Peninsula. Contours show the depth of the upper surface of the Philippine Sea Plate, which is subducting beneath the North American Plate.

Kanto Asperity Project Program A: Geophysical/geochemical properties of slow slip and stick–slip asperities in the southern Kanto region –investigation of factors that produce different types of seismicity under the same P–T conditions–

Reiji Kobayashi (Kagoshima Univ.), Yuzuru Yamamoto, Takehiro Hirose, and Hisao Ito (JAMSTEC), and Toshinori Sato (Chiba Univ.)

Keywords: great earthquake, slow slip event, Sagami trough, geohazard, ultra-deep drilling, monitoring

The recent discovery of slow slip events (SSEs) in subduction zones worldwide has provided renewed impetus for studies of slip localization. At the time when IODP ISP was planned, there was no understanding of SSEs, and the NanTroSEIZE and CRISP proposals were written based on the concept of the ISP, prior to the discovery of SSEs; however, it is becoming increasingly important to fully understand the nature of slip processes, both in seismic and in aseismic zones.

The southern Kanto region (Tokyo metropolitan area) is a densely populated economic center that has been subjected to repeated great earthquakes. The 1703 Genroku and 1923 (Taisho) Kanto earthquakes caused severe damages in the Tokyo metropolitan area. Slow slip events have also repeatedly occurred in an area adjacent to the asperities of the great earthquakes, off Boso peninsula.

Kanto Asperity Project (KAP) focuses on three different types of slip events occurring repeatedly at the almost same depth of the seismogenic zone along the Sagami trough (5–20 km).

(1) The 1923 M~7.9 Taisho Kanto earthquake, located in Sagami Bay. Maximum slip is approximately 6 m, the recurrence interval is 200–400 yrs, and the coupling rate is 80%–100% ("coupling rate" = "slip amount during earthquakes or SSEs" / ["rate of motion of the Philippine Sea Plate" – "recurrence interval"]).

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(3) Slow slip events (SSEs) located southeast of Boso Peninsula. Maximum slip is 15–20 cm over ~10 days, the recurrence interval is 4–6 yrs, and the coupling rate is 70%–100%.

A unique feature of this region is that these different types of seismic activity occur in close proximity, at similar and drillable depths. This setting provides us with an opportunity to increase our understanding of great earthquakes and SSEs.

A hypothesis suggests that the differences of normal earthquakes and SSEs can be explained in terms of differences in the frictional properties and effective normal stress along the fault. The most appropriate approach to obtaining the frictional properties of a fault zone is to perform experiments on materials from fault zones, whereas pore pressure is best obtained from *in situ* measurements. Thus, ultra-deep drilling (coring) is required to obtain realistic values of frictional parameters and pore pressures.

Program A of the KAP would involve detailed analyses of core materials collected from source areas of the Taisho earthquake and Boso SSEs drilled by the D/V Chikyu in the actively deforming KAP region, with the aim of (1) determining the constitutive parameters of fault zone materials, which can then be incorporated into numerical simulations of earthquakes; and (2) resolving important questions such as the nature of the physico-chemical properties of materials in areas where SSE/normal earthquakes occur. The main scientific objectives of this program are as follows:

(A) Determine the nature of spatial variations in the constitutive parameters within the framework of a rate and state friction law.

(B) Assess the distribution of fluid pressure along subduction fault zones.

(C) Determine the conditions of diagenesis and low-grade metamorphism associated with SSE and normal earthquakes.

(D) Constructing optimum earthquake generation model based on the nature of fault rocks and fault structure encountered in the boreholes.

KAP provides the best opportunity to evaluate the earthquake-generation model which will be proposed by KAP Proposal-B by determining the values of the constitutive parameters from fault zone materials, in situ fluid pressure (e.g., effective normal stress) around the fault zone, and the diagenetic/metamorphic conditions of the fault zone. The values of parameters in the constitutive law can be measured by laboratory friction experiments on the fault zone materials to be recovered from the asperity/SSE regions. Spatial differences in effective normal stress may reflect spatial variations in pore-fluid pressure along the faults. The preliminary simulation predicts higher pore-fluid pressure in SSE regions. Therefore, measurements of pore fluid pressure in both the asperity and non-asperity regions would be important in revealing which factors cause the different events. Thus, ultra-deep drilling through both stick-slip/SSEs regions is the only way to assess the validity of the current simulation of earthquake generation around the KAP region.

In situ monitoring using seismometers, tiltmeters, strain meters, pressure gauges (the depth at which each sensor is located will be set to ensure successful operation) will yield data on physico-chemical processes operating in the asperity and SSE regions, which would help to improve models of the earthquake/SSE generation cycle. Horizontal stresses will also be measured. The nature of the present-day stress field is important when seeking to assess the validity of the earthquake/SSE generation model. Vertical seismic profiling (VSP) will verify structure models inferred from seismic surveys and enable the modification of models of the earthquake/SSE generation cycle. Performing VSP with an appropriate interval may also detect temporal variations of seismic structure, especially reflections from the source areas of SSEs.

HIGH RESOLUTION SEISMIC IMAGING AND ITS CONTRIBUTION TO TRENCH AXIS DRILLING AT THE JAPAN TRENCH

Shuichi Kodaira[1], Yasuyuki Nakamura[1]

[1] Institute for Research on Earth Evolution, JAMSTEC

Keywords: Japan trench, tsunami earthquake, high resolution seismic

Introduction

JFAST (Expedition 343 in April-May and July, 2012) demonstrated that drilling at deep water near the trench by Chikyu can have a distinct potential to study physical and geological properties along an earthquake fault reaching to the trench axis. One of key contribution of this great success of JFAST is pre-drilling fault zone imaging by using high resolution seismic system. The high resolution seismic images were not only used for site survey data but also showed that trench-filled sediment preserve a fault process and records of a slip reaching to the trench axis. For example, a possible décollement is imaged as a seaward dipping reflection which short-cuts a horst-graben normal fault and the majority of overlying hemipelagic mudstones is offscraped and imbricated at the trench axis as a result of plate boundary compression including earthquake fault slip reaching to the trench axis (Fig.1). Those fault slip process and records of the slip to the trench earthquakes will be further studied by drilling project proposed by several white papers (e.g., Kirkpatrick and Ujiie; Strasser et al.; Kanamatsu; Ikehara).

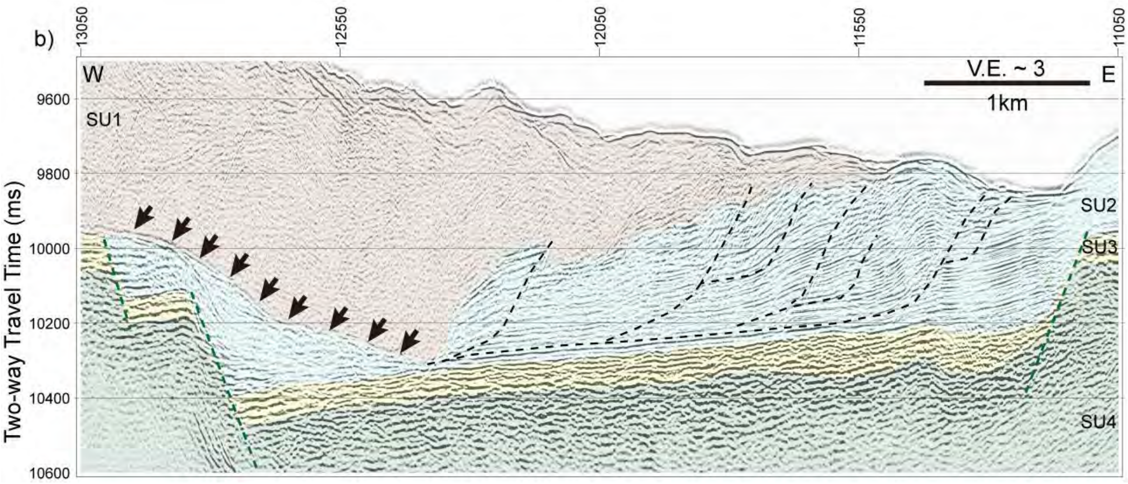


Fig. 1 High resolution seismic image at trench-ward side of JFAST site (Nakamura et al., submitted). A possible décollement as a seaward dipping reflection and offscraped and imbricated hemipelagic sediment are imaged at the trench axis.

Why we need additional high resolution seismic surveys

In order to understand the nature of slip along strike related to the 2011 Tohoku-oki earthquake, along trench axis drilling transect can provide fundamental data. Currently available high resolution seismic data in the trench are only acquired close to the epicenter region of the 2011 event. There is, therefore, little information to know lateral continuation of the structure we imaged in the trench close to the JFAST site. A key structure which may control the slip process at the trench axis is subduction of graben at the trench axis (Fig. 2), but horst or even seamount seems to be situated close to the trench axis in other area of the Japan Trench based on seismic and bathymetry data. Subduction of those structures may attribute a different process to control the slip near the trench. It is therefore necessary to acquire along trench axis high resolution seismic data to cover the entire Japan Trench, including a possible slip zone of the 1896 Meiji-Sanriku earthquake for future drilling.

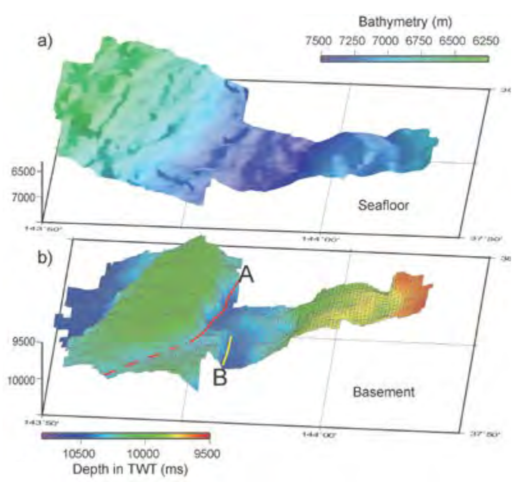


Fig. 2 Seafloor (top) and basement (bottom) image at the trench-ward of the JFAST site. Subduction of graben structure is imaged.

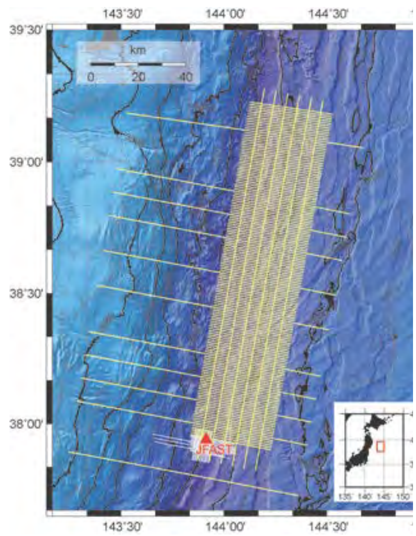


Fig.3 A map showing planned high resolution seismic profiles to be acquired in March 2013 (yellow lines).

What is a contribution to trench axis drilling

JAMSTEC plan to acquire high resolution seismic data in the trench axis to the north of the JFAST, from 38°N to 39 °N in March 2013 (Fig. 3). The new data will cover the northern end of the large slip area of the 2011 earthquake and the southern part of the possible slip area of the 1896 Meiji-Sanriku earthquake. Following the survey in 2013, other area of the trench axis will be imaged in the next 3- 5 years. Those data are necessary to define future strategy to make the trench axis drilling transect as they will help to examine lateral extension of the structures which can be evidences of slips to the trench. The planed profiles in the 2013 survey are designed to be 1 km spacing along the trench axis, which can provide a psude-3D image to understand the detail framework of the structure. These seismic data can be also used to extend fine scale physical properties obtained by future drilling in this area using core-log-seismic integration.

RETURN TO VERY DEEP WATER DRILLING IN THE JAPAN TRENCH: AN UMBRELLA WHITE PAPER

Shuichi Kodaira[1], Jim Sample[2], Jim. Mori[3]
[1] Institute for Research on Earth Evolution, JAMSTEC
[2]School of Earth Sciences and Environmental Sustainability, Northern Arizona University
[3] Disaster Prevention Research Institute, Kyoto University
Keywords: the Japan Trench, JFAST, earthquake fault, deep water, trench axis

Building on the successes of JFAST (Expedition 343 in April-May and July, 2012), we propose a return to the Japan Trench region to further investigate the geophysical and geological issues associated with the unprecedented fault slip (50 meters) to the trench axis and huge tsunami of the 2011 Tohoku-oki earthquake (Mw9.0).

Results from JFAST show that the shallow portion of the plate boundary fault zone has low friction and other unique properties, which likely contributed to the relatively slow velocity slip during the 2011 earthquake. There are a number of important fundamental issues that can be investigated with additional boreholes into the accretionary wedge and décollement structures, many of which can only be addressed during the current post-seismic period. 1) How often does this fault zone slip in great earthquakes? 2) What is the nature of slip along strike related to this large earthquake? 3) What are the present post-seismic deformation rates and how are they related to the earthquake cycle? 4) What are the current hydrologic conditions that characterize this active high-slip fault zone? 5) What can we infer about pre-earthquake pore pressures from denser sampling across faults?

The following white papers present science topics that can make valuable contributions to this project.

Hino R., Drilling into shallow interplate thrust zone for monitoring fault motion in the shallowest portion of megathrust

Ikehara, K., Turbidite paleoseismology using the trench deposits

Kanamatsu, T., Paleo-seismological record in subducton trench basin

Kodaira, S. and Y. Nakamura, High resolution seismic imaging and its contribution to the trench axis drilling at the Japan Trench

Kirkpatrick, J., K. Ujiie and M. Ikari, The physics and mechanisms of tsunamigenic earthquake slip from deep drilling in the Japan Trench

Lin, W., et al., Stress variation during a seismic cycle: A comparison between new drilling and

previous JFAST
Sample, J. et al., The role of fluids in controlling tectonic processes along the northern Japan margin: A hydrogeology transect across the northern Japan margin using the D/V Chikyu
Strasser. M. et al., Deep sea archive for earthquake history
Ujiie, K. et al., Understanding the shallow seismic slip along the Japan Trench by deep ocean drilling

Chikyu is the only research ship (and one of the few vessels in the world) that can achieve this non-riser drilling in very deep water (6000 to 7000 meters, the depth of the Japan Trench). This is because of her capacity to hold the great weight and maintain control of such a long drill string. Experience in deep water drilling gained during JFAST is an important factor for the expected technical success of this difficult drilling.

Stress variations during seismic cycles

Weiren Lin[1)], Yuzuru Yamamoto[2)], Saneatsu Saito[2)], Timothy Byrne[3)]
[1] Kochi Institute for Core Sample Research, JAMSTEC
[2] Institute for Research on Earth Evolution, JAMSTEC
[3] Center for Integrative Geosciences, Univ. of Connecticut

Kew words: stress variation, earthquake fault, JFAST, NanTroSEIZE, Slow-slip earthquake

Stress state on an active seismogenic fault starts to build up from the end of an earthquake through interseismic period for the next earthquake. Variations of stress state and fluid pressure during seismic cycle are key to understanding earthquake-generation processes and mountain building along plate subduction zones. Multi-phase coring with borehole monitoring, for instance before/soon after earthquake, will reveal variation of stress state and fluid pressure during a seismic cycle. We proposed a plan to determine stress variation in the plate interface during seismic cycle by means of multi-phase drilling of seismic fault before and soon after earthquakes. To achieve the objectives, the following projects are suitable: 1) J-FAST; 2) NanTroSEIZE; 3) proposals related to drilling of slow-slip earthquakes (e.g. Kanto, Japan; Hikrangi, New Zealand). We believe that the achievements by the proposed studies will re-define "earthquake models" lead to a new perspective of subduction process.

Through the research, we can address the following questions.

1) If and how stress builds up in the frontal plate interface in the first stage of a seismic cycle?
2) How strength of the fault recovery in about ten years?
3) How stress state differs at different location (landward, frontal prism, subducting plate) in the subduction system?

If clear stress variations are recognized, we can examine whether the rate of stress building up in the whole seismic cycle is nearly constant. To complete the proposed stress measurements, logging while drilling (LWD) data are necessary for completing borehole breakout and/or drilling induced tensile fractures (DITF) analyses, and core samples are necessary for paleo-stress analyses and anelastic strain recovery (ASR) measurements.

Proposed Drilling Sites:

1) JFAST

The stress state at the frontal plate interface after the 2011 Mw9.0 Tohoku-oki earthquake has been determined from the previous Japan Trench Fast Drilling Project (JFAST) (Lin et al., 2013). In addition, a comparison with the inferred stress state before the Mw9.0 earthquake showed a near total coseismic stress drop during the earthquake. 1) Site C0019: A comparison between the new drilling and previous JFAST drilling at the same location may reveal that the stress variation in early stage during a long seismic cycle. 2) New site at the seaward of the Japan Trench where numerous outer raise aftershocks with normal faulting focal mechanism occurred. Therefore, stress state was considered to be normal faulting stress regime (Obana et al., 2012) after the Mw9.0 earthquake. 3) New site on the deep sea terrace with a water depth of 2000 –

2500 m which is the similar location with the ODP sites 1150 and 1151 drilled in 1999 prior to the 2011 Tohoku-oki earthquake. In the ODP sites, borehole breakouts and DITFs occurred and showed that stress state before the Tohoku-oki earthquake was approximately trench normal compression (Lin et al., 2011).

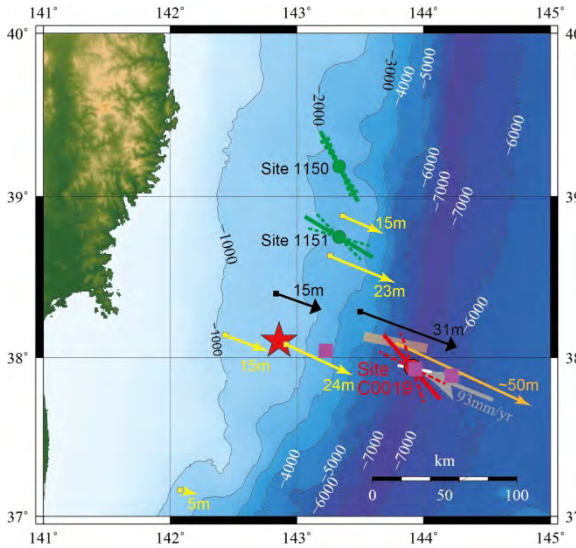


Figure 01. Conceptual locations of proposed new drilling sites showed by purple square symbols (Modified from Lin et al., 2013). Red circle is the previous JFAST site (C0019), green circles are the ODP sites 1150 and 1151. Red star shows the epicenter of the 2011 Tohoku-oki earthquake main shock.

2) NanTroSEIZE

The Nankai subduction zone is one of most investigated active margin in the world and examinations of stress state during interseismic period have been accumulated (e.g. Byrne et al., 2009; Lin et al., 2010). We propose to keep the flexibility of rapid drilling soon after earthquake like JFAST if relatively larger earthquakes occurred in the next decade.

3) Drilling of slow-slip earthquakes

Short recurrence intervals of slow slips: 5-6 years in the Kanto, central Japan; 1-3 years in the North Island of New Zealand give us an advantage to observe multiple slow slip earthquakes. Multi-phased core sampling and logging during a seismic cycle will provide information variation of pore-fluid pressure, and stress state. Given the variation of the rupture processes of SSE, plausible variations on these aspects in different SSE region are expected.

Ocean Transform Fault Drilling and Water Injection: An Active Experiment to Trigger Earthquakes

Jim Mori and Yasuyuki Kano
Disaster Prevention Research Institute, Kyoto University

From the time of the famous Rangely, Colorado example 30 years ago (Raleigh et al., 1967), it has widely been observed that increasing fluid pressure in the vicinity of faults can induce earthquakes. More recently, there has been a great interest in the oil industry for inducing tiny seismic events with fluid pumping in wells to recover hydrocarbons in old wells. Also, filling of water reservoirs often produces small earthquakes, and was apparently responsible for causing the 1967 Koyna, India (M6.5) and 1975 Oroville, California (M5.7) earthquakes. Induced seismicity is becoming an
important science topic with broad societal impacts.

We propose an experiment to understand the initiation of large earthquakes by inducing seismic events on a shallow fault with water injection. Increasing the fluid pressure near an active fault will reduce normal pressure on a fault and bring it closer to failure, according to the classic Coulomb failure criterion. A study to monitor the water pressure and subsequent triggered earthquakes can help answer some fundamental questions in seismology about the stress levels that cause earthquakes and the physical conditions that are necessary for a large earthquake to occur.

Scientific Motivation

The standard explanation for fluid induced earthquakes, is that increases in pore pressure reduce normal stress on a fault and bring cracks closer to failure, in terms of the Coulomb Failure Criterion. This provides a framework for understanding changes in water pressures in terms of the stress levels associated with earthquakes. Producing local changes in the pore pressure and observing changes in the earthquake occurrence can provide answers to question such as,

What is the level of stress needed to initiate (or trigger) an earthquake ?

In a simple model of earthquakes, an event occurs when the accumulating stress reaches the breaking strength of the fault. However, anticipating this level of stress when the earthquake happens is very difficult

How is the time dependence of increasing stress related to causing earthquakes ?

For large tectonic earthquakes, the stress that causes the event builds up over years to millennia. It is very difficult to say at what point in this process the earthquake occurs. The mid-ocean transforms are one of the places in the world where this stress accumulation and earthquake occurrence is most regular (McGuire et al., 2008).

Are there differences in the initiation of small and large earthquakes ?

What conditions are necessary to initiate a moderate to large size earthquake ?

Small earthquakes are common and occur almost continuously in seismic areas, but very little is known about that rare initiation that grows into a large damaging earthquake. The most interesting observations would be if a relatively large (M5 to M6) event could be induced. With data from this experiment we can begin to understand how large earthquakes are different from small earthquakes.

Possible Location for an Experiment

Appropriate sites for such an experiment would be transform faults near mid-ocean ridges, such as Blanco on the Juan de Fuca Ridge and Quebrada, Gofar, or Discovery on the East Pacific Rise. In such settings, shallow moderate (M5 to M6) earthquakes occur at repeating intervals of 5 to 15 years (McGuire et al., 2005). The source faults and hypocenters of these strike-slip earthquakes are shallower than for onshore faults because of the high thermal gradient and thus are more easily accessible by drilling to depths of a few kilometers.

An interesting experiment would be to carry out a water injection experiment at one of these sites a few years before the expected earthquakes recurrence, to try to trigger an early occurrence of the event. In addition, earthquakes in this region are often preceded by foreshock sequences. Triggering foreshocks would also provide important information on earthquake initiation processes.

Technical Considerations

A 2 to 3 km deep borehole would be drilled close (within a kilometer) to the hypocentral region of a moderate earthquake. Earthquakes along the transforms occur at shallow depth above the 600 $_{o}$C isotherm at depths of about 2 to 5 km (Behn et al., 2007).

Fluid pumping can probably increase pore pressure over a fairly large region, so the drilling does not have to be exactly at the (unknown) earthquake hypocenter. The hole needs to be cased and open near the bottom. Water pressurized at various pressures from about 0.001 MPa (about 0.1 psi) to higher values, (possibly 1 MPa, 140 psi) would be pumped into the borehole in order to raise pore pressure in the region of the hypocenter. The upper value for the pumping pressure approach the values of the static stress drops of the earthquakes. This could be an interesting utilization of riser drilling.

An appropriate site in water depths of about 2500 meters can likely be found. However, if the technical capabilities allowed drilling at depths of 3500 to 3800 meters, a much better location could be chosen.

A complete explanation of the earthquake activity needs understanding of the local fluid, thermal and stress distributions. Depending on the scale of the planned project, several near-fault boreholes to install seismometers along with fluid and strain monitoring instrumentation will also be considered. Also, there would obviously be important information on the physical structure of the fault zone from the borehole cores.

Behn, M.D., M.S. Boettcher, G. Hirth (2007), Thermal structure of oceanic transform faults, *Geology* 35, doi:10.1130/G23112A.1.

McGuire, J.J., M. S. Boettcher, and T. H. Jordan (2005), Foreshock sequences and shortterm earthquake predictability on East Pacific Rise transform faults, *Nature*, 434, doi:10.1038/nature03377.

Raleigh, C.B., J.H. Healy, J.D. Bredehoeft (1967), An experiment in earthquake control at Rangely, Colorado, *Science*, 26, 1230-1237.

The Nankai 3-D Vertical Seismic Profiling for Detailed Structure and Physical Properties of the Subduction Plate Boundary Fault System

Jin-Oh Park[1], Yoshinori Sanada[2], Masataka Kinoshita [2], Ryota Hino[3], Takeshi Tsuji[4], Shuichi Kodaira[2], Yasuyuki Nakamura[2], Eiichiro Araki [2], Nobu Eguchi [2], Moe Kyaw Thu [2], Kimihiro Mochizuki[1], Eiichi Asakawa[5], Jun Matsushima[1],
Nathan Bangs[6], Gregory Moore[7], Roland von Huene[8], and Martin Karrenbach[9]
[1]University of Tokyo, [2]JAMSTEC, [3]Tohoku University, [4]Kyushu University, [5]JGI, Inc.,
[6]University of Texas, [7]University of Hawaii, [8]University of California, [9]SR2020, Inc.
Keywords: Nankai, VSP, structure, physical properties, fault

Introduction

The Nankai Trough subduction zone off southwest Japan is one of the convergent margins best suited for studying large megathrust earthquakes as well as the formation of accretionary prisms. Historic, great megathrust earthquakes with a recurrence interval of 100-200 yr (e.g., Ando, 1975) have generated strong motion and large tsunamis along the Nankai Trough margin. In particular, the Nankai subduction zone off Kii Peninsula is characterized by steeply landward-dipping megasplay faults (Park et al., 2002; Moore et al., 2007) in the rupture area of the 1944 Tonankai (M 8.1) earthquake. This megasplay fault branches upward from the plate boundary (i.e., the megathrust fault), breaking through the overlying accretionary wedge. The 1944 Tonankai megasplay fault and the basal décollement are major drilling targets for the Nankai Trough Seismogenic Zone Experiment (NanTroSEIZE) which is a multiexpedition, multistage Integrated Ocean Drilling Program (IODP) drilling project focused on understanding the mechanics of seismogenesis and rupture propagation along subduction plate boundary faults.

Knowledge about detailed structure and physical properties of the subduction thrust fault system are quite essential to achieve the main objectives of the NanTroSEIZE program. Although a significant volume of site survey data has been collected in the NanTroSEIZE drilling area over many years, including surface 2-D seismic reflection (e.g., Park et al., 2002), surface 3-D seismic reflection (e.g., Park et al., 2008; Moore et al., 2009), and OBS wide-angle reflection/refraction (e.g., Nakanishi et al., 2008) surveys, the detailed structure and physical properties of the fault system are not well understood, because of relatively low resolution due to deep target reflectors. Moreover, recent drilling of IODP Expedition 338 at Site C0002 in the Kumano Basin, which is planned to access down to the major targets, was interrupted at a depth of ~2000 meter below seafloor (mbsf). Here, we propose to conduct 3-D vertical seismic profiling (VSP) using a deep borehole at IODP Site C0002, which is expected to deepen down to the basal décollement (~7000 mbsf) through the megasplay fault (~5000 mbsf), for high-resolution seismic imaging and physical properties estimation of the subduction plate boundary faults.

Why, 3-D VSP?

During the IODP Expedition 319 in 2009, we have carried out 16-level, 2-D walk away and walkaround VSPs (e.g., Tsuji et al., 2011) using D/V Chikyu and R/V Kairei (shooting vessel) of Japan

Agency for Marine-Earth Science and Technology (JAMSTEC) at Site C0009 in the Kumano Basin. Anisotropy analysis by the walkaround VSP with 3.5 km radius circle indicates that orientations of P wave strong amplitude and S wave polarization axes are aligned with the convergence vector of the Philippine Sea plate, and also consistent with borehole breakout analysis result at the Site C0009. However, ~53-km-long walkaway VSP data does not exhibit better images of the megasplay fault and basal décollement, compared with surface 3-D seismic reflection data, probably because of a lack of shots resulting in low-fold stack, small number of receivers, and too shallow receiver level creating low S/N ratio.

The 3-D VSP is a state-of-the-art technology that provides (1) more accurate 3-D image in complex geological environments, compared with 2-D VSP and surface 3-D seismic, (2) precise P and S wave data, and (3) a detailed velocity model through 3-D tomography. The 3-D VSP data is very useful for determining total drilled depth (TD) down to the major targets from a viewpoint of drilling strategy design. By doing core-log-seismic integration using drilling, surface 2-D/3-D seismic, and 3-D VSP data at Site C0002, we will address primary scientific questions as follows:

- What are the detailed characteristics of the megasplay fault and basal décollement?
- What is the thickness of the damage zone, slip zones, and materials thrust beneath the megasplay fault?
- What are the physical properties (P and S wave velocities, seismic attenuation Q, etc.) of the zones?
- How do these vary laterally away from the borehole?
- How do these fault properties correspond with properties inferred from surface seismic reflection data?
- What is the significance of the high-amplitude, reversed-polarity seismic reflections of the megasplay fault and what does the lateral variation tell us about the behavior of the fault broadly?

Plan of Data Acquisition and Processing

We will conduct 3-D VSP (Fig. 1) using a cased borehole at Site C0002, which is expected to deepen down to the basal décollement (~7000 mbsf) through future IODP Expeditions. We have already results of survey design and pre-survey modeling to illuminate and image the major drilling targets using a 3-D VSP. Illumination of the megasplay fault and the basal décollement are used as a guide to derive the optimal marine surface shooting pattern for the 3-D VSP. We will use tuned air-gun arrays of R/V Kairei for every 20 sec shot along spiral grid with 15 km maximum offset from drill hole and 650 m line spacing. At least 60 (ideally, more than 100) receivers should be used, because smaller receivers will result in very low fold and small patchy image. The receivers with 20 sec recording length will be deployed between 2300 and 3600 mbsf of the borehole. After pre-processing such as orientation of three components by hodogram analysis, picking first breaks, deconvolution filtering, upgoing/downgoing wavefield separation, and multiple suppression, 3-D tomography and migration will be applied to all the traces to obtain accurate velocity model and seismic image in 3-D. Furthermore, we will carry out 4-D (time lapse) VSP for monitoring behavior of the subduction thrust fault system.

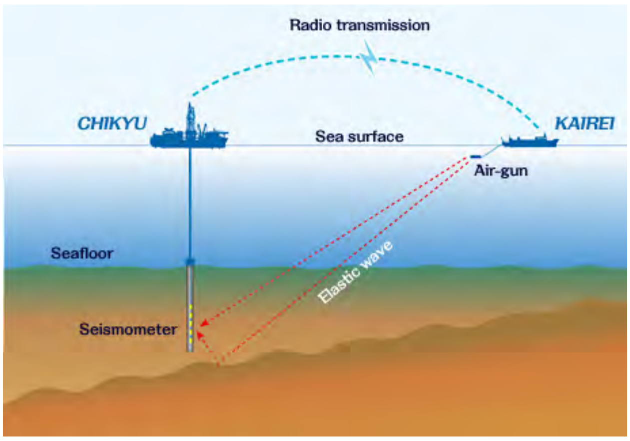


Fig. 1. Schematic diagram of 3-D VSP

P-CABLE 3D HIGH-RESOLUTION SEISMIC SITE SURVEY TECHNOLOGY

Sverre Planke[1], Frode N. Eriksen[1], Christian Berndt[2], Jürgen Mienert[3], Stefan Bünz[3], and Craig Lippus[4]

[1]P-Cable 3D Seismic AS, Oslo Innovation Park, 0349 Oslo, Norway; [2]GEOMAR, 24148 Kiel, Germany; [3]University of Tromsø, 9037 Tromsø, Norway; and [4]Geometrics, San Jose, California

Seismic acquisition, site surveys, drilling safety, core-log-seismic integration, CHIKYU+10

SUMMARY

Three-dimensional (3D) seismic data provide unique images of the sub-surface, and is routinely acquired by the industry prior to drilling. However, 3D seismic data are not commonly available for scientific boreholes. This is mainly due to the high acquisition cost of conventional 3D surveys. We have developed a new cost-efficient technology for acquisition of high-resolution 3D seismic data, the P-Cable system. The technology is very well suited for imaging of the sub-surface around scientific boreholes. Small cubes (10 to 50 km^2) with high-resolution (50-250 Hz) seismic data can be acquired in 3 to 10 days using existing research vessels. Currently, five P-Cable3 systems are available by academic and commercial operators.

BACKGROUND AND TECHNOLOGY

Seismic data are essential for both safety and scientific purposes for deep-water scientific drilling. However, only limited amount of seismic data are commonly available for these sites. We have developed a new technology, the P-Cable, for cost-efficient acquisition of high-resolution 3D seismic data (Figures 1 and 2; Planke and Berndt, 2003). More than 50 P-Cable cubes have been acquired between 2004 and 2012, with cube sizes from 5 to 200 km^2. Survey aims include landslide dynamics (e.g. Berndt et al., 2012), gas hydrates and shallow gas migration (e.g., Hornbach et al., 2012), and shallow gas exploration.

The P-Cable system consists of a seismic cable towed perpendicular to a vessel's steaming direction (Figure 1). This configuration allows a number of seismic profiles to be acquired simultaneously in a cost-efficient way. A three-dimensional image of the subsurface can be obtained by collecting a number of parallel sail lines in the region of interest. Conventional 3D seismic technology rely on very long streamers (several up to10 km long streamers is common), large sources, and costly operations. In contrast, the P-Cable system is light-weight and fast to deploy from small vessels. Only a small source is required as the system is made for relatively shallow imaging, typically down to sub-bottom depths similar to the water depth.

CHIKYU+10 USAGE

The P-Cable technology is very well suited for site surveys, drilling safety, core-log-seismic integration, and geoscientific research. The technology is proven and ready for usage for a future CHIKYU+10 drilling program.

The P-Cable system is particularly useful for acquisition of small 3D cubes, 10-50 km^2, in focus areas. The rapid deployment and recovery of the system makes it possible to acquire several 3D cubes during one research cruise. Very high-quality data have been acquired by the P-Cable system (Figure 2). Typical data characteristics are:

- cube size: 5 to 300 km^2
- frequency range: 50 to 250 Hz
- water depth: 200 to >3000 m
- bin size: 6x6 m
- vertical resolution: ~1.5 m

There are currently four academic P-Cable systems available, which are operated by University of Tromsø, GEOMAR, National Oceanography Center, Southampton, and University of Texas. New and rental systems are available from Geometrics Inc. (www.geometricspcable.com). Finally, WGP (www.wgp-group.com) offers commercial P-Cable acquisition services.

REFERENCES

Berndt, C., Costa, S., Canals, M., Camerlenghi, A., De Mol, B., and Saunders, M., 2012. Repeated slope failure linked to fluid migration: the Ana submarine landslide complex, Eivissa Channel, Western Mediterranean Sea. Earth and Planetary Science Letters, 319-320, 65-74. doi:10.1016/j.epsl.2011.11.045

Hornbach, M., Bangs, N., and Berndt, C., 2012. Detecting hydrate and fluid flow from bottom simulating reflector depth anomalies. Geology, 40, 227-230. doi:10.1130/G32635.

Planke, S. and Berndt, C. (2003) Anordning for seismikkmåling, Norwegian Patent no. 317652 (UK Pat. No. GB 2401684; US Pat No. US7,221,620 B2).

Figure 1. P-Cable acquisition off southern California. A cable is extended perpendicular to the vessel's steaming direction using two paravanes. Fourteen 50-m long seismic streamers are attached to this cross-cable.

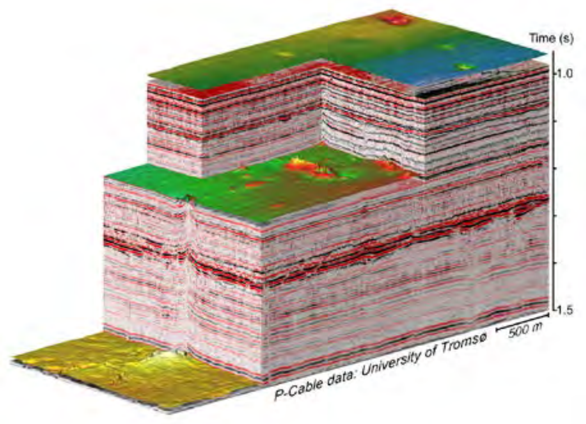


Figure 2. Example of P-Cable data showing shallow gas (high amplitude reflection at 1.25 s), vertical pipe structures, and pockmarks in the Nyegga area, offshore mid-Norway.

NICOYA, COSTA RICA: STILL AN EXCELENT CHIKYU TARGET WHERE THE SEISMOGENIC ZONE OF LARGE EARTHQUAKES CAN BE DRILLED AND INSTRUMENTED

Marino Protti[1] and Yoshiyuki Kaneda[2]
[1]OVSICORI-UNA and [2]JAMSTEC

Keywords: subduction, seismogenic zone, Costa Rica, large earthquakes

Nicoya is a segment of the subduction zone at the Middle American Trench where the Cocos plate subducts at 78 mm/yr (Protti et al., 2012) under the Caribbean plate (Fig. 1). Nicoya had large earthquakes (Mw>7) in 1853, 1900, 1950 and in 2012. The September 5th, 2012, Mw=7.6, Nicoya earthquake ruptured only the deeper portion of the seismogenic zone. Pre, co and post earthquake deformation data suggests that the shallow portion of the plate interface might still be locked.

The Nicoya segment has two important advantages over most subduction zones. It has a peninsula sitting right over the seismogenic zone of large (Mw>7) earthquakes that allows recording crustal deformation in the very near field with geodetic techniques such as CGPS, as well as with seismic instrumentation; also the upper limit of the seismogenic zone is reachable by drilling with the CHIKYU capabilities.

Geodetic and seismic instrumentation have recorded slow slip events on the Nicoya segment (in 2003, 2005, 2007, 2009 and 2011) with an average recurrence interval of 22±2 months (Yan et al., 2012). Recent crustal deformation data from the Nicoya peninsula indicates that locking on this plate boundary starts as close as 30 km from the trench (Norabuena et al., 2004 and Feng et al., 2012) where the plate interface is around 6 km deep (Fig. 2). These results make this subduction segment an attractive target for drilling the plate interface and seismogenic zone at several different depths in a margin where it is reachable by CKIKYU.

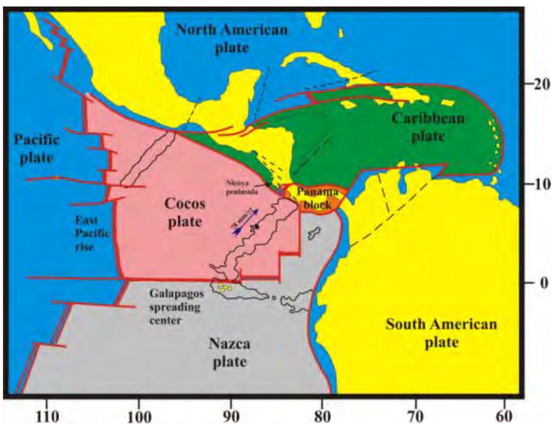


Figure 1.

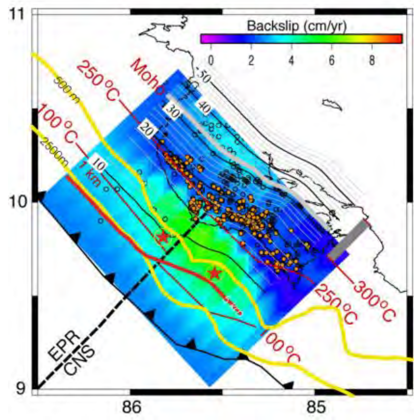


Figure 2.

Figure 2 shows the Nicoya segment of the Middle American Subduction zone (DeShon, et. al., 2005). Color pattern shows the quality of locking along the plate interface (Norabuena et. al., 2004) with the strongest patch where the plate interface is from 5 to 15 km deep. The plate interface is represented by a red line labeled 5 km and solid black lines labeled 10, 20 30, 40 and 50 (Newman et al., 2002). Orange circles represent interplate seismicity. Temperature isotherms from Spinelli and Saffer (2004) updip and Harris and Wang (2002) downdip; the grey box indicates the potential variance in the modeled 300ºC isotherm. Yellow solid lines mark the 500 m and 2500 m depth contours, which is the operational water depth interval for Chikyu. Within this depth range Chikyu could target the seismogenic zone at 6 to 7 km (red stars).

Why Nicoya? : 1) it generates large earthquakes; 2) short recurrence times; 3) its deepest portion failed 4 months ago; 4) fast deformation rates; 5) logistically and politically easy to drill; 6) lots of data available; 7) small area (10s of km rather than 100s of km); 8) near land for logistics and data links; 9) the seismogenic zone is reachable by drilling.

References

DeShon, H. R.; S. Schwartz, A. Newman, V. González, M. Protti, L. M. Dorman, T. H. Dixon, E. O. Norabuena, E. R. Flueh; 2006; Seismogenic zone structure beneath the Nicoya Peninsula, Costa Rica, from 3D local earthquake P- and S-wave tomography; Geophysical Journal International; Vol 164, issue 1, Jan.

Harris, R.N. and K. Wang (2002), Thermal models of the Middle America trench at the Nicoya Peninsula, Costa Rica, Geophys. Res. Letts., 29, 2010, doi:10.1029/2002GL015406.

Feng, L., A. V. Newman, M. Protti, V. González, Y. Jiang, and T. H. Dixon (2012), Active deformation near the Nicoya Peninsula, northwestern Costa Rica, between 1996 and 2010: Interseismic megathrust coupling, J. Geophys. Res., 117, B06407, doi:10.1029/2012JB009230.

Jiang, Y., S. Wdowinski, T. H. Dixon, M. Hackl, M. Protti, and V. Gonzalez (2012), Slow slip events in Costa Rica detected by continuous GPS observations, 2002–2011, Geochem. Geophys. Geosyst., 13, Q04006, doi:10.1029/2012GC004058.

Newman, A; S. Schwartz; V. Gonzalez; H. DeShon; M. Protti and L. Dorman; Along-strike variability in the seismogenic zone below Nicoya Peninsula, Costa Rica; Geoph. Res. Lett.; Vol. 29, No. 20, 2002.

Norabuena, E., T.H. Dixon, S.Y. Schwartz, H.R. DeShon, M. Protti, L. Dorman, E.R. Flueh, V. González, P. Lundgren, A. Newman, F. Pollitz, and D. Sampson 2004 Geodetic and seismic constraints on some seismogenic zone processes in Costa Rica, J. Geophys. Res., 109, B11403, doi: 10.1029/2003JB002931.

Protti, M., González, V., Freymueller, J., and Doelger, S.; Isla del Coco, on Cocos Plate, converges with Isla de San Andrés, on the Caribbean Plate, at 78mm/yr; Rev. Biol. Trop. (Int. J. Trop. Biol. ISSN--0034--7744) Vol. 60 (Suppl. 3): 33--41, November 2012

Spinelli, G.A. and D. Saffer (2004), Along-strike variations in underthrust sediment dewatering on the Nicoya margin, Costa Rica related to the updip limit of seismicity, Geophys. Res. Letts., 31, 4613, doi:10.1029/2003GL018863.

Costa Rica SEISMOGENESIS Project (CRISP)

C.R. Ranero[1]; P. Vannucchi[2]; R. von Huene[3] and CRISP proponents

[1]ICREA at ICM-CSIC, Barcelona Center for Subsurface Imaging, Spain. [2]Royal Holloway University of London, UK. [3]UC Davis, USA; GEOMAR Kiel, Germany.)

Keywords: mega-thrust fault mechanics, seismogenesis, earthquake hazard.

An ongoing shift in paradigm: Our limited knowledge of the processes that govern earthquake seismogenesis has been periodically synthesized during the past ~40 years into different conceptual models to provide a basic framework for the understanding of the generation of *Great-magnitude Earthquakes* by subduction-zone mega-thrust faults. To our dismay, most basic predictions put forward by those hypotheses have been shaken by the unexpected occurrence of several *Giant Earthquakes* during the last decade.

In an early concept, it was proposed that the largest-magnitude earthquakes occurred in fast-converging subduction zones receiving thick trench-sediment infill which when under-thrusted should smooth irregularities in the mega-thrust fault structure and facilitate propagation of earthquake rupture. This hypothesis was partially disproven during the 2004 Aceh-Andaman Mw9.3 event occurring along a segment of the obliquely (slowly) converging Sumatra subduction zone. More recently, the 2011 Tohoku-Oki Mw9.0 event ruptured along a plate boundary that receives only a thin veneer of subducting sediment, indicating that a laterally homogeneous mega-thrust fault is not required for the generation of *Giant Earthquakes*.

In addition, the modern and abundant high-quality data obtained in relation to those events has also been used to show that a number of other frequently (and freely) utilized concepts are primarily incorrect.

For instance, the 2011 Tohoku-Oki Mw9.0 event re-ruptured a region that had been recently partially ruptured by Mw8.0-8.3 events. Such Mw8.0-8.3 earthquakes had previously been frequently regarded as "large enough" to release most of the stress. Thus, the 2011 Tohoku-Oki event was un-expected by most.

Another important matter indicated by the Tohoku-Oki Mw9.0 event - and paleoseismological data - is that, at least in some regions, the release of elastic energy by earthquakes may follow a cycle that is more complex that previously assumed. In Japan Trench, and possibly other regions like Cascadia, a decadal-centennial cycle of ~Mw8.0-8.5 *Great Earthquakes* may be "superimposed" to a longer-time scale cycle (perhaps millennia) of *Giant Earthquakes*.

A last example worth mentioning of an ongoing paradigm shift is the mounting evidence that the concept of the seismogenic zone of the mega-thrust fault has been too simplistically applied to the complex fault behavior occurring during earthquake nucleation, rupture and propagation. High-quality records inverted to map fault rupture of recent *Giant Earthquakes* including Aceh-Andaman, Tohoku-Oki, and Maule (Chile) strongly indicate that seismic rupture extended along the shallow portion of the faults to reach close to the deformation front, where conceptual models infer that deformation normally occurs a-seismically.

The above growing body of evidence points out that an insufficient understanding of fault mechanics and deformation at the scale of the mega-thrust fault has led to long-standing, oversimplified conceptual models. These models require evaluation by quantitative approaches that accurately calculate deformation at subduction zones. The result will necessarily imply a new appraisal of earthquake hazard at global scale. Accurate quantitative approaches will require high-resolution observational data including geodetic data, and in situ observations of the mega-thrust fault. *CRISP main goal is to obtain a deeper understanding of the* *processes governing the mechanical behavior of the mega-thrust and capture their time evolution*.

CRISP objectives: CRISP selected the mega-thrust of Costa Rica for 2 main reasons: **1**) An exceptionally well-studied region, with over-a-decade intense US-Margins/German-SFB574 programs involving hundreds of scientist and about 15 cruises. **2**) A shallow-depth seismogenic zone. Other favorable conditions are mild sea state year round, excellent seismic images including 3D volumes, and good transportation infrastructure.

CRISP investigates a mega-thrust dominated by tectonic erosion. About 50% of the world's subduction zones are erosional, including Japan Trench where the 2011 Tohoku-Oki event occurred. A comparison of the Japan Trench and Costa Rica shows considerable structural similarities (Figure 1).

CRISP Drilling, Monitoring and Laboratory Experiments have Four Major Goals: **1)** Quantify effective stress and plate boundary migration via focused investigation of fluid pressure gradient and fluid advection across the erosional plate boundary. **2)** Determine the structure and fault mechanics of an erosional convergent margin. **3)** Constrain how fluid-rock interaction affect seismogenesis by studying fluid chemistry and residence time, basement alteration, diagenesis, and low grade metamorphism. **4)** Obtain physical properties of a rock volume that spans the seismogenic zone.

CRISP science will test five hypotheses related to seismogenesis : **1)** The change from velocity strengthening to weakening in the plate boundary parallels the transition from a fluid-rich and broad fault zone, with distributed slip, to a narrower zone of active deformation with localized shear and fluid compartmentalization. **2)** Fluid pressure gradients and fluid advection affect the migration and mechanical coupling of erosional plate boundaries both temporally and spatially. **3)** The lithology, physical properties, and structure of eroded materials influence fault mechanics and the transition from velocity strengthening to weakening. **4)** Fluid chemistry, P-T conditions and residence time affect the state of eroded material through basement alteration, diagenesis and low-grade metamorphism. **5)** Lateral variability in subducted plate relief, subduction channel thickness, material properties and fluid distribution affect seismogenesis and rupture propagation.

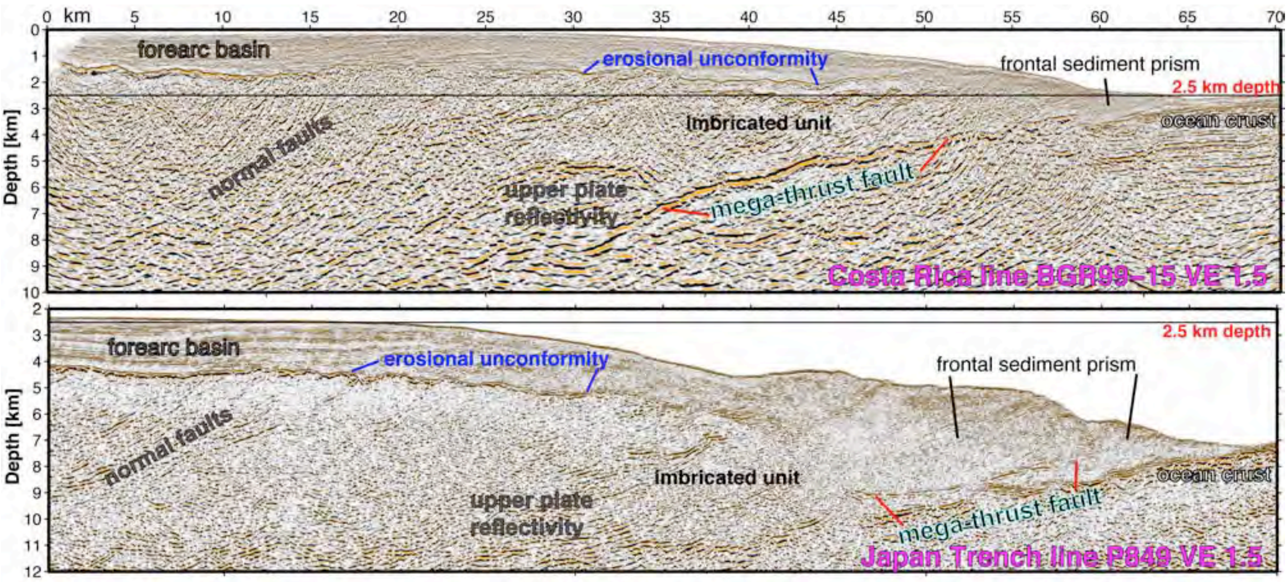


Fig 1. Comparison of Japan Trench and Costa Rica. Note structural similarities. Erosional plate-boundaries contain material removed from the upper plate mixed with under-thrusted sediment with unknown physical properties. Plate boundary drilling in Costa Rica at < 2.5km water depth may occur across the entire slope.

GEODYNAMICS OF ACTIVE MARGINS IN THE OKHOTSK SEA REGION

A.G. Rodnikov, N.A. Sergeyeva and L.P. Zabarinskaya
Geophysical Center, Russian Academy of Sciences, Moscow, Russia

Introduction. We studied the deep structure of the active margins in the Okhotsk Sea region. This region is characterized by high seismicity, volcanic eruption and natural cataclysms hazardous for the people living there. It is also the area of recent intense tectonic movements and hydrothermal processes, place of accumulation of different kinds of useful minerals.

The task of the research is (1) to study the deep structure and processes beneath seismic hazardous zones, volcanic areas, mineragenetic fields, and sedimentary basins; (2) to determine the role of the deep processes, going on in the upper mantle, in the formation of major structural units of active continental and oceanic margins; (3) to study of the deep causes of geological phenomena to assess, predict and mitigate the natural disasters, specifically earthquakes, and volcanic eruptions.

The Okhotsk Sea Region. The Okhotsk Sea region is a lithosphere plate located between the North American, Eurasian and Pacific plates which determined its tectonic, seismic and volcanic activity (fig.1).

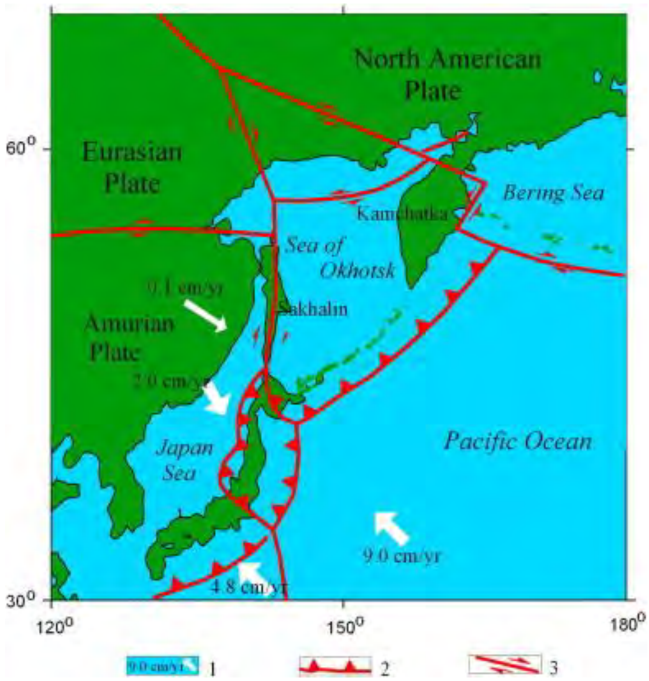


Fig. 1. *Tectonic chart of the Okhotsk Sea region. 1- plate motion velocity from GPS data; 2 – subduction zones; 3 – faults.*

The highest seismic activity is noted along the Kuril island arc. There the Pacific plate is subducted under the continent, forming a seismofocal zone, which is traced to the depth of 700 km. In the west, the Okhotsk Sea plate is bounded by deep faults extending along Sakhalin.

The research was conducted along a geotraverse (fig.2). The cross-section runs from Mesozoic structures of Sikhote-Alin to the Pacific. The asthenosphere is located in the upper mantle of the Okhotsk Sea at a depth of 50-70 km and is revealed at a depth of approximately 100 km beneath the Northwest Pacific Basin. From the asthenosphere, diapirs with partially melting of the rocks go up to a depth of 20-30 km under the sedimentary trough of the Tatar Strait, Deryugin Basin and Kuril Basin, causing an active tectonic regime that manifests in volcanic, seismic and hydrothermal activity.

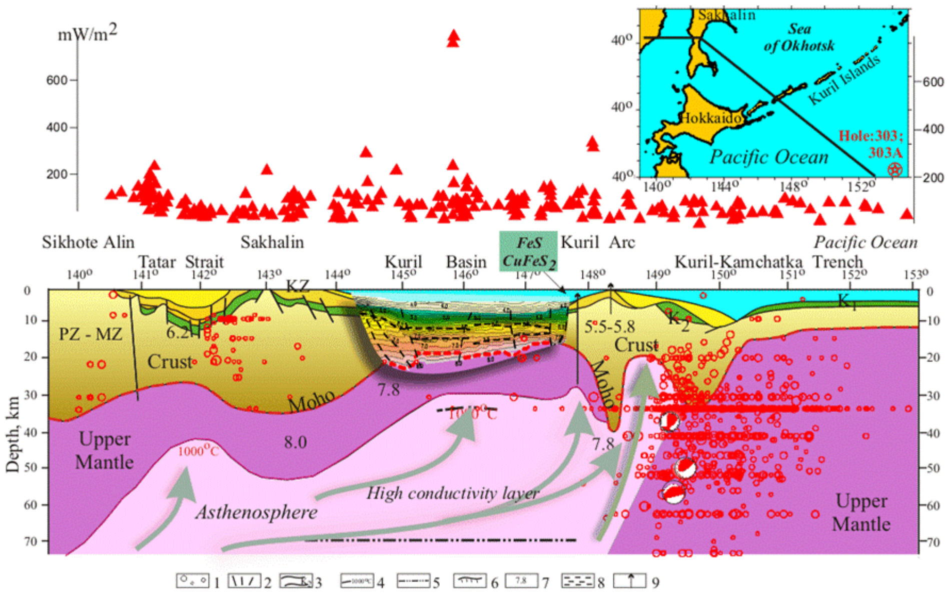


Fig. 2. *Geotraverse of the Okhotsk Sea region. In the right upper corner, the geotraverse location is given. Below the distribution of the heat flow measured values (mW/m^2) along the profile. PZ - Paleozoic, MZ -Mesozoic, KZ – Cenozoic, K_2 – Upper Cretaceous. 1- earthquake sources locations; 2 – faults; 3 – geological layers; 4 –isotherm, ^{o}C; 5 –boundaries of high electric conductivity layer; 6 – M-discontinuity; 7 – seismic waves velocities, km/s; 8 – water mass; 9 – volcanoes.*

Sedimentary basins of the Sea of Okhotsk are located over asthenospheric diapirs containing hot mantle fluids. Some stages of mantle degassing appear to be associated with eruption of magma. The Tatar rift basin locates in the western part of the geotraverse. Its basement incorporates a thin continental crust (up to 25 km). The asthenospheric layer is up to the level of 50 km. This region is characterized by high heat flow values reaching 123–132 mW/m^2. The temperature in the upper zone of the asthenospheric diapir is about 1200^{o}C. In the Tatar rift basin, where oil-gas manifestations were found out, three stages of magmatic activity stand out. This clearly demonstrates various depths of magma generation areas. The Eocene-Oligocene basalts (55-24 million years) of initial riftogenesis are assigned to them. The low – middle Meocene stage (23-15 million years) is represented by tholeiites, associated with a stage of the maximum stretching. The formation of hydrocarbon deposits in the sedimentary basin is dated this time. The magmatic activity comes to the middle Meocene - Pliocene basalts.

The Kuril basin is bounded by deep fault zones. This area incorporates the asthenospheric diapir (up to 20 km high) accompanied by high heat flow values of 346–354 mW/m^2. In the Kuril basin the magma eruption occurred in the low-middle Miocene (14-11 million years), middle-upper Miocene (9-7 million years) and Pliocene (1.07 and 0.84 million years) times. Basalt eruptions are associated with the stages of the extension of the continental crust caused by the introduction of the asthenospheric diapir. Over the asthenospheric diapir at tops of submarine volcanoes the sulfide mineralization is revealed.

Conclusion. The characteristic feature of the deep structure of the margins in the Okhotsk Sea region is the presence of an asthenosphere in the upper mantle. The upwelling of the asthenosphere at a depth of 10-20 km causes the breaking of the lithosphere, the formation of rifts, basalt lava eruptions, seismicity and hydrothermal activity.

What controls the magnitude of earthquakes in subduction zones?

Arito Sakaguchi[1], Robert Harris[2] Paola Vannucchi[3], Kohtaro Ujiie[4], Katerina Petronotis[5], Expedition 334 and 344 Scientists

[1]JAMSTEC, [2]Oregon State University, [3]University of Florence and [4]University of Tsukuba and [5]USIO

Keywords: Large subduction earthquake, seismogenic fault, accretion and erosive margin

Differences in state and deformation processes between different subduction zones may cause the observed differences in characteristic earthquake magnitudes and recurrence intervals. Their determination are important for a better understanding of earthquake mechanics and seismic hazards. The Nankai subduction margin has a 1300-year historical earthquake record with a recurrence interval of 100-150 years (Ando, 1975). Great earthquakes at Nankai are typically tsunamigenic and include the 1944 Tonankai (Mw=8.1) and 1946 Nankaido (Mw=8.1) earthquakes (Kanamori, 1977). In contrast, the Middle America trench offshore Costa Rica margin, megathrust events with magnitude as high as 7.6Mw have so far occurred only in the NW, at the Nicoya Peninsula area. The known events took place in 1853, 1900, 1950 and 2012. So, assuming a simplified earthquake cycle, the "recurrence" there might be a bit over 40 years. In frictional stick-slip system, the recurrence interval and event displacement varies with the stiffness of the system. We propose that the characteristic magnitude of large subduction earthquakes and recurrence intervals are influenced by the stiffness of the upper plate. This hypothesis may be best tested at the Nankai and Costa Rica margins.

Tectonics and Seismicity

Variations in earthquake magnitude and recurrence intervals of fault behavior need to be understood in the context of regional tectonics. Convergent margins may be divided into two end-member types that are termed erosive and accretionary plate boundaries (e.g. von Huene and Scholl, 1991; Clift and Vannucchi, 2004). A fundamental difference between these styles of subduction is the transfer of material between the overriding and downgoing plates. At accretionary margins material is transferred from the downgoing plate to the upper plate through either frontal accretion or underplating at the base of the forearc accretionary prism, leading to a net growth of the margin. In contrast, at erosive margins the plate boundary cuts into the overriding plate transferring material may be transferred from the upper plate to the lower plate. The composition and strength of the upper plate may play a role in modulating accretionary and erosive margin tectonics (McCaffrey, 1993). Bilek (2010) suggests that great earthquakes ($M > 9$) are more likely to be generated at accretionary margins. In previous models, erosive and accretionary margins differ greatly in lithology, physical properties and thermal conditions, making them difficult to compare.

Nankai and Costa Rica

IODP has drilling plans at both the Nankai accretionary margin (NanTroSEIZE) and the Costa Rica erosive margin (CRISP). NanTroSEIZE is designed to drill into, sample, and measure the seismogenic portion of a subduction thrust fault (Tobin and Kinoshita, 2006). CRISP is designed to understand seismogenesis by drilling and sampling updip within the seismogenic zone. In the CRISP drilling area offshore Osa Peninsula of the Cocos ridge stands about 2.5 km higher than the surrounding seafloor and lifts the seismogenic zone to 4-6 km below the seafloor and thus within reach of scientific drilling using the D/V CHIKYU. Drilling at the CRISP site also has the advantage of low sea states and weak currents. Both drilling areas are characterized by the subduction of young oceanic crust with high heat flow and active fluid flow (Spinelli and Wang, 2008; Spinelli and Harris, 2011; Harris et al., 2010). However, important differences exist between these sites including the convergence rates, and the thickness and the composition of incoming sediments. In summary, these two drilling projects complement each other by, 1) providing independent information on subduction zone seismogenesis; 2) samples of fault rocks updip and within the seismogenic zone; 3) in-situ measurements or state; and, 4) data on accretionary and erosive margin tectonics and hydrogeology.

CRISP Program-A has carried out the first step toward the deep riser drilling by characterizing the shallow lithologic, hydrologic, stress, and thermal state of this area (Vannucchi et al., 2011; Harris et al., 2013). CRISP drilling reveals that the shallow basement of upper plate crust is composed of terrigenous sediment accumulated at a high rate. A large sediment flux to the forearc may have originated from the uplifted back-arc Talamanca Cordillera due to Cocos-Ridge subduction (Lonsdale and Klitgord, 1978; van Andel et al., 1971). Our model predicts that event displacement, and thus magnitude, is smaller at Costa Rica than at Nankai because the upper plate is stiffer at Costa Rica. This hypothesis can be tested based on elastic parameters estimated from seismic data and physical properties of core samples obtained from deep drilling.

References

Ando, M., (1975), Tectonophysics, 119-140

Bilek, S. L. (2010), Geology, 38(5), 479-480. doi: 10.1130/focus052010.1

Clift, P. D., and P. Vannucchi (2004), Rev. Geophys., 42. 10.1029/2003RG000127.

Harris, R.N., Sakaguchi, A., Petronotis, K., and the Expedition 344 Scientists, (2013), *Prel. Rept., IODP*, 344, doi:10.2204/iodp.pr.344.2013

Harris, R. N. et al. (2010), Geochem. Geophys. Geosyst., 11, Q12S28, doi:10.1029/2010GC003272.

Harris, R. N., F. Schmidt-Schierhorn, and G. Spinelli (2011), Geochemistry, Geophysics, Geosystems., 12, Q0AD16, doi:10.1029/2011GC003593.

Kanamori, H. (1977), J. Geophys. Res., 82 (B7), 2981-2987.

Lonsdale, P., and K. D. Klitgord (1978), Geol. Soc. Am. Bull., 89(7), 981-999. doi:10.1130/0016 7606

McCaffrey, R. (1993), J. Geophys. Res., 98 (B7), 11953-11966.

Spinelli, G.A., and Wang, K., 2008. Effects of fluid circulation in subduction crust on Nankai margin seismogenic zone temperatures. Geology, 36(11):887–890. doi:10.1130/G25145A.1

Spinelli, G. A., and R.N. Harris (2011), J. Geophys. Res, 116, B09102, doi:10.1029/2011JB008248.

Tobin, H.J., and Kinoshita, M., (2006), NanTroSEIZE: the IODP Nankai Trough Seismogenic Zone Experiment. Sci. Drill., 2:23–27. doi:10.2204/iodp.sd.2.06.2006

van Andel, T. H., G. R. Heath, B. T. Malfait, D. F. Heinrichs, and J. I. Ewing (1971), Geological Society of America Bulletin, 82(6), 1489-1508. doi:10.1130/0016 7606

Vannucchi, P., Ujiie, K., Stroncik, N., and the Expedition 334 Scientists, 2012. *Proc. IODP*, 334: Tokyo. doi:10.2204/iodp.proc.334.2012

von Huene, R., and D. W. Scholl (1991), Rev. Geophys., 29(3), 279-316.

THE ROLE OF FLUIDS IN CONTROLLING TECTONIC PROCESSES ALONG THE NORTHERN JAPAN MARGIN: A HYDROGEOLOGY TRANSECT ACROSS THE NORTHERN JAPAN MARGIN USING THE D/V CHIKYU

Jim Sample[1] , Tsuyoshi Ishikawa[2] Ken Takai, Elizabeth Screaton[3], and Marta Torres[4]

[1]Northern Arizona University, [2]JAMSTEC, [3]University of Florida, and [4]Oregon State University

Keywords: fluids, megathrust, Japan Trench, hydrogeology

The 2011 Tohoku-oki earthquake presents a rare opportunity to examine fluids in the immediate aftermath of a great megathrust earthquake. Although questions about the nature of the megathrust zone were partially answered during Expedition 343, we know very little about fluid pressures and fluid flow before and after the event. This kind of information is critical for assessing the future seismic and tsunami hazards at this and similar margins. As previous drilling has shown, the best approach to gain a full understanding of the hydrogeology of the system is to drill a transect across the Japan Trench margin, where the greatest fault slip occurred. The *D/V Chikyu* is the only platform with the proven capabilities to drill in the required water depths.

Motivation and goals

Expedition 343 demonstrated that the *D/V Chikyu* can successfully operate under the challenging drilling conditions of the northern Japan margin. The results from core sampling during that expedition suggest there has not been significant fluid flow along the megathrust boundary. This raises a fundamental question about the relationship between fluids and tectonics preceding large megathrust earthquakes at this and similar margins around the Pacific basin. To move forward we need to address outstanding questions, which include: 1. Is there evidence for fluid overpressuring in fault zones before and following rupture? 2. Does overpressure contribute to fault slip here? 3. Are there multiple tectonically and hydrogeologically significant fault horizons in the prism? 4. What can fluid chemistry tell us about possible fluid flow along the megathrust boundary, including variations in hydrogeology perpendicular to the trench related to basement topography? 5) What can diagenetic mineral phases tell us about past water-rock interactions, their effects on physical properties, and the long-term hydrogeology of the system? 6) Are there differences in hydrogeology between areas with and without large slip and can the differences be related to coseismic and postseismic processes? These fundamental issues are best answered through a better understanding of the hydrogeology of the Tohoku-oki rupture area.

Scientific and drilling approach

Fluid overpressures along fault zones in accretionary prisms can promote seismic activity, and fluid overpressures commonly result in flow recognized by geochemical anomalies. At Costa Rica or Nankai for example, fluid expulsion has been recognized along vertical faults and horizontally near the subduction front, with contributions from in situ mineral dehydration reactions. Flow in the highly permeable upper layer of oceanic crust might be an important process in for heat and mass redistribution.

Initial results from Expedition 343 to the Japan Trench have signaled both important similarities and differences there relative to other margins. During Expedition 343, samples of the megathrust boundary were likely recovered, and interstitial water data provided some intriguing and puzzling results. Prior to the expedition we anticipated that a number of geochemical anomalies might be associated with faults in the prism, including variations in chlorinity and elevated H_2 concentrations related to rapid slip. We did encounter a H_2 anomaly at a fault horizon ~100 m above the inferred megathrust, but there is not an obvious flow anomaly along the megathrust itself. There is a steady chlorinity decrease in the lower ~30 m of the hole indicating communication with a low-chlorinity fluid at depth. But there are several dissolved constituents, including chlorinity, sulfate, calcium, magnesium, and strontium, which show no anomaly in the megathrust zone and appear to represent a diffusion profile to a deeper basement fluid reservoir. Alternatively we might have missed chemical anomalies in the megathrust zone due to undersampling-only 12 interstitial water samples were collected over the ~ 840 m of section drilled. The dissolved sulfate concentration at the bottom of Hole C0019E is higher than has ever been observed from drilling in a megathrust zone. The source is unclear but likely indicates hydrologic communication with interstitial waters in basement. Further investigation is required to assess to what extent these unique interstitial-water geochemical characteristics are related to very large megathrust slip and the abrupt change in state of stress.

We support a drilling effort that includes a transect of Sites from the incoming plate to inboard of Site C0019 to inform models of fluid flow and pressure along the megathrust before and after the 2011 rupture. The *D/V Chikyu* is required because it has the unique capability of drilling the depth of holes necessary in water depths approaching 7000 m. This future effort should prioritize collection of a suite of samples that contribute to our understanding of the relationship between fluid and tectonics, and should ideally be coupled with in situ pressure and permeability measurements. One Site should be located near Site C0019 to build on results obtained from the installed temperature observatory. The drilling program would return complete sets of samples for studies of physical properties (e.g., porosity, permeability, shear strength), interstitial water chemistry (e.g., isotopic tracers of waters, inorganic and organic concentration data, isotopic tracers of dissolved constituents), and lithologies and mineralogy of primary and secondary solid constituents (e.g., clay mineralogy, ash and ash alteration, diagenetic phases). Geochemical anomalies can be modeled to constrain the scale and duration of fluid flow, including the sources of fluids found in flow horizons, and the pressure gradients necessary to drive the flow. With a transect collecting multiple types of data on fluids and solids we can understand how fluids migrate in the prism, how flow and diagenesis impact physical properties between great earthquake events, and how the system responds to abrupt deformation as well as postseismic processes. We would support parallel efforts to install borehole observatories monitoring time series of fluid pressures, strain, and microseismicity.

These objectives are directly aligned with a major and high-priority challenge of the new IODP science plan (Challenge 12). In addition to addressing issues directly related to seismogenic behavior of this margin, the proposed expedition will also address important scientific challenges outlined in the new Science plan, particularly the role of fluids in these environments, deep microbial processes (Challenges 5 and 6), as well as role of subduction zones in geochemical global budges (Challenge 10) and the links between fluid flow with thermal and biogeochemical processes (Challenge 14).

Long-term observation of slow slip events for assessing earthquake generation models using borehole observatories.

Toshinori Sato[1],Hisao Ito[2], Masanao Shinohara[3], Reiji Kobayashi[4]

[1]Chiba University, [2]JAMSTEC, [3]ERI, University of Tokyo, [4]Kagoshima University

long-term borehole observation, earthquake generation models, slow slip events, earthquake cycle, check and predict

To assess and improve earthquake generation cycle models, we propose that a long-term observation should be conducted over the entire area of large slow slip events which have short recurrence time as a few years and locate in a depth where earthquakes occur (about 10-20 km). This observation should be used several borehole observatories for precise and near-field measurements and area coverage.

1. Earthquake generation models

In the last two decades, there has been a lot of progresses in studies on earthquake generation from laboratory experiments, field observations and theoretical investigations. We, now, accept that the process of earthquake generation cycle at plate boundaries consists of the following four elements (Matsu'ura 2002; Matsu'ura 2005) ;

1) Tectonic loading due to relative plate motion. 2) Quasi-static rupture nucleation. 3) Dynamic rupture propagation and stop. 4) Stress redistribution and fault strength recovery.

Many studies have been conducted on each element of the process, and proposed quantitative descriptions and/or governing equations of each element, and developed physical models of the earthquake generation cycle.

2. Long-term observation of slow slip events for earthquake generation cycle models

In the next decade, we should assess these models using real earthquake cycles. To assess the models, we make a forecast of the next step by the models, then check this through observations, and make correction in the models. We should continue this revising process in several times. Therefore, it is very important to obtain data sets over entire earthquake cycle. Unfortunately, since earthquakes have recurrence time as a few hundred years, we can not observe entire earthquake cycle in the next decade. Recently, however, we found that some of slow slip events (SSE) have short recurrence time as a few years, and locate in a depth where earthquakes occur (about 10-20 km) (e.g. Ozawa et al. 2007), which means that some SSEs and earthquakes exist in almost the same pressure-temperature conditions. To investigate SSE processes, many geophysicists have applied earthquake generation models, usually used for earthquakes, to SSEs (e.g. Shibazaki and Iio, 2003; Liu and Rice, 2007; Rubin, 2008). We think that the converse approach may be fruitful. Although Ide et al. (2007) classified earthquakes and slow events as different phenomena, Peng and Gomberg (2010) argued that slip modes should span a continuum rather than be separated into fast and slow groups. If that is true, we may be able to treat earthquakes and slow events as events of the same category. If our hypothesis is correct, we can obtain data for two or three SSE cycles and establish realistic models within 10–15 years that may be applicable to earthquakes with much longer recurrence intervals. The strategy to establish realistic models is diagrammed in Figure 1. From geodetic and geophysical observations obtained with tiltmeters, strainmeters, GPS, and onshore and offshore seismometers, we estimate the spatial and temporal distributions of slip at each step of the SSE cycle, including coupling rates, nucleation processes, dynamic behaviors, and aftershocks and afterslips. Next, slip distribution data are assimilated into distributions of parameters such as stress drop and critical displacement (Dc) by using the relation between stress changes and slip amount or slip rate. Then, by conducting numerical simulations of SSE cycles using the estimated parameters and various sets of fault constitutive laws, we try to reproduce the estimated slip distributions, searching for the optimum constitutive law and parameter combination. Then, by using the optimum models, we can predict slip behavior, check the prediction through observations, and correct the models. At least two or three such cycles of model improvement must be conducted to establish realistic models.

3. Monitoring network with borehole and ocean bottom stations

In the observations, we expect the following phenomena;

1) For tectonic loading, slip deficits occur on plate boundaries. 2) For rupture nucleation, deformation due to a quasi-static slip at a small area about 1/10 of main slip is observed. 3) For rupture propagation, deformation due to main slip is observed. 4) For stress redistribution, aftershock and afterslips occur.

Some of these phenomena, like rupture nucleation, may generate only small deformation. So, we need to choose large slow slip events (>M6), and a sensitive monitoring network over the entire area of the slow slip events. To construct this network, it is essential to integrate ocean borehole observatories and sea floor observatories, which are connected by sea floor cables for power supply and real-time data transmission. Borehole observation provides high sensitive measurements using strainmeters, broadband seismometers, and tiltmeters.

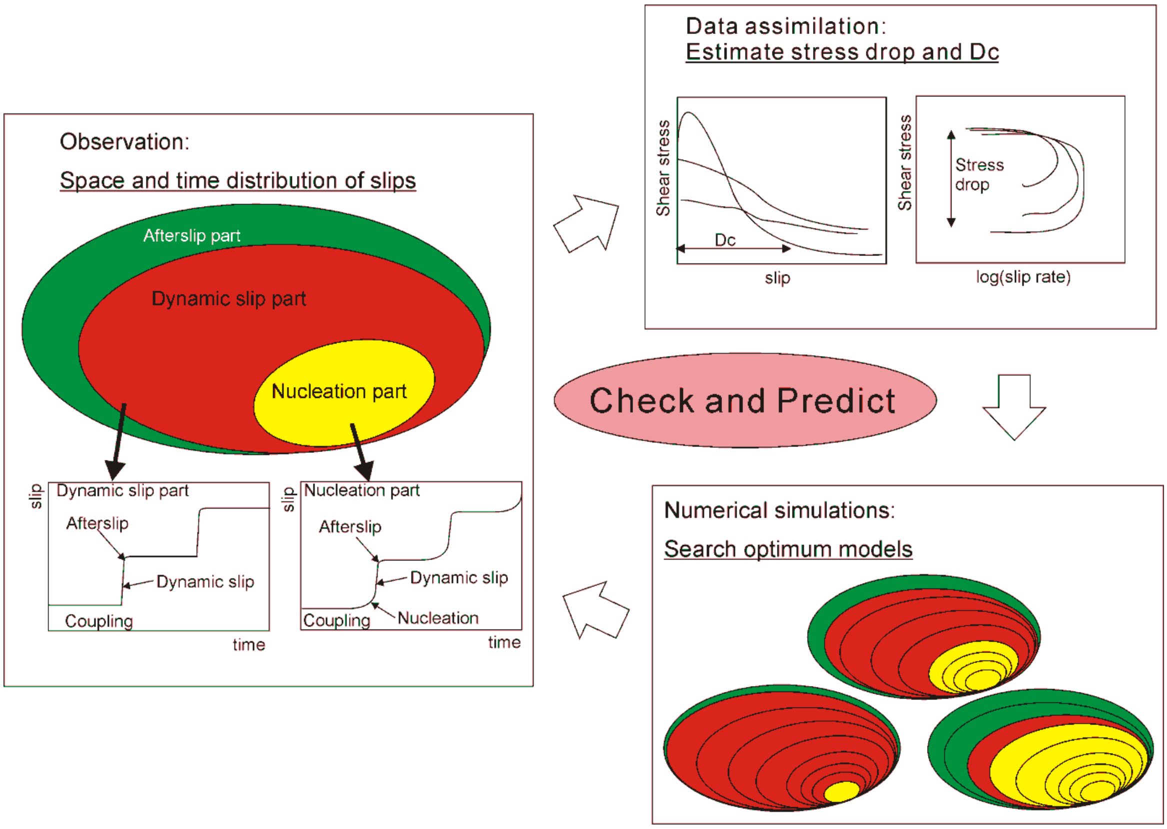


Figure 1. Schematic diagrams outlining our strategy for establishing realistic earthquake generation models

Strain Energy Release from Hydoro-visco-elastic Fault System

[Author] Insun Song and Hikweon Lee

[Institution] Korea Institute of Geoscience and Mineral Resources, Daejeon 305-350, Korea

[Keywords] fault system , frictional slip, hydr omechanics, visoelasticity, fault m echanics, seismogenic zone

[TEXTBODY] Most seismic events occur along tectonic plate boundaries, specially subduction zones where the accumulation and release of viscoelastic strain energy recur periodically as a result of the convergence of two plates [1]. Seismogenic zone, a relatively shallow region of unstable slip along the un derthrusting plate surface, is known to generate most of world's great earthquakes (M_w>8.0) often accompanied with tsunamis devastating heavily populated coastal areas [2]. One of the major IODP challenges for next 10 years is to understand mechanisms controlling the occurrence of destructive earthquakes, landslides, and tsunam i by direct access to the interplate megathrust zones for sampling, logging, and monitoring [3]. Most earthquakes are associated with frictional slips on existing faults. It is of fundam ental importance to investigate the frictional behavior of the seism ogenic zones for und erstanding earthquake mechanisms. This is the reaso n that most previous studies of fault m echanics have focused on the properties and behaviors of fault surfaces and fault gouges. The central parameter in constitutive relations of mechanical slip is the friction coefficient which is understood as a material property governing the relation between the shear and normal stresses for frictional slip, but is actually varied with slip rate and system compliance [5].

Subduction plate boundaries are divided into three zones: a shallow aseismic updip zone, the sei mogenic zone, and a deep downdip aseismic zone [2]. Defining the controlling mechanisms of the updip and downdip limits of the seism ogenic zone is crucial to determ ine the location and widt h of the seismogenic zone [4]. The periodicity of great earthquakes also remains to improve our understanding of when, where, and how the great events may recur [3]. Most previous studies to answer the above que stions have f ocused on the frictional behaviors of faults or faults gouge. However, many evidences have been given that the fault behaviors are dependent n ot only on the properties of fa ult but also on those of surrounding rock mass [5]. The coseismic fault slip and its periodicity m ay be more dependent u pon the behaviors of fault system including the huge rigid plates and overriding soft sediments that can be descri bed with hydro-visco-elastic couplings.

Some previous studies show that the slip behavior can be dependent on the compliance of test system [5]. Figure 1a shows the frictional stress (τ) as a function of the displacem ent (δ) under a constant normal stress (σ) in a stiff but not rigid test system. At the beginning of slip, the frictional stress increases fast and reaches a peak followed by a stable sliding stage at a sligh tly lower level of τ. When the sliding stops, the friction drops due to the compliance of test system. It rises again goes over a small peak when the slip resumes. If we have another cycle, the transient stage i s reproduced. If th e test system is perfectly rigid, the transient stage does not occur. Thus, the compliance of fault system may control the unstable sliding and its periodicity. Here we propose experimental simulations of fault system in which a shear sliding test is carried out in a test system the compliance of which is controlled.

A typical periodic slip is known as stick-slip behavior [6]. The mechanical model of stick-slip behavior can be realized by the simple experiment illustrated in Figure 1b. If the test system is extremely rigid (high stiffness *k*), the stick-slip behavior will be less clear. The system stiffness is reduced, the stick-slip behavior will be clearer [7]. It is not realistic that the huge tectonic plate is entirely and perfectly elastic. Better assumption is that the plate visco-elastically reacts to the constant rate convergence against the frictional resistance. Phenomenological model of the unstable sliding along the seismogenic zone for nearly constant velocity of the plate could be more like Figure 1c as a simplest model. The viscous dashpot represents the rheological behavior of plate body that includes time-dependent behavior. Controlling of the viscosity of deshpot and the stiffness of spring and rearranging of these components in our test system may allow the more realistic model for frictional behaviors along the thrust zones. We also apply fluid pore pressure in the fault gouge in undrain conditions. The fault simulations in a visco-elastic test system will yield unstable dynamic slips that generate fluid pressure fluctuation. Analysis of results from a series of tests will give us better understanding of coseismic unstable slip along the underthrusting plate surface.

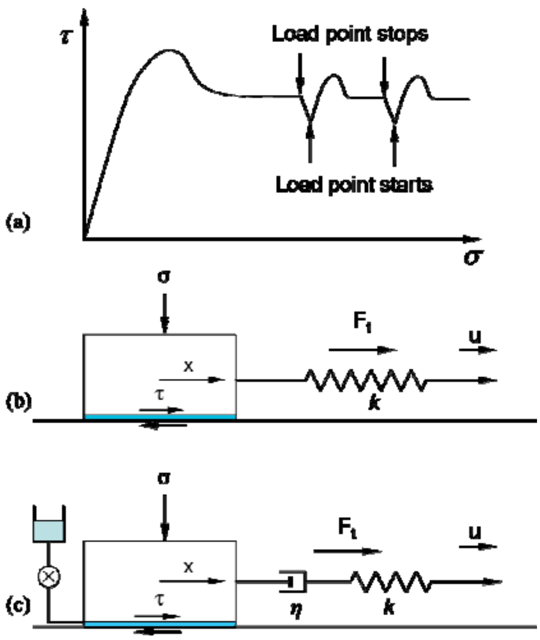


Figure 1 (a) A qualitative friction response of a surface at constant σ in a stiff but not rigid loading system showing a transient behavior when the load point stops and resumes [*Ruina*, 1985]. (b) A typical friction test model yielding stick-slip response to a constant velocity u at the end. (c) A proposed friction test model including visco-elastic loading on the sliding surface and undrained pore fluid in the fault gouge. In this model, we can control not only the fractional property of gouge but also the system behavior.

[1] Benioff, *GSAB* 62, 331-338, 1951
[2] Hyndman *et al*., *The Island Arc* 6, 244-260, 1997
[3] IODP, *Illuminating Earth's Past, Present, and Future*, 2011
[4] Saffer and Marone, *EPSL* 215. 219-235, 2003
[5] Ruina, *Mechanics of Geomaterials*, Bazant Ed., 169-188, 1985
[6] Brace and Byerlee, *Science* 153, 475-486, 1966
[7] Turcotte and Schubert, 1982

Deep sea archive for earthquake history

Michael Strasser[1], Ken Ikehara[2], Toshiya Kanamatsu[3], Shuichi Kodaira[3] and Gerold Wefer[4]

[1]ETH Zurich, [2]Geological Survey of Japan (AIST), [3]JAMSTEC, [4]MARUM (Univ. Bremen)

Keywords: Paleoseismology, Earth in Motion, Japan Trench, Earthquake, Seismoturbidite

Abstract/Summary:

D/V Chikyu has proven success in drilling in ultra-deep waters. It might be the only platform capable of drilling a north-south transect along the 7-8 km deep Japan Trench to recover continuous samples from isolated trench-floor basins, characterized by a high resolution sedimentary records comprising evidence of past, 2011-Tohoku-oki-type earthquakes. This white paper, highlights how D/V Chikyu could potentially become a flagship in submarine paleoseismology research by providing invaluable access to sub-seafloor samples for spatially and temporarily correlating seismo-turbidites to unravel the history of Japan Trench mega earthquakes, the occurrence of which along this part of the Pacific "Ring of Fire", we would mostly not have considered to be possible only 2 years ago.

Overall motivation and societal relevance of paleoseismologic research:

Natural hazards, such as earthquakes and tsunamis can have severe impacts on civil infrastructures and human society. The devastating wave generated by the 2011 Tohoku-oki earthquake awakened us to the hazardous force of nature quite dramatically. Hence, understanding geological processes that govern nature and evolution of such geohazards is a fundamental and societal-relevant goal of modern Earth Science. In order to advance our knowledge, studying in detail past events, assessing their recurrence intervals and quantitatively reconstructing magnitudes of causal and subsequent processes are key requirements. Most extreme geological events, however, show recurrence rates typically exceeding the time span covered by instrumental data and often also by historical archives. Therefore, studying prehistoric events preserved in the geological record is essential to assess the geohazard potential associated with such rare events.

Submarine paleoseismology:

Most of the largest earthquakes are generated at subduction zones with epicenters located offshore. In marine environments, ground shaking or displacement of seafloor can trigger processes including tsunamis, submarine landslides and turbidity currents, the deposits of which are left behind on the seafloor, mirroring onshore paleoseismic evidence. In subaquatic environments, the sedimentary record generally provides high sensitivity and continuity, and submarine paleoseismic evidence thus is more easily preserved and dateable than their terrestrial counterparts. The concept of using submarine turbidites for paleoseismology (e.g. Goldfinger 2011) has been attempted along various subduction margin. These studies, which are mostly based on ~10 meter long cores recovered from conventional research vessels, have shown the great potential of the emerging new research field "Subaquatic Paleoseismology".

Japan Trench submarine paleoseismology:

The Japan Trench is the submerged topographic expression of the seismogenic plate boundary fault between the Pacific Plate and the Okhotsk Microplate that ruptured during the M_w 9.0 Tohoku-oki earthquake in 2011. The Japan Trench extends over 400km and comprises several isolated trench-floor basins, separated by horst structures on the incoming plate. Sediment gravity flows generated by earthquakes and related phenomena supposedly are focused in the depressions and recorded as seismo-turbidites in the trench-floor sedimentary succession. Indeed, sedimentary cores (up to 10 m length) from research cruises Sonne SO219A and Mirai MR12-E01 document distinct event deposits composed of thin basal sand layers and multiple fining-upward sequences (Ikehara et al., 2012). More strikingly, the cores further document at least three older turbidite units. Some of these paleo-events correlate throughout cores taken from separated trench-floor basins 65km apart. Interbedded volcanic ashes provide tephra-chronological age control and preliminary results suggest that (1) the sedimentation rate in the trench is very high (5-10 m / kyrs), and (2) that one of the event deposits correlates to the Jogan tsunami of 869 A.D., recorded in the Japanese history and as tsunami deposits in the Sendai Plain (Ikehara et al., 2012). While these cores provide an excellent archive, they only cover a few thousand years and the limited along strike coverage of “only” 65 km, hampers conclusive interpretation of margin-wide, earthquake-triggered sediment remobilization pattern and thus inferences on pre-instrumental earthquake segmentation of the entire Japan Trench subduction zone system.

Why Drilling with D/V Chikyu?:

In order to extend the turbidite paleoseismology record of the Japan Trench beyond historical timescales, longer cores exceeding recovery of only the uppermost 10m are required. Non-drilling research vessels either lack the appropriate coring devices to access the deeper subsurface or cannot operated in up to 8 km water depth. D/V Chikyu has proven success in operating and retrieving subsurface cores in ultra-deep water depth during J-Fast Expedition 343 and might in fact be the only platform capable of drilling trench-floor basin in the Japan Trench. Therefore, we here propose that drilling and coring a north-south transect along the entire Japan Trench, could be considered as target for D/V Chikyu operation addressing the IODP Earth in Motion theme of the new Science Plan. D/V Chikyu is instrumental to recover continuous 50-100 meter long samples from the sedimentary sequences of trench-floor basins which are expected to reveal unprecedented archives of mega earthquakes. Such data will allow testing the hypothesis of mega-earthquake super-cycles not covered in instrumental and historical dataset.

References:

Goldfinger (2011) Submarine Paleoseismology based on turbidite records. Annu. Rev. Marine Sci. 2011. 3:35-66

Ikehara et al. (2012) Past «earthquake/tsunami» event deposits found in the Japan Trench. Abstract NH41C-02, AGU FM San Francisco, December 2012

Along strike variation in subduction zone process at Costa Rica margin: Evolution of permeability and pore pressure

[Author (s)] Wataru Tanikawa[1]

[Institution (s)] [1]Japan Agency for Marine-Earth Science and Technology

[Keywords] permeability, earthquake cycle, seismogenic zone, pore pressure, CRISP, Along strike variation

[TEXTBODY]

Background

Offshore Costa Rica provides opportunity to investigate the mechanisms that cause along strike variation of the large earthquakes. Offshore Costa Rica can be simply divided into two domains based on seismicity; near the Nicoya Peninsula (northwest Costa Rica) and near the Osa Peninsula (southeast Costa Rica). There are several contrasting features between the north and the south in off Costa Rica that can influence on the variation in seismicity. In the Nicoya region, the largest earthquakes have historically occurred, suggesting strong seismic coupling; and the Osa Peninsula region is characterized by shallow, smaller magnitude seismicity. Cool smooth oceanic crust formed at the East Pacific Rise is subducing in the north and warm crust generated at the Cocos-Nazca Spreading Center subducts in the south. Heat flow data is consistent with the variation of the crusts; low heat flow values averaging ~30 mW/m^2 exist in the EPR-generated crust offshore the Nicoya Peninsula and heat flow values are much higher than at Nicoya Peninsula (averaging ~130 mW/m^2). Variation in heat flow can influence on the temperature history of subducting sediment in both regions that affects the progress of sediment dewatering reactions. Such diagenetic reaction in thrust is one of the understanding factors affecting the updip limit of seismicity because clay mineral transformation can influence on the friction property and dehydrated fluid can increase the pore fluid pressure. The differences in seafloor age and subduction of the Cocos ridge would have contributed to the contrast of the topography and the crustal thickness. Previous IODP programs, expedition 344, showed the colorful lithological variation in incoming sediments (various ratios in calcareous and siliceous materials) that will form the decollement in future, and such variation in incoming sediment may control on the seismic behaviors as well.

Target and plan

There are numbers of factors that explain the contrasting earthquake behavior in Costa Rica margin, though one of the critical parameters is pore pressure and fluid transport property at subduction zone. Pore fluid pressure change in the plate boundary fault is expected before, during and after earthquakes, and its change is associated with the evolution process of subduction zone and induces the seismicity. To evaluate the evolution process of pore pressure at the fault zone, direct borehole observation at the target depth is the simplest way. However, to understand the physical process of the pore pressure change, evaluation of hydraulic property and understanding of physico-chemical process of fault material associate with the change in hydraulic property are critical. Long term continuous permeability measurement using boreholes together with reaction and deformation tests using core samples can provide the comprehensive understanding of evolutional process of fluid flow and pore pressure in Costa Rica margin.

Costa Rica margin has a strong potential to intersect seismic plate boundary using deep riser drilling system. Therefore deep drilling into northern and southern sites in off Costa Rica will be proposed to provide our understanding of mechanism to cause the along strike variations in seismicity off Costa Rica. In addition that, clarifying the complexity of Costa Rica erosional subduction system can give hints to understand entire subduction zone process. Previous IODP expeditions 334 and 344 have succeeded in providing the enough information of shallow slope sediment and incoming sediment, which will support the future deep riser drilling.

NANTROSEIZE RISER DRILLING TO THE MEGATHRUST AND LONG TERM MONITORING OBSERVATORY CONSTRUCTION

Harold Tobin[1], Gaku Kimura[2], Demian Saffer[3], Masataka Kinoshita[4], Gregory Moore[5], Lisa McNeill[6], Michael Underwood[7], Eiichiro Araki[4], Michael Strasser[8]

[1]Un. of Wisconsin-Madison, [2]Un. of Tokyo, [3]Penn. State Un., [4]JAMSTEC, [5]Un. of Hawaii, [6]Un. of Southampton, [7]Un. of Missouri, [8]ETH-Zurich

Seismogenic zone, megathrust, fault zone drilling, tsunami, Nankai Trough, observatory

The Nankai Trough Seismogenic Zone Experiment (NanTroSEIZE) was selected as the lead-off riser drilling program for D/V *Chikyu* in the first decade of IODP. First proposed in 2001, NanTroSEIZE is a transect of both riser and riserless drill sites designed to span the shallow (up-dip) transition from the so-called aseismic zone into the locked portion of the plate boundary fault system – the megathrust seismogenic zone. The selling point for NanTroSEIZE from the start of IODP has been riser drilling, sampling, and long-term monitoring of the plate boundary fault system at 5-7 km below the seafloor at Site C0002 (see figure). However, for technical and budgetary reasons, riser-based drilling of this site did not *begin* until October 2012. If anything, the scientific and societal urgency of drilling the seismogenic zone has increased in IODP Phase 2. The unique capabilities of *Chikyu* must be utilized to: (A) drill, sample and case at minimum to the “mega-splay” reflector at ~ 5 km bsf, and (B) install a seismological, geodetic, and hydrogeologic observatory system to monitor the mega-splay fault zone.

NanTroSEIZE implementation began with Expedition 314 (*Chikyu’s* first) in 2007 and has continued into 2013 with Expedition 338. Meanwhile, major events including the devastating 2004 Sumatra and 2011 Tohoku earthquakes and tsunami have focused the attention of both the scientific community and society as a whole on tsunamigenic processes and hazards. Advances in offshore seismology and geodetic studies have led to the discovery that the shallowest portion of the subduction fault system – far from being “aseismic” – is both capable of hosting massive tsunamigenic slip in megathrust earthquakes (Tohoku) and of nucleating VLF earthquakes, tremor, and slow slip (uniquely identified at Nankai, to date). The NantroSEIZE transect, and Site C0002 in particular, are perfectly situated to address a whole new set of key questions that have arisen in earthquake science since the project was first proposed. Such questions include: *What is the degree and nature of fault locking and strain accumulation vs. more passive propagation of slip from depth, in the up-dip transition region? How do VLFE, tremor, slow slip and other phenomena affect potential seismic and tsunami hazards? What are the interseismic stress state (including fluid pressure), temperature and permeability around the fault zone? What is the rock record of past events and how can this be applied to improve earthquake and tsunami hazard assessments at subduction zones globally?* In short, this site is now even more high-priority for the seismic processes and hazard community than it was when first proposed.

The most compelling objective of the NanTroSEIZE transect – a deep riser hole into the plate boundary fault system for sampling, logging, and long-term monitoring – is as yet unrealized. Originally conceived and explicitly described in the IODP Science Plan (2003-2013) as a "multi-platform" operation, NanTroSEIZE drilling has been carried out by *Chikyu* alone without the *JR*. Fifteen sites have been drilled, and two riserless holes have been drilled to host long-term observatories, including the most sophisticated CORK-style installation achieved to date in scientific ocean drilling. NanTroSEIZE results from both toe thrust and splay fault cores at modest (100s of meters) depths strongly suggest that past rapid co-seismic slip has propagated to the sea floor, as it did in the March 2011 Tohoku event with disastrous results.

From the earliest planning stages, the Kuroshio Current was recognized as a major technical obstacle to deployment and use of the riser at Site C0002. This obstacle was overcome through innovative engineering design but caused multi-year delays in implementation. Riser drilling finally began at Site C0002 in October 2012, during Expedition 338. A series of riserless holes was drilled at Site C0002 during Exp. 314, 315 (2007) and 332 (2010) to 1400 mbsf for logging, coring, and installation of the CORK-style riserless observatory. The "top hole" drilling and casing as preparation for riser drilling was completed during Exp. 326 (2010). The borehole is now cased to 856 mbsf and open to 2005.5 mbsf, awaiting deepening and completion in 2013 and beyond. The new IODP era will be responsible for drilling across the megasplay fault reflection for sampling, logging, downhole measurements, and ultimately installation of a deep borehole observatory connected to the DONET cable system. Technical and budgetary challenges must be overcome to realize the goal of installing and maintaining such instruments if this *or any* riser borehole is to become a true seafloor observatory. Therefore progress and results from the NanTroSEIZE program will be invaluable for all proposed deep borehole drilling and observatory installations.

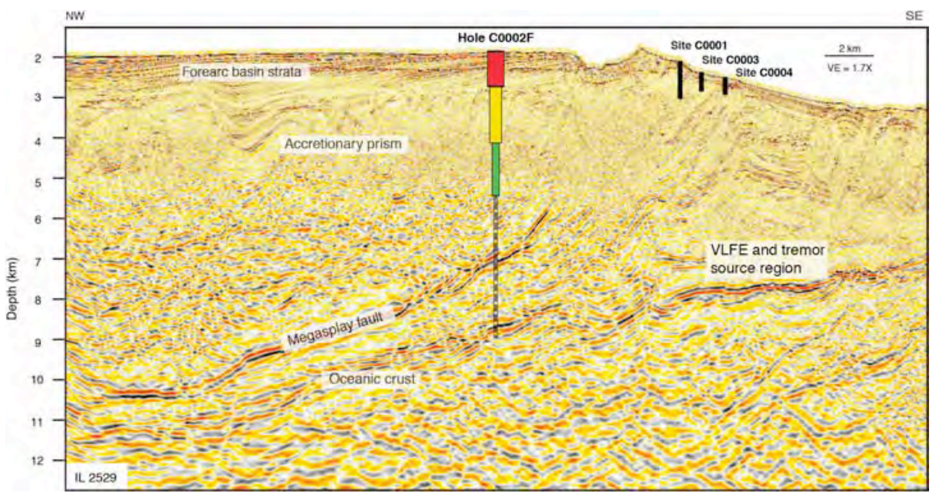


Figure: Seismic image of the Nankai mid-prism region off Kumano, Japan, showing the location of selected IODP Sites including riser hole C0002F, which targets the prominent ~5 km depth reflection termed the mega-splay fault (also hypothesized to be the position of the main plate boundary displacement surface). If conditions permit, drilling could continue to the ~7 km subducting basaltic crust of the Philippine Sea plate. Red interval is cased, yellow interval was drilled but not cased on Exp. 338. Green interval is planned total penetration and casing to ~3.6 km, planned for upcoming Expedition 348 in 2013-2014.

ACTIVE FAULTS STUDY OF POTENTIAL GREAT EARTHQUAKE IN SUNDA ARC

Udrekh[1], Nugroho Hananto[2], Haryadi Permana[2], Yusuf Surachman[3] Irwan Meilano[4], Agustan[1], Danny H. Natawidjaja[2]

[1]BPP Teknologi, [2]LIPI, [3]BIG, [4] ITB,

Sunda Arc, Real Time Measurement, Deep Sea Drilling, Potential Great Earthquake.

Introduction

The seismogenic zone in Sunda arc produced giant to great instrumentally recorded earthquakes since 2004. In Sumatra, where the subduction is in oblique direction, hosted the 26 December 2004 Mw=9.3 earthquake, followed by huge tsunami that devastated large coastal region in Indian Ocean. The earthquake was triggered at 20 - 30 km depth and then ruptured about 1300 km all the way to the north toward Andaman Island. This event was the biggest during last 40 years. Three months later, on 28 March 2005, another great earthquake (Mw=8.7) triggered in offshore Nias Island ruptured a region of ~350 km around Nias and Simuelue Island. Another important seismic event was the 25 October 2010 Mw=7.8 that produced 8 m tsunami at southwest coast of Pagai Island. The epicenter of this earthquake was reported at ~10 km depth correlated with the aseismic slip region, which was unlikely. In Java, where the subduction is in normal direction, the seismic activities indicate no giant earthquakes to date, hence it is likely that the stress is potentially accumulated to trigger great earthquake in the near future.

The question of how and why great earthquake occurs along oblique and normal subduction and vertical extend of the updip and downdip limit of a seismogenic zone is very important for earthquake and tsunami hazard mitigation. The updip limit play a strong control on deformation in the accretionary wedge hence controlling the tsunami generation, while downdip limit that located usually close to the volcanic arc may induce the intensity of ground shaking. However, the general mechanism of earthquake and tsunami generation of this active tectonics margin is remains incomplete. Following 2004 Sumatra great earthquake, a series international efforts on marine geoscientific research were deployed in Sumatra margin to address those problems using latest technology available. These efforts provide new data and set new inside and ideas of earthquake and tsunami generation. In Japan, where the tectonics settings are similar to Sunda Arc, an extensive, complex and multiphase deep drilling project (NanTroSEIZE, *Nankai Trough Seismogenic Zone Experiment*) of IODP have been deployed. The project includes the deployment of R/V Chikyu, the biggest riser and non-riser drilling platform to drill the Nankai Trough. The preliminary results demonstrated fundamental new insight into this active tectonics setting.

Marine geoscientific research in Sunda Arc following 2004 Sumatra great earthquake

The 2004 Sumatra great earthquake was the biggest instrumentally recorded earthquake. This very rare event provides opportunity to study the details of the seismogenic zone that produce the event. The international marine geoscience communities in collaboration with Indonesian research institutes/agencies have been initiate a large, multi-national research experiment to collect various geological - geophysical data. We noted that the first marine geophysical experiment was deployed just about two months following the 2004 Sumatra great earthquake was onboard JAMSTEC's R/V Natshushima. This expedition successfully recorded aftershocks using OBSs short and long period, bathymetry data acquisition and submarine video recording using ROV Hyper Dolphin.

All these initiatives results in new ideas of the location of the seismogenic zone. The aftershocks relocation reveals the first seismogenic zone geometry beneath Sumatra subduction (Araki et al., 2006). Based on deep seismic reflection data, Singh et al. (2008) proposed that the seismogenic zone may be located in the mantle. More data and methods have been applied and some detailed effort will be deployed to extract physical information from those available data. These data will be very important for deep drilling for near field observation and monitoring of the seismogenic zone.

Deepsea drilling of NanTroSEIZE project

The Nankai Trough Seismogenic Zone Experiment (NanTroSEIZE) is a multi-phase drilling program of IODP. One of the key objectives of NanTroSEIZE project is to establish a dedicated network for long term observatories from the subducting plate to the forearc basin. This network will collect time series of physical data relevant to study of the earthquake generation. The experiment have used the drilling vessel (D/V) Chikyu in the riser and non-riser mode to drill the transect since 2007. The objective of this drilling is to install observatories for real time measurement of the physical properties that can be connected to the existing real time network of DONET (Dense Oceanfloor Network System for Earthquake and Tsunamis). Considering geologic similarity between Nankai Trough and Sunda Arc, we consider that of important for a similar deep drilling and compare those results.

Drilling the seismogenic zone of Sunda arc

Time series analysis of recurrent great earthquake along Sumatra margin revealed a large unbroken section in the Mentawai segment located beneath Mentawai Island of Sunda Arc. This segment ruptured during 1797 Mw=8.8 and 1833 Mw=9.0 earthquakes. Konca et al. (2008) suggested that the partial rupture of 2007 and 2009 Mentawai earthquakes released only a fraction of the slip since 1833 earthquake. Paleoseismic records study based on coral microatoll suggested empirical forecast of future rupture patch along Mentawai Islands (Sieh et al., 2008). Moreover, the Mentawai segment are capable to produce earthquake, which is capable to produce tsunami such as 1907 Mw=7.6 (Kanamori et al., 2010) and 2010 Mw=7.8 Pagai earthquake (Singh et al., 2011). It is of great importance for deep sea drilling for real time observation of the seismogenic zone in Mentawai Islands and Sunda Strait to anticipate next great earthquake in the near future.

With this "white paper", we request for participation of Indonesian scientists in deep drilling project using *Chikyu* platform. For this purpose we have formulated drilling location in Mentawai Islands and Sunda Strait in Sunda Arc - Indonesia, which may enhance our knowledge about the seismogenic zone and hazard mitigation of this active tectonics setting.

Understanding the shallow seismic slip along the Japan Trench by deep ocean drilling

Kohtaro Ujiie[1,2], James Kirkpatrick[3], Matt Ikari[4], Takehiro Hirose[5], and Bunichiro Shibazaki[6]
[1]University of Tsukuba, Japan, [2]IFREE, JAMSTEC, Japan, [3]Colorado State University, USA, [4]MARUM, University of Bremen, Germany, [5]KCC, JAMSTEC, Japan, [6]Building Research Institute, Japan

Keywords: Earthquake, Japan Trench, tsunami, shallow seismic slip

Motivation and scientific objectives

Shallow portions of subduction plate boundaries generally slip aseismically. However, the 2011 Tohoku-oki earthquake (M_w9.0) produced the large shallow slip near the Japan Trench (Ide et al., 2011; Fujiwara et al., 2011). In addition, tsunami earthquakes, which are marked by slow rupture velocities with long period radiation, sometimes occurred at shallow portions of plate-boundary thrusts including the 1896 Meiji-Sanriku earthquake in the Japan Trench subduction zone (Kanamori, 1972). The shallow seismic slip caused the large seafloor motion, resulting in devastating tsunamis. However, physical mechanisms and dynamic processes responsible for the shallow seismic slip remain poorly understood. Deep ocean drilling in the rupture areas of the 2011 Tohoku-oki and the 1896 Meiji-Sanriku earthquakes by the D/V Chikyu will provide an invaluable opportunity to answer the following questions:

1. While both deep and shallow portions of the plate-boundary thrust ruptured during the 2011Tohoku-oki earthquake, why did only shallow slip occur during the 1896 Meiji-Sanriku earthquake?
2. What is the cause of the large slip at shallow depths? Is it due to the accumulation of strain energy by sufficient coupling of two plates? Alternatively, does it result from the rupture propagation through unstrained portions at shallow depths by fault lubrication at seismic slip rates?
3. What are the seismic slip mechanisms at shallow depths? Do they produce geologic evidence similar to that recorded in the seismogenic fault rocks (e.g., pseudotachylytes and fluidized rocks) exhumed from deeper parts of subduction-accretion complexes?

The investigation of shallow seismic slip along the Japan Trench also has the social importance of understanding large tsunami potentials for future earthquakes.

Drilling targets

We propose to drill along the shallow portions of the plate-boundary décollement along the Japan Trench where the shallow seismic slip occurred during the 2011 Tohoku-oki and the 1896 Meiji-Sanriku earthquakes (Fig. 1). Target sites include a revisit to Site C0019 off Miyagi where the largest shallow slip occurred during the 2011 Tohoku earthquake, the region of relatively small shallow slip off Fukushima, and the region of tsunamigenic slip during the 1896 Meiji-Sanriku tsunami earthquake off Iwate. At Site C0019, the plate-boundary décollement was cored by IODP Expedition 343, Japan Trench Fast Drilling Project (JFAST) (Chester et al., 2012). However, the upper and lower boundaries of the décollement were not recovered. Since seismogenic fault rocks are commonly observed along the upper or lower boundaries of tectonic mélanges formed along décollements (Ujiie et al., 2007), coring décollement boundaries would provide physical properties measurements and direct observations of the seismic slip zones associated with the large shallow slip; this would shed light on the coseismic processes at shallow depths and the magnitude of shear resistance. Coring the plate-boundary décollement is crucial to clarify the followings:

1. Fault zone structure and lithology: whether variations in fault zone structures and/or incoming sediments along the Japan Trench control the variations in shallow slippage along the Japan Trench during the 2011 Tohoku earthquake. JFAST identified the characteristic fault zone structure at Site C0019, showing a highly localized plate-boundary fault along pelagic clays (Chester et al., 2012). It is unknown whether

this structure is specific to the region of the largest slip. The spatial distribution and thickness of pelagic clays will be important factors controlling shallow coseismic slip;

2. Frictional properties: whether variations in frictional properties of plate-boundary materials along the Japan Trench affect the ease of earthquake rupture propagation from greater depths. The effect of slip acceleration on shallow seismic slip is also important (Chang et al., 2012). The high slip acceleration imposed by the rupture front may trigger the shallow seismic slip during the 2011 Tohoku earthquake, while the shallow slip during the 1896 Meiji-Sanriku earthquake may occur under the relatively low slip acceleration with earthquake nucleation at the shallow depth; and
3. Numerical modeling: The previous modeling of the cycle of subduction earthquakes along the Japan Trench has not considered the frictional properties of the plate-boundary material in the Japan Trench (Shibazaki et al., 2011; Noda and Lapusta, 2013). To construct realistic models for the generation processes of Tohoku earthquakes and tsunami earthquakes, we consider the friction behavior of the fault zone materials in the shallow Japan Trench subduction zone. From numerical simulations considering the variations in friction properties along the subduction zone, we clarify the mechanisms of the rupture processes for the 2011 Tohoku and the 1896 Meiji-Sanriku earthquakes.

The deep ocean drilling capabilities of D/V Chikyu are essential to achieve the scientific objectives outlined above. The proposed drilling operation and sites are the same as those in the white paper by Kirkpatrick et al. (2013).

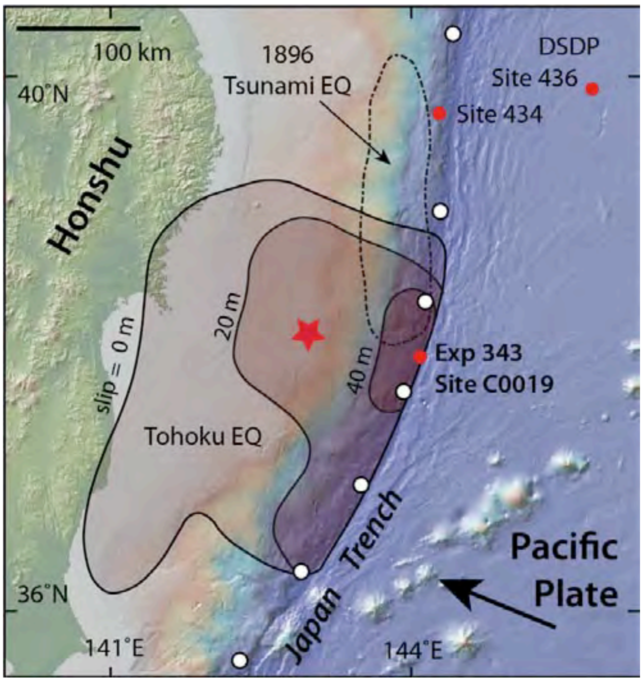


Figure 1. Location of the M_w9.0 Tohoku-oki and 1896 Meiji-Sanriku earthquake ruptures in comparison to the Japan Trench. Red dots mark the locations of previous ocean drilling expeditions, and white dots represent target sites for the work proposed here. Note we also propose to revisit Site C00019 from Expedition 343. Modified from Chester et al. (2012).

References

Chang, J. C. Lockner, D. A. & Reches, Z. (2012). *Science*, *338*, 101–105.

Chester, F.M., Mori, J.J., Toczko, S., Eguchi, N., and the Expedition 343/343T Scientists (2012). IODP Prel. Rpt., 343/343T. doi:10.2204/iodp.pr.343343T.

Fujiwara, T. et al. (2011). *Science*, *334*, 1240.

Ide, S., Baltau, A., & Beroza, G. C. (2011). *Science*, *332*, 1426–1429.

Kanamori, H. (1972). *Physics of the earth and planetary interiors*, *6*(5), 346-359.

Noda, H., & Lapusta, N. (2013). *Nature*, *493*(7433), 518-521.

Shibazaki, B. Matsuzawa, T. Tsutsumi, A. Ujiie, K. Hasegawa, A. & Ito, Y. (2011). *Geophys. Res. Lett*, *38*, L21305.

Ujiie, K., Yamaguchi, H. Sakaguchi, A. & Toh, S. (2007). *J. Struct. Geol*., *29*(4), 599–613.

CRISP: FROM STAGE 1 TO STAGE 2. PILOT STUDIES

Paola Vannucchi[1], Cesar R. Ranero[2], Roland von Huene[3]
[1]Royal Holloway University of London, UK, [2]ICREA, Barcelona, Spain, [3]UC Davis, USA
Keywords: seismogenesis, subduction erosion, Costa Rica

The Costa Rica Seismogenesis Project, CRISP, was designed to reach the plate boundary megathrust at seismogenic depth in the southern margin of Costa Rica offshore the Osa peninsula. This site is a rare location where the seismogenic zone of a subduction megathrust extends to depths reachable by Chikyu drilling. Because of this as well as the fact that this is a type-example erosive margin, the Central America subduction system has been the focus of several international projects such as the US program MARGINS for the separate thematic topics of "seismogenesis" and "subduction factory". The Central America margin was also the study area of the German SFB (Sonderforschungsbereich) project 574 "Volatiles and Fluids in Subduction Zones. These major programs gathered significant data that led to new discoveries on the behaviour of forearcs at erosive margins and subduction margin dynamics and fluid processes in general.

The Costa Rica Seismogenesis Project (CRISP) started from the idea that it would be a scientific coup to drill through a seismogenic megathrust at an erosive subduction margin. This drilling should recover upper plate material that is sheared along the megathrust as the consequence of its progressive upward migration. The physical and structural characteristics of the eroded upper plate material, and how shear is localized and how different styles of slip can develop in these types of margins are key questions to be studied. The roles of fluids are now frequently cited, but still little is known about fluid-rock interactions in this tectonic environment. Subduction erosion is particularly evident where the incoming plate is characterized by rugged topography and the variation of relief affects earthquake nucleation and rupture propagation. CRISP proposed to look into the tectonic and slip behaviour characteristics of erosive margins. Several major pilot studies for this planned deep drilling were conducted during the CRISP A IODP Expeditions 334 and 344.

PILOT STUDIES AND PILOT HOLE

The area offshore the Osa Peninsula in southern Costa Rica was drilled for the first time during CRISP A IODP Expeditions 334 and 344. The two expeditions concentrated on the transect defined by the seismic reflection line BGR 99 Line 7 (see proposal 537Full -http://iodp.tamu.edu/scienceops/expeditions/costa_rica_seismogenesis_334.html) and on the 3D- reflection seismic box located about 10-20 km to the NW of the transect (http://publications.iodp.org/scientific_prospectus/344/). The upper slope/shelf portion of the area covered by these two surveys is sited above the seismogenic zone of the plate boundary. In particular this zone has been defined by the mainshock and subsequent aftershocks of the June 2002 Mw 6.4 EQ off Osa Peninsula (fig. 1).

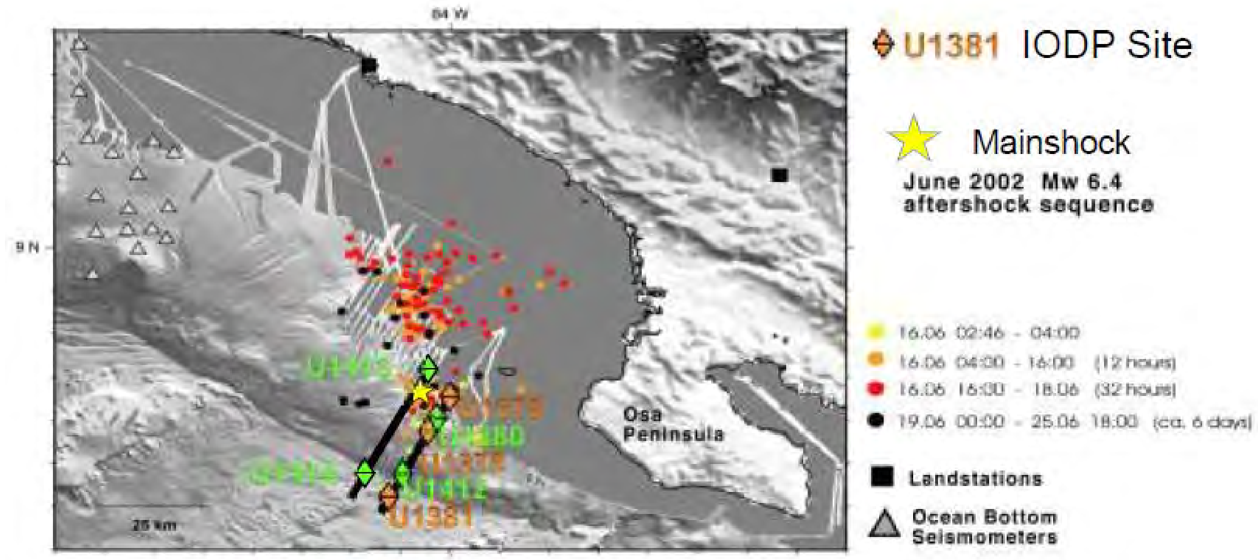


Fig. 1: Location of the mainshock and aftershocks of the June 2002 Mw 6.4 EQ off Osa Peninsula. Diamonds represent IODP Exp. 334 (Orange) and 344 (green) sites. IODP Site U1413 is the pilot hole for CRISP 2. Seismic data and elaboration by S. Bilek and I. Arroyo.

This seismogenic zone lies within riser-drilling capability (~4.5 km below sea floor in ~550 m of water depth). A pilot site, Site U1413, was drilled in the 3D-reflection seismic box during IODP Exp. 344 recovering sediments to a depth of 580 mbsf. Samples for the geotechnical analyses necessary to investigate the feasibility of riser drilling were taken at Site U1413 – sample code AOIK.

IODP Site U1379, which lies at about 12 km SE from Site U1413, was drilled to a depth of 980 mbsf during Exp. 334. Site U1379 is located above the seismogenic portion of the plate boundary at a water depth of about 125 m. There, the cored interval revealed a continuous sedimentary record covering the last 2.5 Ma, which allowed us to infer the recent tectonic evolution of the area. In particular the upper sedimentary sequence (0 to 880 mbsf) started with a beach/seashore deposit at the bottom, it evolved to deep water sediments with turbiditic layers, to end up with the present-day shelf deposits. The sediment accumulation rate was particularly high, especially in the last 0.5 Ma when 600 m of sediments were deposited on the shelf. The sedimentary sequence also records margin subsidence and uplift with differences of water depths of ~2000 m. Vertical movements of the margin are best proxy to infer subduction erosion which in this case has been estimated in the order of 1000 km3/Ma per km of trench (data from Vannucchi et al. submitted). This high subduction erosion rate suggests that this site will be an exceptional place to study subduction erosion at a convergent margin. Furthermore, CRISP offers the opportunity to sample fault rocks at the plate boundary that will reveal the roles that variations in physical conditions can play in seismogenesis.

CRISP: ADDRESSING SOCIETAL IMPACTS OF ERODING CONVERGENT MARGINS

Roland von Huene, U.C. Davis, USA, GEOMAR, Kiel, Germany, (emeritus)
Paola Vannucchi, Royal Holloway University of London, UK
Cesar Rodriguez Ranero ICREA, Barcelona, Spain
Keywords: earthquake and tsunami hazards, subduction erosion, Costa Rica

Introduction Earthquakes and tsunamis occur UNEXPECTEDLY as catastrophic events that disrupt populations and national economies. Although the maximum effects are local, the impacts are wide ranging and anticipating such events better is a major scientific goal. Seismogenic behavior is related to the material through which the plate interface fault runs. In accreting margins it runs through subducted trench sediment, whereas in eroding margins, it runs through fragmented rock eroded from the base of the upper plate. The response of each material differs because the metamorphic reactions in subducting trench sediment have already occurred in fragmented upper plate rock. The first stages of diagenesis in subducting trench sediment were sampled during NanTroSeize whereas fragmented crust in active subduction zones has NEVER BEEN SAMPLED. Fossil erosive subduction zones show how important the feedback between the fluid pressure cycle and the plate boundary stress regime are in guiding frictional strength. Direct observations of active seismogenic megathrusts can provide the ONLY UNAMBIGUOUS INFORMATION ON FLUID PRESSURE AND OTHER TRANSIENT PARAMETERS that are a key to understanding earthquake mechanics along all plate interfaces.

Costa Rica and Tohoku Understanding tsunami generation during the devastating 2011 Tohoku earthquake rupture has advanced significantly including results from Jfast scientific drilling. Subduction erosion became more widely accepted 35 years ago based on scientific ocean drilling along the northern Tohoku margin. At the Costa Rican margin, ocean drilling overturned conclusions that it was actively accreting, conclusions based only on structural information. The eroding Costa Rican and Tohoku margins exemplify a kind of margin around the Pacific Rim, margins along which a majority of devastating tsunamis are generated. Both margins have similar histories of subsidence, the ~1km thick trench sediments are mostly subducted, both margins have only 8-10 km wide tectonically active frontal prisms and the margin framework extends close to the trench axis (fig 1). Their structure is typical of the Kuril, Alaska/Aleutian, and Peru/Chile margins, that have all generated transocean tsunamis. In these margins, framework rock nearer to the trench than at accreting margins, extends greater plate rigidity and seismogenesis toward the lower slope. Deep water facilitates generation of large tsunamis. A well-defined erosive seismogenic zone is reachable with Chikyu riser drilling in the CRISP transect.

The Costa Rica and Tohoku margins are the most extensively studied erosional ones. The unmatched wealth of information in both regions has the greatest potential to significantly advance understanding of their seismogenesis. Logging and drill sampling along the CRISP transect in 2011 and 2012 has prepared the transect for deeper riser-drilling. The information includes results from a broad suite of modern geophysical, geochemical, and geological instrument systems, and monitoring of fluids in CORKS. Patchiness of subduction zone coupling is like the pattern of lower plate relief entering the Costa Rican subduction zone and similar to images from 3D seismic surveys. A preliminary image from the 2011 RV Langseth 3D seismic survey shows, with reflective amplitude information, a probable change in fluid concentration along the plate interface fault. This change occurs at temperatures where seismogenesis is thought to begin (fig 2). Observing physical parameters through at least a partial seismic cycle can show evolution of the dynamic environmental during an inter-seismic period as strain increases. The frequency of subduction zone earthquakes off Costa Rica makes it likely that monitoring may document a significant part of a relatively short seismic cycle. This would complement similar monitoring off Japan.

Many compelling and unanswered questions about seismogenic fault behavior are addressed with the detailed structural, lithologic, fluid, and modeling studies made possible with IODP drilling. More than a decade of preparation for riser drilling culminating in a drill campaign will form a cornerstone to advance understanding of earthquake mechanics and tsunamis. The impacts from earthquakes and tsunamis are anticipated to increase with time as population grows in coastal areas and as sea level rises thru global warming. Great earthquakes along eroding convergent margins structured like Costa Rica have devastated coastal populations when they are tsunamigenic, and they took hundreds of lives across the Pacific. Tsunamis and subduction zone earthquakes rank very high in social impacts from geohazardous events and mitigating their effects through scientific understanding is an ongoing research goal that a general public and politicians can understand.

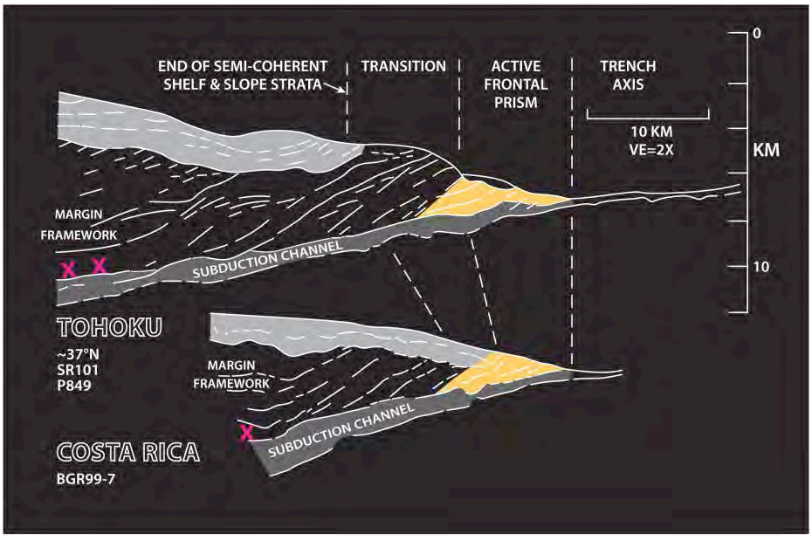


Figure 1. Line drawings of seismic images that show similarity between the erosional Tohoku and Costa Rican margins. The seismic lines are noted beneath geographic names. Margin framework rock is older and more rigid than the frontal prism and separated from it by a break in geologic history. Red Xs indicate the groups of interseismic events inferred to mark the up-dip end of the seismogenic zone. The Tohoku section crosses the north end of the 2011 earthquake's aftershocks. The Costa Rica section is on the subducted flank of Cocos Ridge along the CRISP transect.

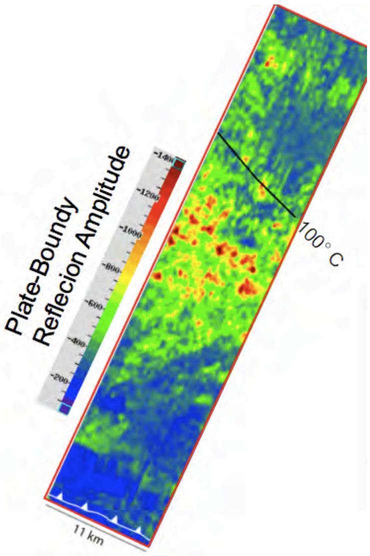


Figure 2, from Nathan Bangs et al, (in preparation, 2013). Seismic reflection amplitude distribution in the 3D seismic transect recently acquired along the CRISP transect. Sawtooth line at the lower edge is the trench axis and the upper edge is on the shelf. The 100^{o}C contour is generally associated with the up-dip end of the seismogenic zone. Greater reflection amplitude is inferred to show greater fluid concentration. A decrease of fluid is proposed to cause increased stick slip along the plate interface. Processing of these data is ongoing so as to provide the primary data for siting 2 drill holes: one to sample the plate interface prior to seismogenesis, and another in the seismogenic zone itself. Amplitude data provide a sharper "stable sliding to stick-slip" boundary zone than microseismicity.

MONITORING SEISMOGENIC ZONE PHYSICAL PROPERTY AND SEISMICITY CHANGES IN 4 D

R. von Huene

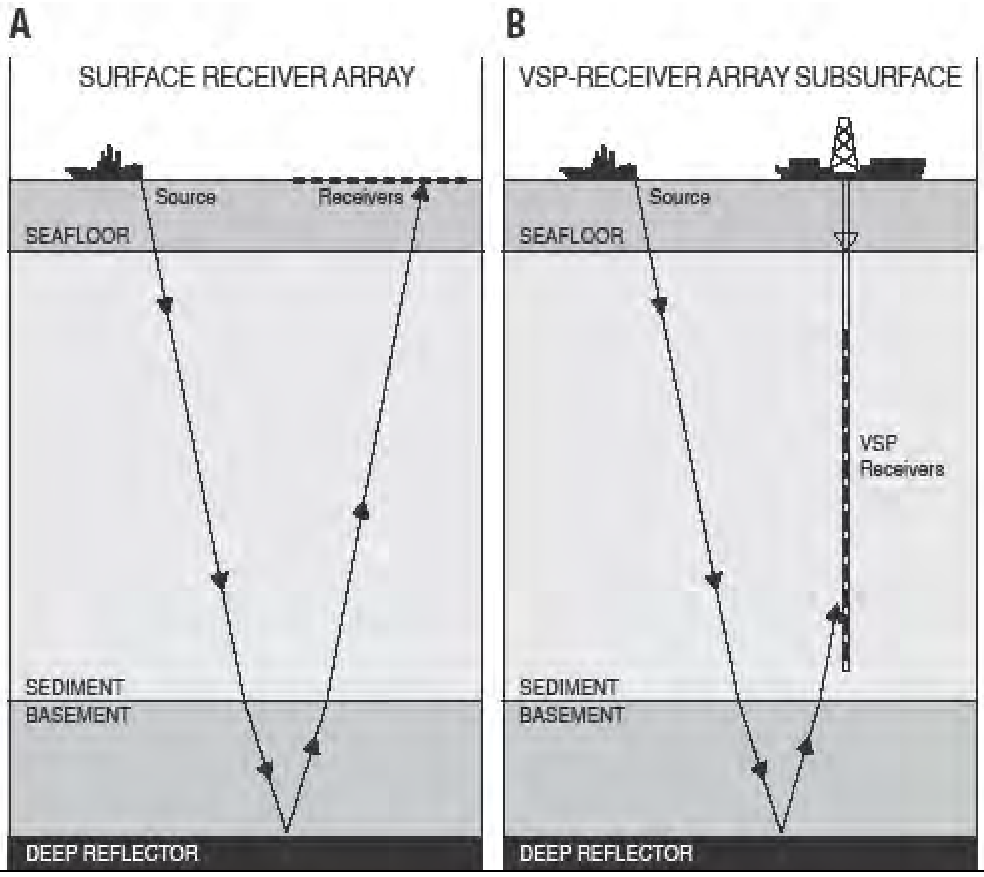
U.C. Davis, USA, GEOMAR, Kiel, Germany, (emeritus)

Seismogenic zone goals of IODP were formulated before drill ship capabilities and costs of deep drilling were tested during actual operations. Although it is common knowledge that the deepest drilling is the most difficult, it is now even more apparent that drilling to the plate interface will be very difficult, similar to the experience at SAFOD. But the benefits and value of the IODP seismogenic goals became more compelling after the 2011 Tohoku earthquake and tsunami. Understanding seismogenesis involves knowledge of physical properties and the condition of rock along a subduction zone. Current rational is that the plate interface encompasses a patchwork of different conditions on a scale of kilometers. Therefore, a drill hole, as informative as it can be, will sample only one of several seismogenic plate interface environments.

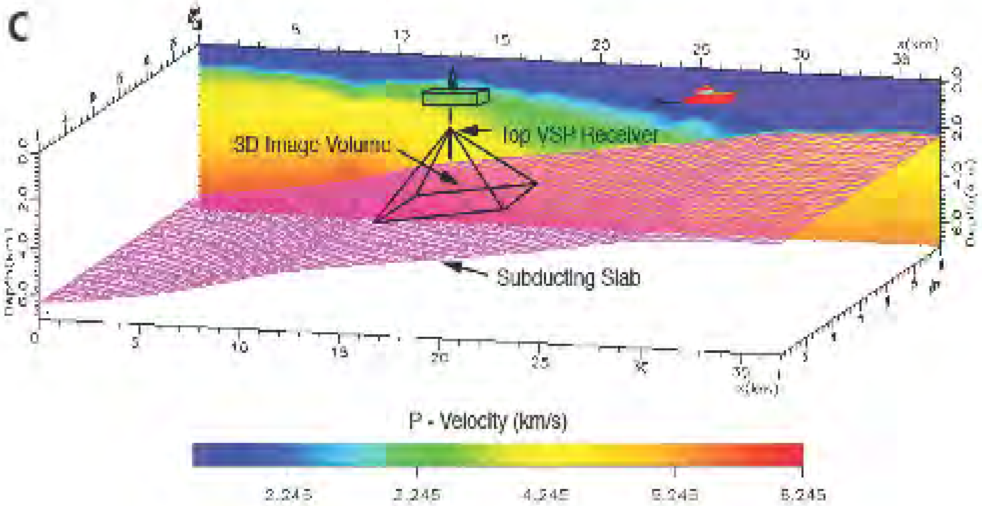
A geophysical approach may be more practical. Physical properties in subduction zones can be obtained with vertical seismic profiling (VSP), not only around a drill hole but in a rock volume of the lithospheric plates. A VSP has far better resolution than surface seismic reflection images and records shear waves directly from which physical properties can be extracted. It images the plate interface over several km. Drilling depth necessary to acquire a VSP can be completed kilometers above the plate interface thereby eliminating the most challenging and most expensive drilling. Improvements in VSP geophone arrays during the past decade allow deployment in the drill hole for an extended period. A semi-permanent deployment to continuously record seismicity, and repeat measurements of physical property changes during a seismic cycle, are observations of seismogenic dynamics. Semi-permanent VSP deployment is a means for 4D monitoring of a time period in the seismogenic cycle.

The potential of a 3D VSP to characterize the Costa Rican seismogenic plate interface in the CRISP area was investigated with commercial and academic modeling for a 1 to 1.5 km deep drill-hole in which a VSP array was deployed (G^3 2008, v9, #7). The VSP frequency response was 50% higher than a surface ship seismic record; the VSP acquired much more high fidelity shear wave data, and illuminated ~30 km^2 area of the plate interface with a reflection resolution between 30 and 40 m compared to 80-125m in surface ship acquisition. If drilling allows deeper deployment this estimated resolution improves.

A VSP program can effectively address seismogenic zone problems in critical convergent margins where the plate interface is deeper than the Chikyu can drill, such as Tohoku.



Surface receivers are hydrophones - - - **VSP** receivers are **3-axis geophones** clamped to the drill-hole that can record unconverted shear waves



UNLOCKING THE SECRETS OF SLOW SLIP BY RISER DRILLING AT THE NORTHERN HIKURANGI SUBDUCTION MARGIN, NEW ZEALAND

Laura M. Wallace[1], Yoshihiro Ito[2], Stuart Henrys[3], Philip Barnes[4], Demian Saffer[5], Shuichi Kodaira[6], Harold Tobin[7], Michael Underwood[8], Nathan Bangs[1] and the Hikurangi Margin Working Group

[1]Univ. Texas, Inst. For Geophysics, [2]Tohoku Univ., [3]GNS Science, New Zealand, [4]NIWA, New Zealand, [5]The Pennsylvania State Univ., [6]JAMSTEC, [7]Univ. Wisconsin-Madison, [8]Univ. Missouri

KEYWORDS: Subduction megathrust, slow slip event, earthquakes, aseismic slip, New Zealand

Slow slip events (SSEs) involve transient aseismic slip across a fault (lasting weeks to months) at rates intermediate between plate-boundary displacement rates and the slip velocity required to generate seismic waves. The importance of these events as a mode of fault slip was unknown prior to the advent of dense, plate-boundary-scale geodetic networks during the last decade. Observations of SSEs and associated seismic phenomena at several subduction megathrusts have ignited a dynamic and exciting field of research in seismology and plate boundary fault mechanics. SSEs appear to bridge the gap between typical earthquake behavior and steady, aseismic slip on faults, but the governing physical mechanisms, rock properties, in situ conditions, and the relationship of these events to destructive, seismic slip on subduction thrusts are poorly known. This deficiency in our understanding is due partly to the fact that most well-studied subduction zone SSEs (Cascadia, southwest Japan) are too deep for high-resolution imaging or direct sampling of the source region. **A notable exception is the northern Hikurangi subduction margin, New Zealand, where well-characterized SSEs occur every one to two years, over a period of 2-3 weeks at depths of only <5-15 km below the seafloor** (Fig. 1). SSEs at northern Hikurangi are, therefore, shallow and frequent enough to sample, log, and monitor in the near field over several cycles of strain accumulation and release.

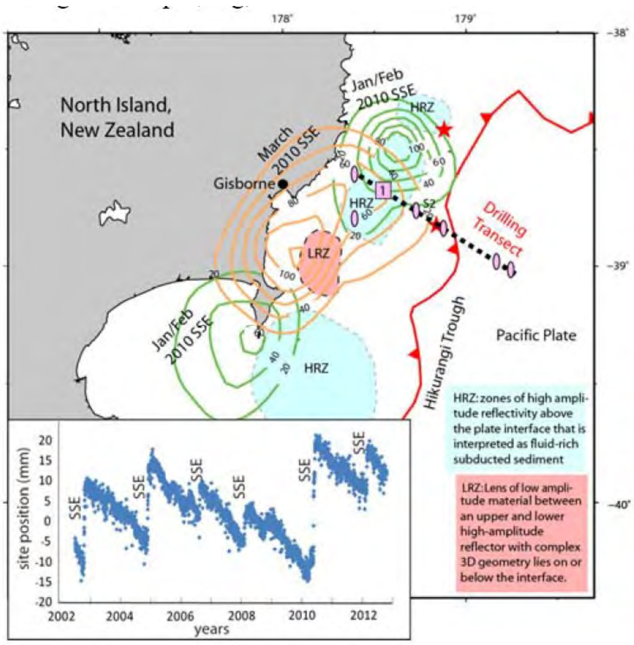


Figure 1: Tectonic setting and location of slip (colored contours) on the subduction interface in a sequence of SSEs in 2010. Black dashed line with pink ellipses shows the location of the proposed riserless drilling transect (proposal 781A-Full), while the pink square (labeled "1") shows the proposed riser drillsite to intersect the SSE source at 5.5 km bsf. Inset figure in lower left shows the east component of the position timeseries for a cGPS site near Gisborne to demonstrate the repeatability of SSEs since they were first observed in 2002.

The Multi-phase Drilling Project proposal "**Unlocking the Secrets of Slow Slip by Drilling at the Northern Hikurangi Subduction Margin, New Zealand"** (781-MDP) outlines a plan for IODP drilling to discern the mechanisms of subduction zone SSEs by a transect of both riserless and riser drilling sites above the SSE source and on the incoming plate (Fig. 2). A proposal for the riser operations will be submitted to IODP by 1 April 2013, just prior to Chikyu+10. A companion proposal for riserless operations (781A-Full) was forwarded by PEP with an "Excellent" rating and is now eligible for scheduling on *JOIDES Resolution*. Riser drilling will be needed to intersect the plate interface within a portion of the fault *where SSEs actually occur*.

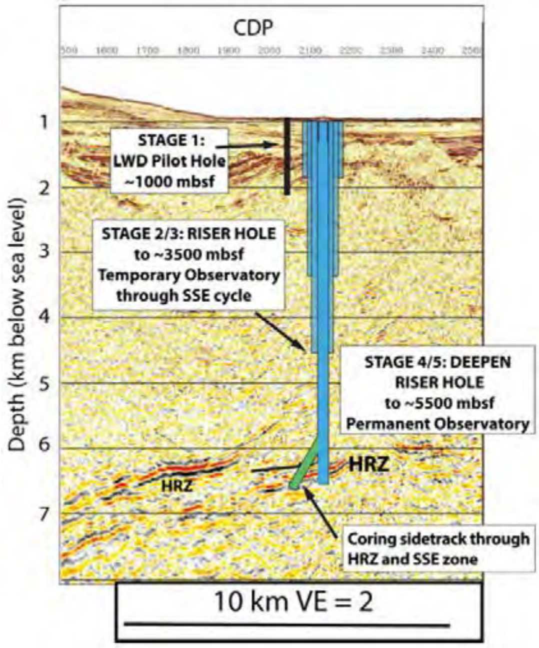


Figure 2: Schematic showing the staged drilling plan for the deep riser hole to intersect the SSE source area and high-amplitude reflectivity zone (HRZ) on the subduction interface.

For riser drilling, we propose a single borehole to intersect the plate interface ~5.5 km bsf. The goal is to **collect samples, geophysical logs, and downhole measurements across the subduction megathrust fault *at the source of SSEs***. Our drilling strategy is also designed to take advantage of scientific opportunities on the way to the subduction interface, including a temporary observatory ~1.5 km above the SSE source, to be in place between drilling phases (Fig. 2). The deep borehole is required to address three fundamental scientific objectives: (1) reveal the composition, mechanical properties, and structural characteristics of the slow slip source zone; (2) characterize hydrological properties, thermal regime, and in situ stress conditions within the SSE source region, and (3) determine hydrological properties, thermal regime, and stress conditions within the upper plate above the SSE source.

Together, these data will test a suite of hypotheses and unanswered questions about the fundamental mechanics and behavior of slow slip events. (1) Are SSEs associated with elevated fluid pressures, and if so, what is the source of the fluids? **(2)** What are the roles of fault strength and frictional properties in facilitating slow slip? **(3)** What is the fault zone architecture associated with slow slip, and does slow slip occur over a broad shear zone or discrete slip zone? **(4)** Which lithologies host slow slip, and do they promote conditional frictional stability? If so, do both fast seismic slip and slow aseismic slip occur in the same location on the interface? **(5)** How do fluid chemistry, pore pressure, temperature, and fluid flux (near the surface and at the SSE source) vary in response to SSEs, and vice versa? **(6)** Does temperature influence the down-dip limit of the seismogenic zone and the depth to slow slip events?

Most importantly, drilling into the aseismically creeping northern Hikurangi margin constitutes an ***ideal counterpart*** to deep riser drilling into the Nankai trough seismogenic zone, which is ongoing. If both subduction margins are eventually drilled, holistic comparisons of cores and logs between the two end-member locations will help to ***solve the mystery of why some subduction zones lock up and rupture in Great earthquakes (e.g., Nankai), while others are dominated by aseismic creep (e.g., North Hikurangi).***

Interaction between South China Sea subducting ridge and Manila trench: implication on distribution of volcanoes and origin of earthquakes

Shiguo Wu [a]* Jianke Fan [a, b]

a Key laboratory of Marine Geology and Environment，Institute of Oceanology, Chinese Academy of Sciences, Qingdao, China

Keywords: ridge subduction, slab window, volcanoes, earhtquake

The Philippine, made up of the Philippine Mobile Belt (PMB) (Rangin, 1991; Pubellier et al., 1996; Yumul et al., 2003b) and the continental block, is believed to be as a result of the accretion, collision, subduction, arc volcanism and ocean basin closure. It is located between two opposing subduction systems, from the west and east are the eastward dipping Eurasian Plate along the Early Miocene Manila Trench, Middle Miocene Negros Trench and the Cotabato Trench (e.g., Hayes and Lewis, 1984; Mitchell et al., 1986; Rangin et al., 1999b; Yumul et al., 2008) and the westward dipping Philippine Sea Plate (PSP) along the Philippine Trench and East Luzon Trough, which are connected through an E-W-trending transform fault (Fig. 1). The ~1200 kilometer-long left-lateral strike slip Philippine Fault longitudinally runs through the whole archipelago accommodates the rest convergence besides the two subduction systems.

The extinct mid-oceanic ridge (MOR) of the South China Sea (SCS) slab is subducting below the Luzon Arc along the Manila Trench. Based on the GPS GEODYSSEA data (Seno et al., 1993; Rangin et al., 1999b), the estimated convergence rate gradually decreases from north to south along the Manila Trench, which is twice on the northwest of Luzon as that on the southwest of Luzon. The difference of the convergence rate along the Manila Trench maybe affects the geometry of the subducted South China Sea slab. In this paper, we attempt to use seismic tomography and other geological, geophysical and geochemical data to verify the slab tear along the extinct MOR of the SCS first proposed by Bautista et al. (2001).

Luzon Arc is generated by subduction of the South China Sea slab along the Manila Trench (Taylor and Hayes, 1983), collided with Eurasian Plate at its northern and southern tips (e.g., Stephan et al., 1986; Suppe, 1988; Teng, 1990). There are two volcanic chains, named the Western Volcanic Chain (WVC) and the East Volcanic Chain (EVC) respectively. The WVC and EVC are separated by about 50km at around 18°N and merge into a single volcanic chain near 20°N. After comprehensive analysis of geomorphological, geochronological, geochemical and geophysical features of the WVC and EVC, they proposed a geodynamic model to explain the differences between the two chains. In the early Miocene (>6Ma), the volcanoes in the WVC were active due to the subduction of the South China Sea beneath the Philippine Sea Plate. At 4-5 Ma, the extinct MOR of the SCS reached and was accreted to the Manila Trench. Due to the buoyancy of the ridge and the collision between the arc and the Eurasian Plate, the volcanism north of the WVC ceased. At around 2 Ma, the subduction resumed as a result of the weight of the lower part of the subducted slab and the relative compressive movement between the subducting SCS slab and the PSP. However, because of the buoyancy of the ridge, the subducting slab has a less steep dip angle to form the EVC and cause a tear along the Continetal-Oceanic Boundary (COB) of the SCS which can account for the mantle-enrichment in the EVC. Bautista et al. (2001) presented a refinement of the Yang's model to explain the abrupt change of the dip angle, the gap in the strain energy release and the geochemical differences between the WVC and EVC etc. They also proposed that westward subduction along the East Luzon Trough may be hindered by the arrival of the Benham Rise, the counterpart of the buoyant plateau at around 20°N lat.

The tomographic results obtained from regional seismic data, comprises 2729 well-constrained earthquakes and a total of 16082 P wave arrival times from International Seismological Centre (1960~2008) are utilized to trace the subducted slab of the South China Sea along the Manila Trench. The results reveal that the subducting angle of the SCS slab decreases northward from 14° to 18°N lat., and suggest the existence of tear in the subducted SCS slab along the axis of the fossil ridge. The slab tear, attributed to the subduction of a buoyant plateau at around 20°N lat., can explain the volcanic gap and geochemical difference between the extinct Miocene and Quaternary volcanoes in the Luzon arc and island. The youngest adakites and the related porphyry Cu-Au deposits in the Luzon area are due to the tear of the SCS slab along the extinct mid-ocean ridge initiating the mantle flow upward and resulting in the partial melting of the edge of the slab and the lower crust. The partial melting of the subducted oceanic crust due to the slab tear allows the incompatible elements, e.g. Cu and Au, to be involved into the mantle convection to concentrate to form the the adakites and ore-formation. Based on the characters of the subducted slab, a geodynamic model about the slab tear is proposed. The model suggests that at ~6Ma, the fossil ridge of the SCS slab possibly has subducted since 6Ma, merely the slab tear is uncertain owing to the absence of the deep seismic tomographic data. At 4-5Ma, the buoyant plateau at around 20°N lat. collided with the Manila Trench and impede the succeeding subduction of the northern part of the slab, while the southern of which sustained subducting, brought about the bend of the trenchline. At 2-3Ma, the slab with buoyant plateau resumed subduction. However, the dip angle of the northern subducting slab was less steep than before because of the greater buoyancy of the plateau, which led to the tear of the SCS slab along the axis of the ridge as the weakest zone in the slab.

Multipule drilling in the oceanic plates: ultra-deep drillings, and systematic drilling on the age-transect and different tectonic settings

[Author (s)] Natsue Abe
[Institution (s)] IFREE, Japan Agency for Marine-Earth Science and Technology
[Keywords (six or less)] Mohole, mantle, oceanic plate, crust-mantle boundary, ultra-deep drilling, hard rock drilling

[TEXTBODY]

In this white paper, I propose the multipule drilling for the next decade plan of the entire ocean drilling from 2013-2023 and beyond; 1) in the several different oceanic plates with different tectonic settings, 2) age-transect drilling in the fast-spreading oceanic plate. I would like to emphasize in this plan that D/V Chikyu should conduct her important role of this “the ultra-deep drilling into the earth mantle”.

Necessity of the ground truth of the earth observation:

The solid earth is consist of mainly three layers; core, mantle and crust. Earth scientists have been studying on the earth interior for long time, and established the way to investigate it using by geophysical observations, high-pressure experimental petrology and estimations of the source mantle geochemistry by extracted basalt on the surface. Many scientists have been working on the mantle related studies. We always use the crustal materials, even if that was composed the earth mantle before, we have never touched into the mantle directly in the history. We do not know certain component of the earth mantle yet. We have even not crossed the upper and lower crust boundary yet. Our knowledge is still limited in the crust and some imagination of the earth interior. I would like to emphasize if we have, or will have near future, to drill through the crust mantle boundary (Moho), we, earth scientists have to take this opportunity and conduct the ultra-deep drilling. This is the appointed task of D/V Chikyu. She has to accomplish this responsibility in her life. We need the ground truth of the geophysical model, experimentally studies and models. This is not only the mission of the earth, but also a kind of planetary exploration because the earth is also a planet family in the solar system. We should understand the earth system as well as the other planets and orbits.

Requirement of the drilling into several different tectonic settings:

The MDP proposal Mohole to Mantle (M2M) has already submitted to SAS and well evaluated. That is the one most important step to be accomplished in order to understand the earth system. M2M selected 3 site candidates to drill through Moho into the uppermost mantle by complete drilling in the oceanic crust in the fast-spreading system. The fast-spreading oceanic plates are thought as homogeneous “typical” oceanic plate, and they play the vital role on earth system as the upper thermal boundary layer of the mantle convection. Recent geochemical studies on peridotite, however, suggest that the upper mantle is heterogeneous in its composition, and some of them are recycled material composed the oceanic lithosphere and/or continental lithosphere. And also the architecture and the evolution processes of the fast-spreading plates seem different from the slow-spreading one. The result of the previous cruises of the ocean drilling and ocean floor study show that the fast-spreading plate has more or less the ophiolitic stratigraphy, on the other hand, the slow-spreading plate has complicated litho-stratigraphy.

There are some drilling expeditions has done in the abyssal peridotite bodies in the Pacific Ocean (Hess Deep) and the Atlantic Ocean (MARK area, 15°20' FZ, Atlantis Massif, Iberian Abyssal Plain and off Newfoundland), but nothing conducted in the Indian Ocean. Furthermore, none of the peridotite drilling has done over 400m contrary of about 100 km thickness of the oceanic plate. Then, peridotite drilling, even shallow drilling, should be conducted in the Indian Ocean as well as other Oceans. Also several ultra-deep drilling that complete penetration in the oceanic crust through Moho from the ocean floor should be conducted in the future.

Multipul drilling into the oceanic plate:

As mentioned above, the oceanic plate plays very important role of the earth evolution as the upper thermal boundary layer. It transport mass of heat and element from the mantle, and exchanges them with seawater on its way to migrate from the mid-ocean ridge to the subduction zone, and brings down them into the mantle when it subducts. However, the mass of the elements and the heat can't be estimated without the actual rock materials at least of the oceanic crust. And also we do not know the age progress reactions and heat transfer rate of the oceanic crust exactly. We do not know even the actual geotherm in the oceanic crust. The definite temperature can be measured only directly in the borehole. Geotherm in the ocean is one of the enigmatic factor of consideration of the plate model. It is enough reason to drill into the solid earth as deep as possible for even only one this purpose. However, feasible strategy to work on the plate model is to conduct several shallow drilling and measure the temperature of the boreholes along with the age transect of the oceanic crust. This project should be proposed as well as M2M.

Summary:

D/V Chikyu is the only one fleet, which is going to have the capability to drill into the earth mantle for the first time in the history. She certainly has the obligation to accomplish the ultra-deep drilling into the uppermost mantle. As the conclusion, I strongly argue that D/V Chikyu has to conduct the one ultra-deep drilling through Moho into the uppermost mantle in the normal oceanic plate from the ocean floor (Layer 1). M2M is the appropriate proposal of it.

Get in-situ mantle materials through the whole crustal section

[Author (s)] Norikatsu Akizawa[1] and Shoji Arai[1]

[Institution (s)] [1]Department of Earth Sciences, Kanazawa University

[Keywords (six or less)] mantle, Moho, dunite, harzburgite, whole crust

Moho is defined as seismographic discontinuities, which form a boundary between the mantle and the crust. Our experience in the Oman ophiolite suggests that the uppermost part of the mantle beneath oceanic Moho (or the Moho transition zone) consists of dunite (wehrlite in part), gabbro bands and harzburgite modified by MORB (Fig. 1, 2). This part is the locus of reaction between harzburgite and intruding MORB (e.g., Akizawa and Arai, 2009; Akizawa et al., 2012). Less modified harzburgite is available below this zone. These below-Moho rocks can provide us with information on deep-seated behavior of MORB that subsequently form the crust. Chemical compositions (e.g., major element and trace element compositions of minerals) of upper mantle materials are especially important for our understanding of the MORB evolution process to form the crust. However, genuine “in-situ mantle material” has not been recovered yet and the melt extraction and evolution processes are still enigmatic. Obtaining the whole intact sequence to the mantle through the crust is fundamental for understanding a whole picture of the melt extraction, evolution and solidification processes.

References

Akizawa, N., Arai, S. (2009) Petrologic profile of peridotite layers under a possible Moho in the northern Oman ophiolite: an example from Wadi Fizh. Journal of Mineralogical and Petrological Sciences, 104, 389-394.

Akizawa. N., Arai. S., Tamura. A. (2012): Behavior of MORB magmas at uppermost mantle beneath a fast-spreading axis: an example from Wadi Fizh of the northern Oman ophiolite. Contribution to mineralogy and petrology, 164, issue 4, 601-625.

Figure

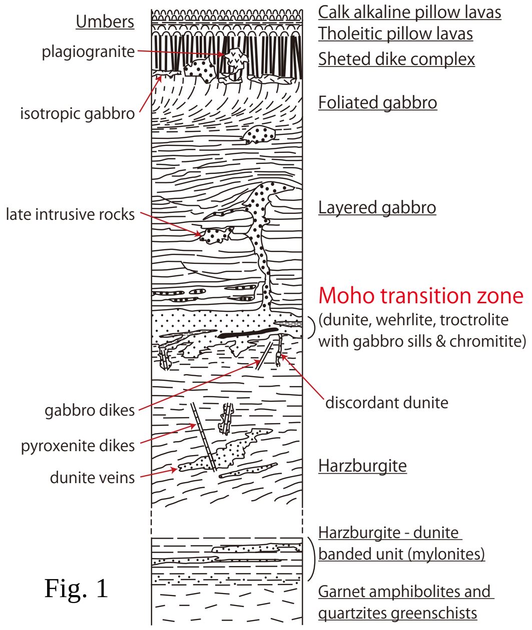


Fig. 1

Fig. 2

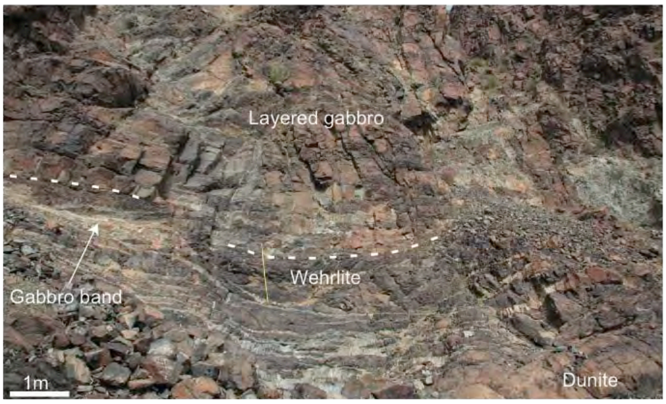


Fig. 1. Schematic column of the Oman ophiolite. Modified from Nicolas (1989).

Fig. 2. Photograph of typical lithology around the Moho transition zone from Wadi Fizh of the northern Oman ophiolite. Modified form Akziawa et al. (2012).

Studies of direct depleted mid-ocean ridge basalt mantle samples and their importance for geochemistry and geodynamics

James M.D. Day
Scripps Institution of Oceanography, La Jolla, CA 92093-0244, USA (jmdday@ucsd.edu)

Keywords: Abyssal peridotite, osmium isotopes, highly siderophile elements, mantle, *Chikyu*

The mantle is the convective silicate engine of Earth. Understanding the geochemical and lithological make-up of the mantle represents a crucial step for defining processes as wide-ranging as continental growth, subduction recycling, core-mantle interaction and the creation of oceanic crust. Oceanic abyssal peridotites reveal that the depleted upper mantle (DMM), the source of mid-ocean ridge basalts (MORB), is both chemically and isotopically heterogeneous, resulting from processes that include variable melt depletion, refertilisation and melt-rock reaction (e.g., [1,2]). The compositional variations preserved in abyssal peridotites and MORB indicate that mantle heterogeneity occurs at scales that range from the size of ocean basins to small (sub-cm) domains within the mantle, yet the timing of the creation of these heterogeneities is poorly understood (e.g., [3-6]).

A key problem in mantle geochemistry lies in the fact that samples recovered directly from the mantle are hard to come by. Ophiolite complexes are valuable for assessing the timing, causes and extent of mantle processes, as they allow field-based observation to be coupled with geochemical investigation of otherwise inaccessible mantle. With few exceptions (e.g., Taitao, Chile [7]), however, ophiolites appear to represent obducted regions of mantle that have suffered supra-subduction zone processes (e.g., [8]). That the DMM lies within reach of the deep riser-drilling vessel *Chikyu* offers potentially transformative opportunities in geochemistry and geodynamics, allowing direct geological observations to be coupled with petrology and geochemistry. While recent studies of abyssal peridotites have found extreme depletions in Sr-Nd-Hf-Os-Pb isotopes not seen in basalts (e.g., [9-14]), this white paper focuses on the insights gained from the study of Os isotopes and highly siderophile element abundances into the nature mantle melt depletion, refertilisation and melt rock reactions from abyssal peridotites.

Osmium isotope and highly siderophile element (HSE) abundance systematics of abyssal peridotites are likely to provide key constraints for interpreting isotopic and elemental signatures preserved in terrestrial lavas, as well as for deciphering melt depletion and recycling in the convecting mantle. Recent new high-precision $^{186}Os/^{188}Os$-$^{187}Os/^{188}Os$ isotope and HSE abundance data for dredged bulk samples of abyssal peridotites from the Arctic (Gakkel), Indian (central [CIR] and southwest [SWIR]), and Atlantic (Kane) ridges illustrate this point, indicating significant Os isotopic and HSE abundance heterogeneity in abyssal peridotites [15, 16]. Abyssal peridotites from the dredged global suite range from relatively fresh to serpentinized harzburgites and lherzolites, with no systematic variation observed for HSE abundances or $^{186}Os/^{188}Os$-$^{187}Os/^{188}Os$ with alteration. Average HSE abundances of different ridge segments are broadly similar (0.007 ±2 × CI-chondrite). The HSE are in approximately chondritic-relative abundances, although all ridges studied have supra-chondritic Ru/Ir (Kane = 1.4 ±0.2; Gakkel = 1.6 ±0.6; SWIR = 1.5 ±0.3; CIR = 1.4 ±0.1), similar to estimates for primitive upper mantle (PUM [17]). Unlike PUM, there is no systematic supra-chondritic Pd/Os in SWIR, CIR, or the majority of Gakkel peridotites. There is greater HSE abundance variability in ultra-slow spreading Gakkel, versus Indian or Atlantic peridotites. Abyssal peridotites have $^{187}Os/^{188}Os$ ratios ranging from 0.1217 to 0.1587. The $^{186}Os/^{188}Os$ of SWIR peridotites (0.1198385 ±4), which were affected by the Bouvet hotspot at ~20 Ma, are, on average, higher than for CIR (0.1198360 ±5), Kane (0.1198353 ±7 [18]), and Gakkel peridotites (0.1198332 ±6). If CIR, Kane and Gakkel peridotites are representative of convecting upper mantle, then this reservoir has evolved with a long-term Pt/Os that is well within the range of chondrites. In contrast, SWIR peridotites derive from a mantle source with higher Pt/Os. If SWIR $^{186}Os/^{188}Os$ values relate to high time-integrated Pt/Os, how this signature is transferred from the hotspot to the peridotites is unclear. Lack of correlation between Pt/Os and $^{186}Os/^{188}Os$ for the suites suggests abyssal peridotites do not record absolute and relative abundances of the HSE in the convecting upper mantle with high fidelity.

Future mantle targets of the *Chikyu* would allow detailed geological observations to be coupled with high-precision Os isotopic and HSE abundance analyses to provide a more refined view of mantle melting and later metasomatic processes, using <50 g of material. Targets associated with 'conventional' ridge processes, corresponding to a range of variable spreading rates, versus mantle at hotspot-ridge interactions will allow a more refined view of how time-integrated (Re+Pt)/Os occurs in the DMM, and the important implications this has for core-mantle interactions and consequently mantle geodynamics. Not only would this work expand the currently extremely limited database on abyssal peridotites (c.f., [19]), it would also allow careful assessment of the degree of mantle heterogeneity and earlier melting events preserved in the DMM and close assessment of the relationship of geochemistry within whole to partially drilled sections of oceanic crust and lithospheric mantle. Coupled with the exciting possibility of direct analysis of coupled Os-Pb isotopes in abyssal peridotite sulphides, and complementary petrology and Sr-Nd-Hf-Pb isotopes studies of abyssal peridotites, drilling to the upper mantle by *Chikyu* is likely to yield an unprecedented view of mantle dynamics and geochemistry on Earth, and for valuable comparison with the mantles and crusts of other planetary bodies in the Solar System [20].

Cited References: [1] Dick, H.J.B. et al. (1984) Earth. Planet. Sci. Lett. 69, 88–106: [2] Liu, C-Z. et al. 2009. Earth. Planet. Sci. Lett. 283, 122-132: [3] Alard, O. et al. 2005. Nature 436, 1005–1008: [4] Dupré, B., Allègre, C.J., 1983. Nature 303, 142–146: [5] Luguet, A. et al. 2007. Geochim. Cosmochim. Acta 71, 3082–97: [6] Standish et al. 2002. G-cubed 3, 1004.doi:10.1029/2001GC000161: [7] Schulte, R.F. et al. 2009. Geochim. Cosmochim. Acta 73, 5793-5819: [8] O'Driscoll, B. et al. 2012. Earth Planet. Sci. Lett. 333-334, 226-237: [9] Cipriani, A. et al. 2004. Geology 32, 657-660: [10] Harvey, J. et al. 2006. Earth Planet. Sci. Lett. 244, 606–621: [11] Liu, C.-Z. et al. 2008. Nature 452, 311-316: [12] Warren, J.M. et al. 2009. J. Geophys. Res. 114 (B12203): [13] Stracke, A. et al. 2011. Earth Planet. Sci. Lett. 308, 359-368: [14] Burton, K.W. et al. 2012. Nature Geosci. 5, 570-573: [15] Day, J.M.D. 2011. Min. Mag. 75, 731: [16] Day, J.M.D. et al. in prep: [17] Becker, H. et al. 2006. Geochim. Cosmochim. Acta 70, 4528-4550: [18] Brandon, A.D. et al. 2000. Earth Planet. Sci. Lett. 177, 319–335: [19] Warren, J.M., Shirey, S.B. 2012. Earth Planet. Sci. Lett. 359-360, 279-293: [20] Day, J.M.D. et al. 2012. Nature Geosci. 5, 614-617.

Nature of the Lower Crust and Moho at Slower-spreading Ridges (SloMo)

H.J.B. Dick, J. H. Natland2, S. Arai, P. T. Robinson, C. J. MacLeod, & SloMo Proponent Group

Introduction: **SloMo** is a multiphase drilling project to drill through the crust-mantle boundary and Moho in a representative section of the lower crust and mantle on the ultraslow spreading SW Indian Ridge. **Phase 1** proposes two JOIDES Resolution legs to drill to 3-km in at Atlantis Bank where a tectonic window exposes the lower crust and mantle. The principal objectives are to test whether Moho is a serpentinization front below the crust-mantle transition, and to recover the full section of the lower crust and shallow mantle. This will, for the first time, fully document in-situ the processes and mechanics of ocean crust formation at the slow end for seafloor spreading. The *IODP Proposal Evaluation Panel* has determined that Atlantis Bank is drilling ready for 2015. **Phase 2** will then bring the Chikyu to the Indian Ocean and Atlantis Bank following additional seismic surveys to complete Moho penetration, documenting its nature and sampling pristine mantle rock for geochemical analysis that will compliment M2M drilling in the Pacific.

Why SloMo? At slow and ultraslow-spreading ridges the lower crust uniquely preserves the critical link described in *Challenge 9* of the *IODP Science Plan*, where magmatic and tectonic processes directly reflect plate dynamics, melt input, and the pattern of mantle flow. Thus, a substantial portion of plate spreading is accommodated in the lower crust by 'tectonic extension' due to faulting and ductile deformation. This exerts a strong control on melt distribution and transport in the lower crust and delivery to the seafloor. At fast-spreading ridges, it is accepted that the crust principally undergoes magmatic accretion by the injection of melt into the lower crust, diking, and eruption of magmas. Thus rollover by ductile flow due to mantle upwelling and plate spreading is believed largely limited to the mantle. With only ephemeral magma chambers at slower-spreading ridges, however, the lower crust can support a shear stress. As a consequence, with lower magma supply rates and colder stronger lithosphere, these ridges have very different morphology and crustal architecture. Thus, a full picture of ocean crustal accretion can only be drawn if both fast- and slowspreading environments are addressed.

Unlike the Pacific, deep plutonic rocks are widely exposed at slower-spreading ridges, and largely intact sections of lower crust and shallow mantle can be drilled without going through a carapace of lavas and sheeted dikes. The latter is challenging due to extensive brittle deformation, and the tough nature of fine-grained recrystallized diabase. As a result, despite numerous past attempts, the dike-gabbro transition has only been barely reached through unusually thin volcanics and dikes in Pacific Hole 1256D. By contrast, drilling lower crust and mantle in tectonic windows at slower-spreading ridges has been highly successful with average recoveries of 87% and penetrations of 1415 m at Hole U1309D and 1508 m at Hole 735B in the Atlantic and Indian Oceans.

Lower crust and mantle are emplaced to the seafloor in several modes including extensional block faulting, and long-lived detachment faults that expose lower crust and mantle for up to several million years on a single fault. The latter produces large domal highs, (oceanic core complexes) where the lower crust and shallow mantle can be explored in three dimensions by geologic mapping and drilling. Numerical modeling shows this 'asymmetric' spreading occurs when 30-50% of extension is accommodated by magmatic accretion. At lower magma supply, extension is largely by block faulting, with widely spaced magmatic centers and intervening long amagmatic segments.

During detachment faulting the lower crust and mantle spread onto the seafloor in one direction, while the sheeted dike and lava carapace spreads in the other. This 'asymmetric" accretion, is distinct from 'symmetric' where the volcanic carapace spreads in both directions. While symmetric spreading has long been regarded as producing 'normal crust', asymmetric spreading is now recognized as a distinct and fundamental mode of crustal accretion at slower-spreading mid-ocean ridges. In well-mapped areas of slow and ultraslow-spreading ridges 50% or more of the ocean crust may be formed in this way.

The new picture of crustal accretion at slower-spreading ridges, based on core complex studies, departs radically from the Penrose model of 6-7 km's of layered pillow lavas, dikes, and gabbro, overlying mantle tectonite. While this overall sequence generally persists; gabbros are sometimes missing or intruded into the underlying mantle beneath dikes and pillow lavas. Elsewhere, only scattered basalt directly overlies serpentinized mantle exposed over broad regions of the seafloor.

Why Atlantis Bank? The extreme variability of the ocean crust at slower spreading ridges presents a dilemma as how to address Challenge 9. None of the sections exposed in tectonic windows represents the architecture of the crust formed during symmetric spreading, which presumably ranges from Pacific crust at high magma fluxes to something similar to Atlantis Bank at moderate flux. Atlantis Bank represents what might be termed "fully magmatic crust", in that the gabbro massif, even if relatively thin (~2-km) extends nearly the full length of the paleo-ridge segment. By contrast, seismic tomography and mapping at the three best exposed and studied MAR core complexes indicate that the gabbros occur in bodies of 10's to ≥100 km^2 with a heterogeneous distribution in the shallow lithosphere. The Atlantis Bank gabbro massif, however, extends over some 750 km^2 and is the magmatic end-member for asymmetric spreading. As symmetric spreading occurs when magmatic extension is >50% and represents around ~50% of slow and ultraslow-spreading crust, Atlantis Bank is likely as close to the average magma flux for slower-spreading ridges as we can get in a tectonic window. Since amagmatic and weakly magmatic spreading segments, with huge mantle exposures can be fairly well explored by seafloor geologic mapping, we suggest there is the most to gain by focusing on the fully magmatic case.

Atlantis Bank, with Holes 735B (1509-m) and 1105A (180-m), is a unique, opportunity to examine lower crustal stratigraphy in three dimensions. It is the best-exposed plutonic massif yet found in the oceans with deep dissection by late transform-parallel block faults and numerous slumps produced by tectonic uplift due to a spreading direction change at ~19.5 Ma. Moreover, uplift to sea level created a ~15-km^2 wave-cut platform revealing the bedrock and true basement below. Unusual current activity and scouring by carbonate bioclastic sand then prevented accumulation of manganese so geologic structures and layering are seen as in glacially polished outcrops. This is critical as at other oceanic core complexes the nature of true basement is unknown due to uneroded sediment cover and fault gouge as was the case at the Atlantis Massif in the Atlantic Mapping at Atlantis Bank shows continuous gabbroic accretion and emplacement to the seafloor on a detachment fault for ~3.8 Ma on a segment scale. The footwall of this non-conservative fault is only broken by ridge-parallel faults at the northern and southern ends of the massif, so observations made by drilling can be extrapolated to a broad region. This cannot be done at the bestknown Atlantic core complexes, where far more heterogeneous basement is exposed - reflecting lower magma budgets. Uniquely at Atlantis Bank, the igneous crust-mantle boundary has been mapped for ~30 km along the transform wall, while Moho has been measured at ~5.5 km beneath the seafloor, making it the best location that has been found for testing whether Moho is a serpentinization front, while numerous inliers of the dike-gabbro transition demonstrate that the detachment fault exposes the full lower crustal section where it can be sampled by drilling. If Moho is a serpentinization front, then as serpentinization is a methanogenic process, drilling may also reveal a previously unknown biosphere beneath the crust at slower spreading ridges.

A single deep hole in the lower crust is of limited use if it is not in a representative section suitable to test three-dimensional accretion models. This requires context provided by geologic mapping. Otherwise, it is a 1-D view of a 3-D problem with other dimensions blank. Documented lithologic continuity at Atlantis Bank ensures that the hole will be representative of the processes operative during accretion, and provide a laboratory for testing the seismic character of the lower crust at appropriate scales. Estimations of seismic velocity of Earth materials are generally made on ~2 cm rock cylinders, whereas the characteristics of massive outcrop, with its internal structures may be very different. With a >2 km hole passing through laterally continuous lithologies; these characteristics can be directly measured using down-hole and hole-to-hole measurements.

Vertical Magnetization Structure of Oceanic Crust and Uppermost Mantle

Toshiya Fujiwara[1]

[1]Institute for Research on Earth Evolution, Japan Agency for Marine-Earth Science and Technology (IFREE/JAMSTEC)

[Keywords] magnetization, crustal formation, alteration, oceanic crust, mantle, paleointensity

One of objectives of drilling a complete section of 'typical' oceanic crust and uppermost mantle includes a study of their vertical magnetization structure. Understanding of variation of magnetization intensity and degree of alteration of in-situ lower crust and uppermost mantle provides a long-awaited opportunity to approach the question of the origin of marine magnetic anomaly.

At least, one deep hole through the oceanic crust to the mantle is absolutely essential to reveal the complete section of the magnetization structure. In addition, several shallow holes should be combined along the seafloor age flow line for the study of spatial and temporal variations. Oceanic lithosphere originated at a fast-spreading ridge is preferable to drill in order to obtain high-resolution records. Of course clear magnetic anomaly stripes are demonstrated at the drilling site.

Spot sampling to save the drilling time is acceptable, but rock core samples are definitely required. Oriented core sampling is critical for the study. Integration with down-hole magnetic measurements and other logging tools is useful to fill gap between sampling. Before going any further, we need to realize technological developments of the down-hole instruments and reduction or estimation of drilling overprint of magnetization.

The understanding of the magnetization structure evaluated from the drilling results benefits a comprehensive understanding of marine magnetic anomaly observed at near-bottom, surface, and satellite. That gives insights of more realistic 4-D magnetization structure and nature of magnetic polarity transition, and thus formation and hydrothermal alteration processes of the oceanic crust, and serpentinization of the uppermost mantle. The drilling results can be important for not only the earth but also magnetic anomaly studies of other planets.

Paleointensity of the geomagnetic field is probably recorded in the oceanic lithosphere. Global variations of the crustal magnetization distributions extracted from globally collected near-bottom magnetic anomalies will provide independent evidences of temporal variations of the paleointensity. The oceanic lithosphere is the consecutive magnetic storage media in the past 200 million years, therefore we expect to decode the long history of the paleointensity.

Hotspot Volcanism and Oceanic Plateaus; Search for the Missing Link

Takeshi Hanyu[1] Takashi Sano[2], Masao Nakanishi[3], Maria Luisa G. Tejada[1], Kenji Shimizu[1], Seiichi Miura[1] and Daisuke Suetsugu[1]

[1]Japan Agency for Marine-Earth Science and Technology; [2]National Museum of Nature and Science; [3]Chiba University

[Keywords] hotspot, oceanic plateau, seamount, large igneous province, mantle plume

LIPs – hotspot link

Large igneous provinces (LIPs) have been considered to be formed by rapid emplacement of voluminous lavas on continental and oceanic crusts. The cause of such magmatism is under debate. The fascinating hypothesis is large-degree partial melting of a rising plume head, but some other existing models include shallow mantle melting induced by plate breakups or meteor impacts (Saunders, Elements, 2005). A supporting evidence for the plume head hypothesis would be the presence of hotspot tracks in connection with many LIPs. Numerical and laboratory experiments demonstrate that LIPs and hotspot volcanoes can be produced by a starting mantle plume head and a following plume tail, respectively (Campbell, Chem. Geol., 2007). This hypothesis should predict that the source materials of LIPs and subsequent hotspot volcanism are related with each other. However, geochemical link between them has not been firmly documented.

An attempt to explore the link between LIPs and hotspot volcanism was made by the studies of the Deccan flood basalts and the Reunion hotspot track. The ages were consistent with a fixed hotspot model in which the starting plume head established the Deccan Traps and its tail formed along-track submarine volcanoes, drilled during ODP Leg 115, and recently active Mauritius and Reunion Islands (Fisk et al., Geology, 1989). Chemical compositions of lavas may imply genetic link between them because one end-component involved in the Deccan source is common to that involved in the Reunion basalts (Peng and Mahoney, EPSL, 1995). However, geochemical trends of the Deccan flood basalts were intricate and severely disturbed by crustal contamination as they were formed on the old continent, while subsequent hotspot volcanism occurred in oceanic settings. In order to test the rising plume hypothesis, studies for oceanic plateaus and related hotspot volcanoes are requisite (Sano et al., White paper).

Deep drilling of hotspot volcanoes

Apart from the LIPs–hotspot link, deep drilling of hotspot volcanoes (seamounts) is a matter of great interest. Basement rocks collected by previous ocean drilling from some hotspot volcanoes (e.g., Hawaii-Emperor chain, Louisville track) have been successfully utilized to elucidate geomagnetic change and paleo-plate motion (Tarduno et al., Science, 2003; Koppers et al., Nature Geosci. 2012). However, petrologists and geochemists always encounter a problem with these rock cores when studying magma sources and volcanic growth of hotspot volcanoes. This is because shallow drilling (several hundred meters) samples only late-stage lavas that may be compositionally different from the lavas that consist of the main volcanic edifices. In fact, Hawaiian Scientific Drilling Project (HSDP) clearly demonstrated temporal compositional change of lavas of Hawaiian volcanoes (DePaolo et al., G-cubed, 2001).

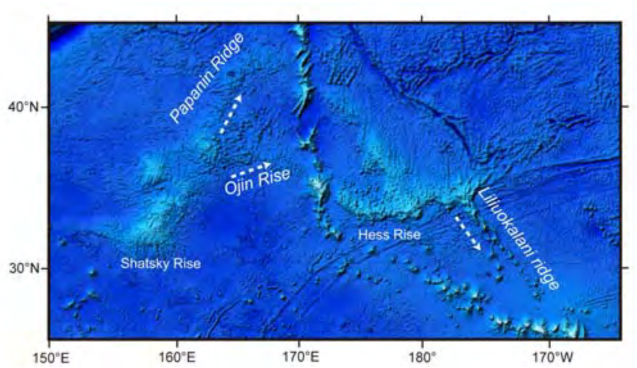
Nothing is known for the growth and magmatic evolution of hotspot volcanoes. HSDP is probably the only case in which temporal compositional change of lavas is explored in great detail, but evolution scheme of Hawaiian volcanoes may not be applicable to many other hotspot volcanoes that are much less voluminous with low eruption rate. Complete penetration into small seamounts with Chikyu's deep drilling ability may enable us to understand whole eruption history of submarine volcanoes and general trends of magmatic evolution of hotspot volcanism. Cored samples can be used for understanding the primary magmatic sources in the deep mantle, but also for surveying important crustal processes, such as hydrothermal circulations that operate on forming some specific minerals and carbonates in seamounts.

Drilling targets

For attaining the abovementioned purposes simultaneously, drilling of seamounts on hotspot tracks in connection with oceanic plateaus may be a good strategy. There are some oceanic plateaus associated with possible hotspot tracks in the Pacific Ocean. Papanin Ridge and Ojin Rise may represent later phase activity of a rising plume that formed the Shatsky Rise (Figure; Tejada et al., White paper). Shatsky Rise has been drilled during the ODP Leg 192 and IODP Expedition 324. Despite some variations in lava compositions, Shatsky Rise lavas exhibit narrow isotopic ranges compared to the global variations, suggesting relatively homogeneous and depleted sources for Shatsky Rise. However, the lavas thus far collected were from the uppermost layer of the oceanic plateaus (similar problem to the previous hotspot drilling), and therefore deep riser-drilling with Chikyu will be proposed on Shatsky Rise (Tejada et al., White paper). Deep drilling at Papanin Ridge and Ojin Rise can be combined with the drilling on the main edifices of Shatsky Rise.

Hess Rise is another promising candidate for this study because it is associated with a clear seamount track (Figure). The main edifice of Hess Rise was drilled during the DSDP Leg 62. However, recovery of basement rocks was insufficient and those rocks were too altered to be used for petrological and geochemical studies. Therefore, thorough sampling on the Hess Rise and associated hotspot tracks may be proposed.

Seamounts alignments are visually identified in the north of eastern salient of Ontong Java Plateau. Some small seamounts are distributed in the south of Mid-Pacific Mountains. Detailed inspection is required whether these seamounts are related with the nearby oceanic plateaus, but they may be possible drilling targets in combination with deep drilling on the oceanic plateaus.



Hotspot tracks (Papanin Ridge, Ojin Rise, Liliuokalani Ridge) that may be related with oceanic plateaus (Shatsky Rise, Hess Rise).

MULTIPLE DRILL CORE SAMPLINGS ALONG THE SURFACE OF THE GODZILLA MEGAMULLION: UNDERSTANDING OF THE ROLE OF HYDROTHERMAL FLUID ALONG THE DETACHMENT FAULT)

Yumiko Harigane[1*], Katsuyoshi Michibayashi[2], Jonathan E. Snow[3], Yasuhiko Ohara[4,5]

[1]*Institute of Geology and Geoinformation, Geological Survey of Japan, National Institute of Advanced Industrial Science and Technology, Tsukuba 305-8567, Japan*

[2]*Institute of Geosciences, Shizuoka University, Shizuoka 422-8529, Japan*

[3]*Department Earth and Atmospheric Sciences, University of Houston, Houston 77204-5007, USA*

[4]*Hydrographic and Oceanographic Department of Japan, Tokyo 135-0064, Japan*

[5]*Institute for Research on Earth Evolution, Japan Agency for Marine-Earth Science and Technology, Yokosuaka 236-0016, Japan*

[Keywords] detachment fault, Godzilla Megamullion, oceanic core complex, hydrothermal fluid

Oceanic core complexes (OCCs) are bathymetric features that were first identified along the Mid-Atlantic Ridge (e.g., Karson, 1990; Cann et al., 1997; Blackman et al., 1998; Tucholke et al., 1998). OCCs usually occur close to the intersection of transform faults and the axis of a spreading ridge, and are characterized by a domed surface, corrugations parallel to the spreading direction, a high mantle Bouguer anomaly, and exhumation of lower crust and mantle material. The mafic and ultramafic rocks obtained from the OCCs are interpreted generally as the result of faultrelated tectonic exhumation. The long-lived, low-angle normal faults responsible for the formation of the OCCs are termed as detachment faults. By analogy to continental metamorphic core complexes, it has been suggested that OCCs represent the exhumed footwalls of oceanic detachment faults.

An extremely large OCC, the Godzilla Megamullion named after the popular giant monster (Godzilla in Japanese) in Japanese movies (Ohara et al., 2003), occurs within the Parece Vela Rift in the central Parece Vela Basin, Philippine Sea (Ohara et al., 2001). Topographic corrugations oriented perpendicular to the spreading segment are clearly visible across the surface of the complex, extending 55 km along the axis and 125 km perpendicular, covering an area about 10 times larger than the typical OCCs described at the Mid-Atlantic Ridge (Ohara et al., 2001). Many fault rocks derived from lithospheric mantle and lower oceanic crust, respectively, have been recovered from the surface of the Godzilla Megamullion using dredges and submersible expeditions (Ohara et al., 2001; Ohara et al., 2003), indicating the existence of a detachment fault exposed on the seafloor surface. More detailed studies from deformed rocks during faulting indicated ductile shear zones were developed in the deeper oceanic lithosphere during the detachment faulting (Harigane et al., 2008, 2009, 2010, 2011), consistent with models describing OCC formation.

Models of detachment fault have been investigated by numerous studies (e.g., Schroeder and John, 2004; Ildefonse et al., 2007; Dick et al., 2008; Smith et al., 2008), whereas the role of a detachment fault on the physical and chemical modifications of the oceanic lithosphere is still uncertain. Escartin et al. (2008) examined ~2,500 km of the Mid-Atlantic Ridge between 12.5ºN and 35ºN, and revealed that asymmetrical accretion appeared as OCCs is widely distributed along almost half of the ridge. They suggested that a detachment fault within an OCCs provides fluid conduits into the deeper part of oceanic lithosphere. This implies that the fluid conduits along the detachment faults are likely to influence the underlying magmatic system, the hydrothermal activities (hydrothermal circulation, deposit and life) and the rheological properties of oceanic lithosphere. A few studies have recorded evidence for hydrothermal activity along the detachment faults in other OCCs (e.g., Gracia et al., 2000; Früh-Green et al., 2003; deMartin et al., 2007; McCaig et al., 2007; Morishita et al., 2009).

We are starting to investigate the effect of hydrothermal alteration on the Godzilla Megamullion. Harigane et al. (2011) also argued a variety of hydrothermal fluid along the detachment fault using amphibole trace element analysis of fault rocks. Furthermore, hydrous minerals formed during hydrothermal circulation provide a focal point for intense strain localization along the detachment fault in the Godzilla Megamullion (Michibayashi, Harigane et al., in prep.). This evidence supports the idea that hydrothermal fluid could infiltrate into the deeper part of the oceanic lithosphere along detachment faults and could modify the rheological properties of the underlying oceanic lithosphere.

Presently, our understanding of such processes along the detachment faults is currently limited due to the fact that rock samples are only obtained by dredge and submersible surveys. Drilling will enable the recovery of the necessary samples to study such processes along the detachment fault in the Godzilla Megamullion. We propose to carry out multiple shallow drill holes at the surface of the Godzilla Megamullion from the breakaway to the termination that will sample the damage zone of the detachment fault, and allow for the characterization of the igneous, kinematic, and hydrothermal metasomatic processes occurring there.

PRESERVATION AND DESTRUCTION OF REFRACTORY MANTLE

Eric Hellebrand[1], Kevin T.M. Johnson[1] and Tomoaki Morishita[2]
(1) Department of Geology and Geophysics, University of Hawaii, Honolulu, USA
(2) Kanazawa University, Kanazawa, Japan
[Keywords] Mantle melting, inherited depletion, reactive melt migration, abyssal peridotite

The proposal to drill a Mohole to the Mantle (M2M), through an intact section of fast-spread crust, is aimed at reaching and studying the unaltered uppermost suboceanic mantle. Several fundamentally important issues can be addressed with such a major effort, including (1) the structure and composition of the oceanic crust, (2) the structure and composition of the underlying residual mantle, and (3) the nature of boundary between these domains: the Mohorovicic discontinuity. All three components are strongly interrelated, and impossible to address by ophiolite studies where a 'normal' oceanic setting is not sufficiently well constrained.

There is a consensus that the upper mantle is heterogeneous at various scales and composed of a range of lithologies. However, it is important to distinguish between two types of heterogeneities: (1) the ones that are present in the upwelling mantle *before* the onset of melting, and (2) the heterogeneities that result from reactive melt transport during the upwelling under a spreading center. The mantle heterogeneities that can be studied during the M2M project are likely to be dominated by the second type and their study will improve our understanding of the physics of melt extraction. Pre-existing mantle heterogeneities may be present, but their preservation, and at least of equal importance, their identification may be strongly affected by the high inferred melt flux.

The aim of this white paper is to propose mantle drilling in areas where pre-existing heterogeneities have been identified in the peridotites exposed on the seafloor. Recent petrological and geochemical studies of abyssal peridotites from slow and ultraslow spreading ridges suggest that a significant, yet unknown fraction of the upper mantle is not the residue of recent melt extraction under the ridge, but instead inherited from previous ancient melting events. They are already too depleted to melt again under nominally anhydrous conditions, and have retained their isotopic signature of previous melting [1-4]. The spatial distribution and the extent of inherited depletion are locally highly variable, as found along the ultra-slow spreading Gakkel Ridge. The entire range of global abyssal peridotite compositions has been found on the scale sampled by a single dredge haul [1,3,4].

The direct and spatially controlled study of these rocks is necessary, because their refractory nature renders them virtually invisible by basalt studies. Our questions assess the impact of refractory mantle on plate tectonics and the formation and extraction of melts from the mantle. How can depleted domains be preserved in a matrix of more fertile mantle lithologies that *does* melt? Do these exotic melts migrate through the refractory peridotite, or do these melts flow around? Does this lead to a decreased melt mass, in other words, do refractory components act as a freezing melt sponge and suppress overall melt production and crustal thickness? What is their viscosity relative to the fertile lithologies? If they are depleted and thus completely anhydrous, they are expected not to mix well with the surrounding material. If their long-time deep residence led to partial rehydration, the viscosity contrast would be less prominent. In order to assess their abundance in the mantle prior to recent upwelling, can we still identify former refractory peridotites that have been overprinted by refertilizing melts?

With spatial constraints acquired during deep drilling of heterogeneous upper mantle peridotites, exposed on the ocean floor at the Gakkel Ridge and other ultraslow and slow spreading ridges, these and other questions can addressed by petrological, geochemical and fabric analyses. The DV *Chikyu*, with its riser drilling capabilities, is the ideal platform to make such an endeavor successful.

References:

[1] Hellebrand et al. (2005) Trace element distribution between orthopyroxene and clinopyroxene in peridotites from the Gakkel Ridge: a SIMS and NanoSIMS study. Contributions to Mineralogy and Petrology, 150, 486-504.

[2] Harvey et al. (2006) Ancient melt extraction from the oceanic upper mantle revealed by Re–Os isotopes in abyssal peridotites from the Mid-Atlantic ridge. Earth and Planetary Science Letters 244, 606-621.

[3] Liu C.Z., Snow J.E., Hellebrand E., Brügmann G., von der Handt A., Buechl A. & Hofmann A.W. (2008) Ancient, highly heterogeneous mantle beneath Gakkel Ridge. Nature 452, 311-316.

[4] Stracke A., Snow J.E., Hellebrand E., von der Handt A., Bourdon B., Birbaum K. & Gunther D. (2011) Abyssal peridotite Hf isotopes identify extreme mantle depletion. Earth and Planetary Science Letters, 308, 359-368.

Carbonation and Serpentinization of Upper Mantle Rocks

Kevin T.M. Johnson[1] and Eric Hellebrand[1]

[1]University of Hawaii at Manoa

[Keywords: carbonation, serpentinization, mantle, lower crust, ultramafic, mineral reactions]

Direct samples of an *in situ* section of the lower crust/upper mantle zone will provide opportunities to observe both primary and secondary characteristics of this geologically significant Earth reservoir. While describing primary compositional and mineralogical characteristics of an *in situ* section of the lowermost crust, Moho, and the upper mantle is clearly a major objective in any Moho drilling program, describing and understanding fluid-rock reactions in these rocks is also very important. Fluid-rock reactions control budgets of mobile elements in the mantle, crust, oceans, and atmosphere, and identifying these reactions and their P-T-X stability parameters will provide a basis for understanding mantle igneous processes, melt production, mantle evolution, element fluxes, and sources and sinks of fluids and volatile species, including many that are relevant to climate change, such as carbon and sulfur species, and water. Carbonation and serpentinization of ultramafic rocks is well-documented and studied in mantle rocks exposed on the seafloor through tectonic processes, but no *in situ* samples from an “undisturbed” mantle section have been collected making unequivocal explanations of natural carbonation and serpentinization processes at true mantle depths elusive to this point.

The depth and extent of seawater penetration in the sub-seafloor environment is important in quantifying the budgets of critically important elements, including C, S, numerous volatile and ore-forming elements, all associated with the reactions between water and silicate igneous rocks. Of considerable and increasing interest is the reactivity of primary mafic silicate minerals that comprise peridotites and basalts with CO_2 and H_2O in hydrothermal circulation scenarios in the oceans. Oceans are a primary reservoir for dissolved atmospheric CO_2 and the ocean crust and upper mantle are potentially a major sink for this CO_2 when it reacts with mafic silicate phases in the rocks to form stable carbonate minerals. Experimental and field studies have investigated these reactions in basalts and peridotites and have documented the carbonation reactions and their stability in P-T space (e.g., *Goff et al*., 1997; *McGrail et al*., 2006; *Matter and Kelemen*, 2009; *Johnson et al*., 2010; *Zhang et al*., 2012). Natural carbonation is observed in seafloor peridotite exposures (e.g., *Kelley et al*., 2001), ophiolites (e.g., *Kelemen & Matter*, 2008), and basalts from flood basalt provinces and ocean islands (e.g., Columbia River basalts - *McGrail et al*., 2006; Hawaii – *Trusdell et al*., 1992). However, we lack deep, *in situ* samples from the upper mantle that can further constrain the extent of these reactions, both carbonation and serpentinization, in this volumetrically important Earth reservoir. These samples will further guide experiments and modeling of these important secondary processes. At present, only the DV *Chikyu* with its riser drilling capability can accomplish this task.

References

Goff F et al., *Preliminary Investigations on the Carbon Dioxide Sequestering Potential of Ultramafic Rocks*, DOE-LA13328-MS, 1997.

Johnson KTM, McGrail BP, Schaef, HT and Owen AT, *Geologic Sequestration Studies with Hawaiian Picrites*, AGU Fall Meeting, 2010.

Kelemen P & Matter J, *In situ carbonation of peridotite for CO_2 storage*, Proc. Natl Acad. Sci. 105, 17295–17300, 2008.

Kelley D et al., *An off-axis hydrothermal vent field near the Mid-Atlantic ridge at 30º N*, Nature 412, 145–149, 2001.

McGrail BP et al., *Potential for carbon dioxide sequestration in flood basalts*, J. Geophys. Res. 111, B12201, 2006.

Matter J and Kelemen P, *Permanent storage of carbon dioxide in geological reservoirs by mineral carbonation*, Nat. Geosci. 2:837–841, 2009.

Trusdell F et al., *Core Lithology of Scientific Observation Hole 4, Kilauea Volcano, Hawaii*, USGS Open-File Report 92-586, 1992.

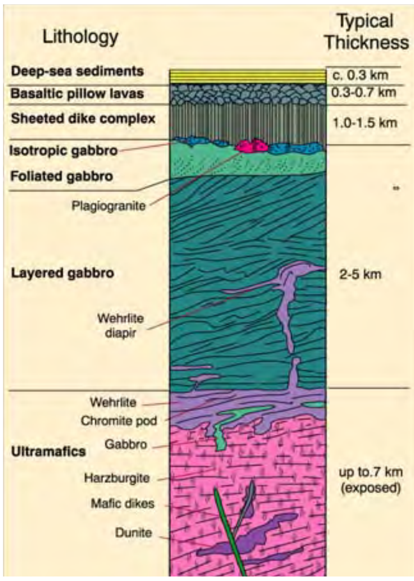
Zhang, S et al., *Experimental study of the kinetics of CO_2-sequestration by Hawaiian picrites*, B33D-0546, AGU Fall Meeting, 2012.

Linkage of seawater–rock interaction through the oceanic crust, environmental change and the relevant development of the life on the earth (MOHO project)

KAWAHATA, Hodaka (Atmosphere and Ocean Research Institute, The University of Tokyo)

Keywords: seawater-rock interaction, oceanic crust, linkage, environment, evolution of life

The Earth is characterized by the existence of life, which is largely classified into 5 stages: 1) the birth of primitive micro-organism, 2) the evolution of archaeum and basterium, 3) the development of skeletal biology, 4) the existence of homeotherm animals, and 5) the appearance of modern intelligent *Homo sapiens sapiens.* The series of the evolution has been closely related to the environmental change, sometimes crucially and/or often greatly controlled by seawater-rock interaction.



Schematic diagram of oceanic crust

[1. Ultramafic rock-water interaction] At the first stage, ultramafic rocks on the earth' surface interacted with seawater and released Ca to the fluid to form huge amount of carbonate, which reduced carbon dioxide concentration in the atmosphere (PCO_2). This process discriminated between the Earth' and Venus's (up to 500 centigrade) environments. The atmospheric temperature was below thermal death point of micro-organism (Max. 117 degree)

[2. First step to oxidative environments on the earth and possible existence of magmatic water] Redox state is important for organism to obtain life energy. Aerobic respiration is the release of energy by breakdown of glucose or another organic compound in the presence of oxygen, an excellent electron acceptor. On the other hand, anaerobic respiration uses other less-oxidizing substances such as sulfate (SO_4^{2-}), nitrate (NO_3^{3-}) and sulfur (S), which are energetically less efficient than aerobic respiration. These compounds started to be used mainly by prokaryotes that live only a few hundred million years after the Earth's birth. Plagiogranite occurs often in the interface between the sheeted dike complex and the uppermost level of gabbros, containing a high proportion of sulfate with a delta^{34}S value of 13.0 per mil in the Cyprus ophiolite in association with magmatic water (Kawahata et al., 1995). This suggests that major fraction of the sulfate is generated in the latest stage of crystallization of the oceanic crust. Currently sulfate-reducing bacteria is living at the second lowest redox state after methanogen. The formation of the oceanic crust could present the great opportunity for the first step of the evolution. Of course, it was long before the appearance of cyanobacteria, releasing molecular oxygen by photosynthesis. Although oceanic crust originated from dry magma even with the original water content of <0.4 wt.%, magmatic water could be possibly separated at the latest stage of solidification. Magmatic water in association with acidic magma is well known to be essential to several typical types of ore deposits. Deep drilling provides important constraints for the first step of the increase in redox state and the existence of magmatic water.

[3. Mg and Ca fluctuation in seawater affected by hydrothermal activity] It is well known that Mg/Ca ratio in seawater fluctuated between <1 and >5 during the last 542 million years with minima in Ordovician-Devonian and Cretaceous, reflecting the change of the hydrothermal activity along the mid-ocean ridges. The recent cultivation experiment indicated that Mg/Ca ratio has a significant influence on both biogenic skeletal carbonate minerals (calcite/aragonite) and the speed of skeletal growth. So it is very worth understanding Ca and Mg geochemical cycle in the ocean.

Although hydrothermal circulation is mainly within the pillow basalt and sheeted dike complex, Sr isotopic composition in the Oman ophiolite clearly demonstrated that hydrothermal fluids penetrated down to and possibly below Moho (Kawahata et al., 2001). Hydrothermal alteration releases Ca to the fluids. Its flux is one third of its river input to the ocean. Ca is a crucial element because of neutralization controlling pH and the skeletal formation of organism. The first appearances of biogenic carbonate in 18 animal clades that independently evolved mineralization during the late Ediacaran through the Ordovician (~550 to 444 million years ago) corresponded to the intervals when seawater chemistry favored aragonite and calcite precipitation, respectively. Another important element in seawater is Mg, a major element in secondary minerals such as smectite, chrolite and actinolite. Although one half of river input of Mg is possibly absorbed in the altered oceanic crust, “Mg budgetary problem in the geochemical cycle” remains unclear. Namely, the question, which part of oceanic crust has been a main contributor to keep small range of chemical properties of seawater, is not quantitatively proved at the moment. The analysis of non-traditional isotopes such as Ca, Mg and B isotopes of modern oceanic crust and river and groundwater provides great improvement of understanding biogeochemical cycle in the past and in future.

[4. Low temperature seawater-rock interaction] During the middle and later Cenozoic, the climate changed to cool condition by decreased greenhouse effect induced by the reduced PCO_2 and the establishment of circum Antarctic current. In cooler climate, homoiothermal animals have more advantage on enzyme activity than cold-blooded animals. Terrestrial and possibly seafloor weathering together work as a sink of carbon dioxide as is often observed in terrestrial chemical weathering and as enhancement of alkalinity. In addition, seawater-rock interaction at high and low temperature supplies silica to the ocean, which enhances primary production to reduce PCO_2.

Anthropogenic release of carbon dioxide induces global warming and ocean acidification, which will result in under-saturation with respect to aragonite in surface Antarctic ocean by 2100AD (~700 ppm). In contrast, much deposition of biogenic carbonate during the Cretaceous excludes definite ocean acidification at much higher PCO_2 (>1,000 ppm) by enhanced alkalinity, which improved the preservation of carbonate. Low strontium isotopic ratio of Cretaceous seawater suggests that there is another unknown process to enhance alkalinity because of relative low contribution of terrestrial chemical weathering. An integrated effects of seafloor seawater-rock interaction at high and low temperature will enable us to understand the detailed process of reaction and to estimate the influence of geochemical flux to the ocean quantitatively.

[5. Comparison of seawater-rock interaction between “DEAD” and “ACTIVE” oceanic crust] Typical ophiolites such as Cyprus and Oman have provided good opportunity to investigate seawater-rock interaction in the oceanic crust and uppermost mantle along spreading centers. However, these ophiolites experienced off-oxis volcanism and the obduction process, which might modify the original features of seafloor alteration. Therefore the collaboration between ICDP (penetrating into the Oman ophiolite) and IODP MOHO projects will bring a fruitful results, comprehensive understanding and whole images of seawater-rock interaction, which proves an intimate relationship with the Earth’ environments and the relevant development of the life on the earth.

An Implementation Roadmap to sample Earth's Mantle with D/V *Chikyu*

Author: Yoshi Kawamura

Institution: IODP Management International

Key words: Mohole, mantle drilling, roadmap, engineering

One of the oldest challenges of scientific ocean drilling, restated in the International Ocean Discovery Program's Science Plan for 2013-2023, is to drill the first borehole into Earth's mantle through the entire ocean crust separated by the seismological Mohorovičić discontinuity. The Alfred P. Sloan Foundation recently made a grant to IODP Management International to develop a framework that would help guide the ambitious mantle drilling project by examining scientific goals in light of engineering approaches, current technology, and risk. We present a conceptual roadmap for reaching the mantle with the deep-sea drilling vessel Chikyu, covering option choices and the key technical steps that must be addressed in order to drill down through the oceanic crust and core key sections above and into Earth's upper mantle with a high probability of success.

The implementation roadmap must consider different bore hole configurations which are possible using today's available technologies in drilling and coring systems, while also evaluating several optional bore hole designs. Options for bore hole (wellbore) design must balance bore hole and casing size constraints against the combination of down-hole problem risks and need for multiple casing strings.

Anticipated new technologies that are expected to be launched by industry during the 2013 - 2017 timeframe will have an impact on project planning and can be incorporated into the eventual roadmap. The constraints of bore hole and casing sizes will be viewed through advanced technology applications, including the use of expandable tubular technology. Probabilistic cost estimates that consider the key variables impacting operational time for the different wellbore design options and operational scenarios must be developed. These will include a proposed metric to evaluate the value of scientific information obtained versus the operational and overall project costs. Long lead time engineering designs and tangible items that require early decisions and financial commitments will be identified.

A critical path time line showing contractual outlays well in advance of the start of operations will be provided. For example, one critical prior-year commitment notably includes the specification, design, and acquisition of additional marine drilling riser components for Chikyu. Such component specification will consider extended operations during all ultra-deepwater met-ocean conditions at some candidate sites under discussion (i.e. near the Cocos Plate, Baja California, or Hawaii), as well as Chikyu riser operations for other future projects that may have harsher conditions.

The conceptual roadmap for reaching the mantle will provide a summary of the key findings from IODP-MI's 2011 high-level Initial Feasibility Study that discussed the broad areas of: marine drilling riser design, BOP/wellhead/conductor casing requirements and design, drill-string design, met-ocean and geo-hazard surveys, high-temperature down hole tools (i.e. drilling, logging, coring, telemetry) and high-temperature drilling fluid systems (i.e. fluid specifications, cuttings handling, in-situ measurement). It will also draw from IODP-MI's 2012 High-Impact Study that shows how drilling and coring times during operations may be optimized using today's industry technology - especially with current and emerging advances in hard rock drill bit technologies.

Finally, the roadmap will define and discuss the key decision points impacting project timing - such as determining in advance the site location and the framing the science plan decisions (i.e. core points and amount of core versus cuttings sampling and logging formation evaluation requirements versus drilling ahead, etc.).

Testing the Ophiolite Model by Scientific Drilling with Chikyu

J. Koepke
Leibniz University Hannover

Keywords: Fast-spreading oceanic crust, Magmatic accretion, lower oceanic crust, reference profile, Oman Ophiolite

Ocean crust formed at fast-spreading rates is known to display relatively uniform seismic stratigraphy. In contrast to oceanic crust generated at slow-spreading ridges, it is regarded as layered and relatively homogeneous. This leads to theoretical models on magma accretion of oceanic crust, thermal models, or mass balance calculations for the complete oceanic crust being only existent for fast-spreading systems. Due to the poor access to deeper parts of the oceanic crust of fast-spreading systems, as well as the general lack of drilled sections reaching the deep basement of fast-spread crust, most models for this are not tested by using natural samples. Ophiolites, like the Oman Ophiolite, representing ancient oceanic crust being obducted on continents, offer a possibility for complementary studies and play a vital role in developing crucial paradigms for understanding sea floor spreading.

We undertook three detailed field campaigns in a specific Wadi, which is located in the Wadi-Tayin Massif in the southern part of the Oman Ophiolite, sampling a complete section through oceanic crust. The southern massifs of the Oman Ophiolite are regarded as the best area for studying primary "normal" fast-spreading ridge processes with so-called "late-stage magmatism" being widely absent. Our profile contains several hundred samples representing mantle peridotite, gabbro, dikes and lavas. With the structural data obtained during the field campaigns we reconstructed the layered stratigraphy of a virtually undisturbed oceanic crust with a thickness of approximately 6 km. We identified pillow lavas (600 m), sheeted dikes (1300 m), varitextured gabbros (400 m), foliated gabbros (1600 m) and layered gabbros (2200 m), resting upon a very thin MOHO transition zone (<50 m) on the mantle sequence, as main lithologies from top to bottom (estimated thickness in parenthesis). We assume that this profile is representative for fast-spread oceanic crust in terms of completeness of the crust-forming structural components as well as coherence of geochemical and petrological data. Thus, it´s well suited for shedding light on accretion processes and the evolution of primary and secondary geochemical cycles of fast-spreading oceanic crust. We followed an IODP-like strategy in performing all analytical investigations, like analyses of major- and trace elements and isotopes, on the same samples to create data sets as coherent as possible. The main interest of the project is to focus on mineral chemical- as well as bulk major/trace element compositional evolution with profile depth. This project provides also scientific support for the "Oman Ophiolite Drilling Project" (full proposal submitted 15. Jan. 2013; lead PI: Peter Kelemen) within the ICDP (Integrated Continental Drilling Program).

In the best case scenario, we will be able to answer major question on the construction and of the cooling of the fast-spreading Oman paleocrust (e.g., sheeted sill, model vs. gabbro glacier model; cooling models for the deep oceanic crust). The big question, however, remains, whether the famous Oman ophiolite represents really "normal" fast-spreading ocean crust at all, and whether our "ophiolite model" for fast-spreading oceanic crust, which is mainly based on the Oman ophiolite, is really applicable for the whole crust of the Pacific Ocean, covering a considerable part of our planet. There are several characteristic features from the Oman ophiolite, which were up to date not recovered in the deep EPR curst, neither by sampling the two existing tectonic windows (Pito Deep and Hess Deep), nor by scientific drilling within the IODP programme. These features are:

- Omnipresence of layered gabbro in the deep plutonic crust
- Considerable volumes of massive wehrlites cutting layered gabbro at many places
- Hundred Meter-sized intrusive bodies of tonalities/trondhjemites
- Considerable amounts of isotropic gabbronorites cutting layered gabbro at many places

The only way to test whether the ophiolite model is the correct model for the accretion of fast-spreading EPR crust, is, by scientific drilling with the riser-drilling vessel Chikyu. Only the Chikyu has the potential to drill completely through the oceanic crust, and into the upper mantle, ~6 km below seafloor. A ultradeep hole, as planned within the IODP proposal "M2M" well-embedded within the IODP program (see "White Paper" of Umino et al, "MoHole to the Mantle, M2M)", will address fundamental questions which are unanswered since decades (e.g., about the formation and evolution of oceanic crust, the mode of magmatic accretion at fast spreading ridges, the understanding of the extent and intensity of hydrothermal exchange between ocean crust and seawater). Finally, the outcome of drilling a ultradeep hole into EPR crust with the Chikyu, will provide evidence for verifying or rejecting our ophiolite model as paradigm for the architecture and formation of fast-spreading oceanic crust.

Unprecedented volcanic catastrophes revealed by drilling submarine calderas

Fukashi Maeno[1]

[1]Earthquake Research Institute, University of Tokyo

Key words: Calderas, Pyroclastic flows, Tsunamis, Rhyolite, Magma chamber, Kikai

Catastrophic caldera-forming eruptions pose one of the great natural hazards on Earth. They can cause devastating impacts on natural environment and human activity at local and global scale. The latest one in Japan occurred at submerged Kikai caldera in southern Kyushu at 7.3 ka, which produced tephra with a volume > 170 km^3. The frequencies of occurrence of such large-scale eruptions are very low, but they have repeated on island arc setting like Japanese islands (Fig. 1a), and many of them have occurred in ocean. Although our knowledge of such eruptions has advanced in the past few decades, issues still abound.

In general the eruption process of a single caldera-forming event is characterized by a preceding plinian phase, a subsequent most intense phase producing large-scale pyroclastic flows and co-ignimbrite ash-fall which is dispersed to a very wide area, and a coincidental caldera collapse. Submarine caldera-forming eruptions have not been well constrained but would induce huge pyroclastic flows, great tsunamis, explosive magma-water interaction and so on. Moreover, a release of an enormous amount of volatiles dissolved in silicic magma, resulting in an injection of gases into stratosphere and aerosol formation, must have caused a long-lasting global effect called ‘volcanic winter’, as evidenced by ice cores in polar region. Stratigraphies, components, sedimentary structures of eruption products will give a lot of information on transport processes and timing of the powerfully erupted volcanic materials and energy. All these data will contribute to deeply understand the nature of caldera-forming eruptions and related hazards.

One of noticeable features of caldera-forming eruptions is their cyclic behavior. For example, the large Aso caldera has had four major caldera-forming events since 0.3 Ma. In many calderas, multiple caldera-forming events have created their present shape and structure. Frequency of eruption events and predicted patterns for future explosive activities should be better constrained based on tephra layers in ocean floor sediments. Discrimination and dating for each sedimentary layer is crucially needed for this purpose. Determination of a thickness distribution of pyroclastic deposits will be also important to constrain the volume of erupted magma. Combination of sedimentological, geochemical and geochronological studies with supports by biostratigraphic, paleomagnetic, and Ar-Ar/K-Ar dating techniques will enable to construct the patterns of past and future events. In order to unveil the sequence and variation of eruptions and also to reconstruct the eruption processes precisely, systematic multiple drilling outside submarine caldera will be necessary. The 3D sedimentary structures of volcaniclastic deposits should be extracted based on core data. ‘Non-disturbed’ and ‘high resolution’ cores obtained by riser or non-riser drilling and sampling technology of *Chikyu* should be suitable for this purpose (Fig. 1b).

Large-scale caldera-forming eruptions represent that large silicic magmatic system has been produced and evolved in arc crust. The development of such magmatic system along volcanic front reflects the evolution of the plate tectonic system and the crust-mantle thermochemical structures of mantle wedge, where mantle-derived basalts fuel crustal magmatism in upper or lower crust. Cyclic eruptions at the same caldera may be attributed to magma fluxing, magma differentiation, and episodic generation of silicic magma chambers. For further understanding of why and how gigantic caldera-forming eruptions (repeatedly) occur there, a perspective view of the large silicic magmatic system, indicated by magma chamber depth, temperature gradient, physicochemical and stress condition of chamber and surrounding rocks, and structure of collapsed caldera, will be important. Although, for some calderas, the depth of magma chamber top was estimated, such data include many uncertainties. High-resolution 3D caldera structures should be imaged (like a tomographic image) by extensive acoustic, seismic and electromagnetic surveys. In general it is difficult for terrestrial calderas to obtain such geophysical data because installation sites of observatories and instruments are very limited. On the other hand, these geophysical surveys are easier by means of on board observation from the sea-surface. This is a great advantage of ocean drilling. Seismic surveys should be conducted by a series of single expeditions together with site surveys. Developing riser and high temperature drilling technology will enable to obtain geophysical and geochemical data from magma chamber to sea floor. Time-series geochemical data of eruption products will also constrain the origin, history and future eruptive potential of the large silicic magmatic system (Fig. 1b).

Catastrophic caldera-forming events can be an important cause of environmental and ecological fluctuation in the earth-human system. Detection and reconstruction of the past caldera-forming events will be crucial to find predicted patterns and consequent hazards. Local, regional and global impacts from such unprecedented volcanic eruptions should be highlighted in order to raise interest and educational outreach of the public. Based on renewed knowledge obtained by *Chikyu*, we also should prepare mitigation and evacuation plans for a future event. Exploring a large silicic magmatic system is also economically important, in terms of tapping new resources like mineral deposits and geothermal energy. These goals and scientific results are expected to contribute development of human activity. Drilling targets of *Chikyu* should include Kikai caldera in the Kagoshima volcano-tectonic graben, southern Kyushu, which is one of the most active caldera swarms on Earth.

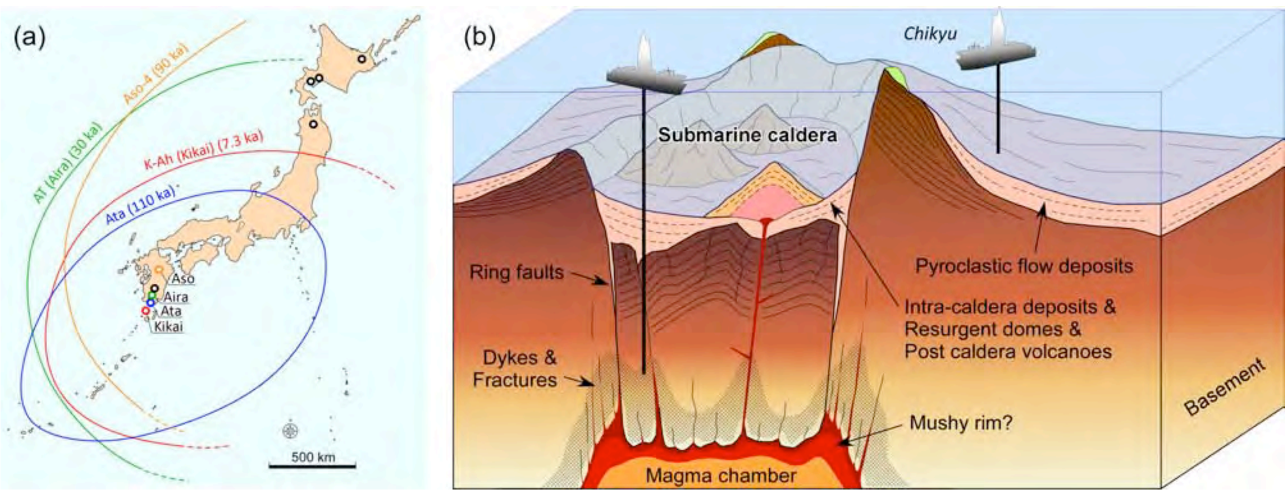


Figure 1: (a) Distribution of the representative Late Quaternary large calderas and their widespread ash-falls. (b) Idealized cross-section of a large silicic magmatic system and possible drilling sites inside and outside submarine caldera.

Drilling on Pacific Oceanic Plateaus for their origin and evolution

Seiichi Miura[1], Takeshi Hanyu[1], Takashi Sano[2], Masao Nakanishi[3], Kenji Shimizu[1], Maria Luisa G. Tejada[1], Daisuke Suetsugu[1], and Shuichi Kodaira[1]

[1]Japan Agency for Marine-Earth Science and Technology, Yokosuka, 237-0061 Japan; [2]National Museum of Nature and Science, Tsukuba 305-0005, Japan; [3]Chiba University, Chiba 263-8522, Japan

Keywords: oceanic plateau, large igneous province, Pacific, plume, deep structure

Pacific Oceanic Plateaus

Oceanic plateaus are submarine topographic features that stand at shallower water depths than surrounding seafloor. The Ontong Java Plateau (OJP), which is a mafic oceanic plateau, is a representative of large igneous provinces (LIPs) thought to be formed by some geologically short events with global scale environmental impact. However, suggestions for the formation mechanisms of Pacific oceanic plateaus have not reached a general consensus yet. Investigation of oceanic plateaus is important not only for LIPs but also for the evolution of the planet earth. The OJP is one of the largest oceanic plateau on Earth covering 1.86 x 10^6 km^2 (Coffin and Eldholm, 1994, *Rev. Geophys.*, 32, 1-36) emplaced mainly around 120 Ma with smaller event at about 90 Ma. Recently, the Ontong Java, Manihiki and Hikurangi Plateaus are thought to be pieces of the single largest LIP called Ontong Java-Manihiki-Hikurangi Plateau (OJMHP) based on the similarities of ages and compositions, bathymetric morphology, and reconstruction of plate motions (Fig.1. Taylor, 2006, *Earth Planet. Sci. Lett.*, 241, 372-380). Although the idea of a single OJMHP seems feasible, crustal thicknesses of the plateaus are varied. The crustal thickness of the OJP is about 33 km at the southernmost region of the OJP based on seismic refraction analysis (Miura et al., 2004, *Tectonophysics*, 389, 191-220), and thought to be thicker at the center of the OJP. Below the OJP crust, low velocity mantle root is suggested by Rayleigh-wave tomography (Richardson et al., 2000, Phys. Earth Planet. Inter., 118, 29-51). The Hikurangi Plateau has thinner crustal thickness of only about 23 km based on seismic reflection profile and gravity modeling (Davy et al., 2008, *Geochem. Geophys. Geosyst.*, 9, Q07004). Manihiki Plateau also seems to have thinner crustal thickness of about 25 km from gravity analysis (e.g. Viso et al, 2005, *Earth Planet. Sci. Lett.*, 233, 179-194). The variation of crustal thicknesses may be related to differences in formation mechanism and/or post-plateau emplacement evolution process.

Drilling on Pacific Oceanic Plateaus

To understand the formation mechanism of oceanic plateaus, deep drilling of the plateau's basement is necessary. Non-riser drilling conducted previously penetrated only several hundred meters of basement lava (e.g. Sano et al., White paper), whereas the crustal thicknesses are exceeding 10 km. A riser drilling using *Chikyu* is one of the most possible ways to penetrate into basement of oceanic plateaus with large recovery rate. Deep drilling at basement high features of seamounts, and atolls of the plateaus, such as that commonly observed on the OJMHP are also some of the best candidates to elucidate the formation mechanisms and evolution of the plateaus. For example, drilling on the seamounts and atolls may recover mantle and crustal xenoliths that could provide information on the plateaus' deeper internal structures, such as those found in the alnoite intrusions in Malaita (e.g., Ishikawa et al., *Journal of Petrology* 45, 2011-2044). The samples from the basement highs will be crucial to detect their formation age and sources and their relationship with their respective plateaus. Whether or not the ages are the same, the formation mechanisms of the basement highs should be related to the origin and evolution of the oceanic plateaus.

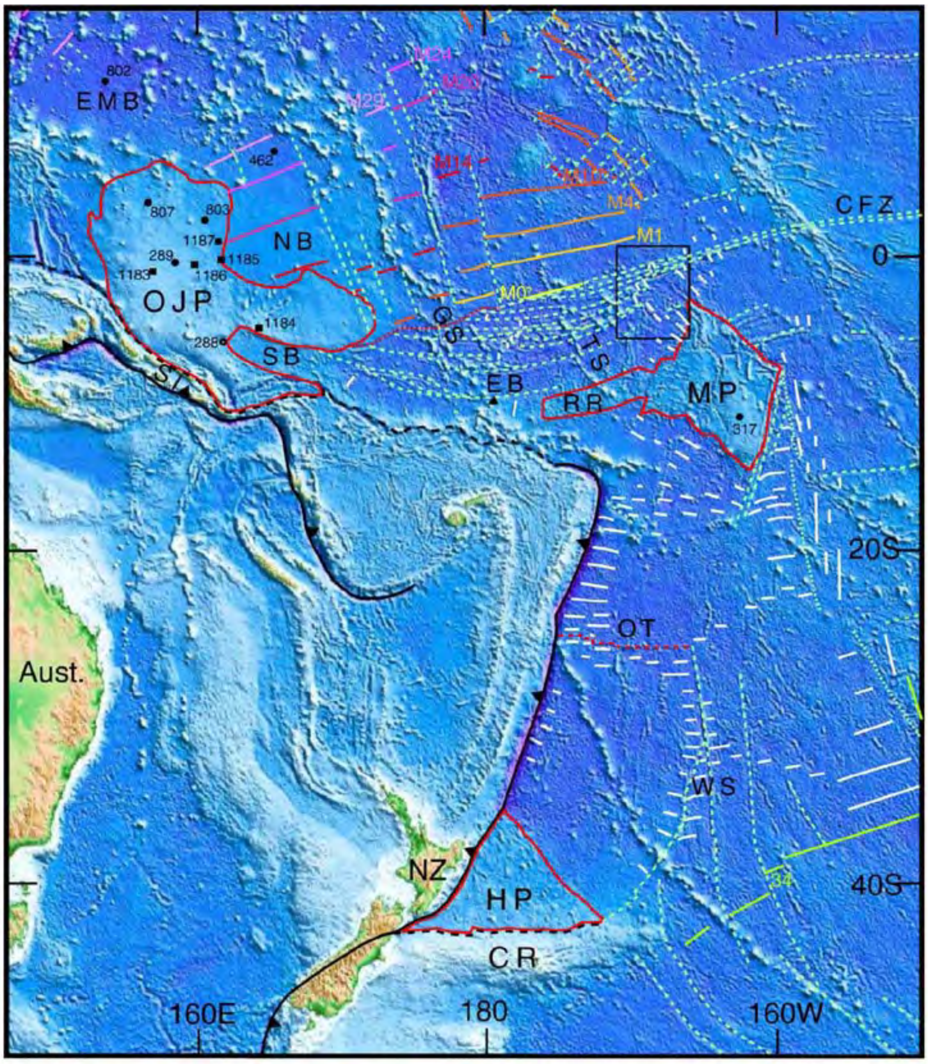


Figure 1. Bathymetric map showing pieces of the single largest oceanic plateau: Ontong Java-Manihiki-Hikurangi Plateau (from Taylor, 2006).

Oceanic Crust and Mantle Evolution From Ridge Through Trench

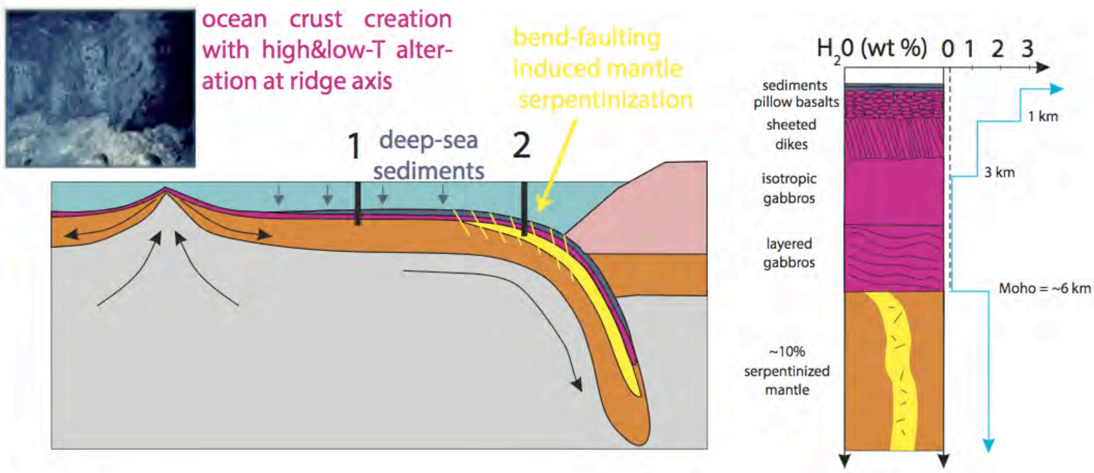
Jason P. Morgan[1] and Paola Vannucchi[1]

[1]Earth Sciences Dept., Royal Holloway University of London

mantle evolution, bend-fault serpentinization

Even before the discovery of plate tectonics, Earth Scientists wanted to drill through the ocean crust to obtain an in-situ sample of Earth's mantle that was already thought to be the fundamental building material of our rocky planet. Since plate tectonics, the community's desire to obtain a drillcore through the ocean crust and into its underlying mantle only increased after the recognition that the oceanic crust and mantle created and modified by partial melting and hydrothermal processes at mid-ocean ridges is then recycled by plate subduction to strongly shape the chemical evolution of our planet. The basic scenario has been that ridge hydrothermalism strongly shapes the chemistry of newly created crust, while off-axis, as the seafloor progressively ages en-route to a subduction zone, it slowly accumulates deep-sea sediments and continues to have weak lower-temperature hydrothermal flow and alteration. Just prior to subduction it may sometimes accumulate terriginous sediments, but, in general, subduction merely returns the subducting plate to the mantle. Since ocean drilling is the only way to obtain this critical drill-hole, and since near-ridge drilling provides extreme difficulties for hole stability and core recovery, the consensus view has long been that a single off-axis drill-site is the best plan to obtain this critical chemical record of mid-ocean ridge processes.

During the past decade, new discoveries have led to a revision to the above narrative for the formation and evolution of the ocean crust that makes it extremely compelling to drill two or more deep holes to study how ridge, off-axis, *and* subduction plate-bending-related processes shape the long-term evolution of Earth's crust and mantle. We now realize that plate bending near a trench is likely to be associated with significant chemical hydration-linked reactions in cold lithospheric mantle and overlying ocean crust. Bend-faults appear to play a key role in this process, providing high-permeability pathways for seawater to flow into the oceanic crust and uppermost mantle Bend-fault serpentinization has now been imaged by seismic reflection and refraction methods at several subduction zones. The process has been proposed (Peacock, 2000) to be linked to the formation of the 'double' Wadati-Benioff zone structure imaged best beneath Japan and less-well elsewhere. The implications of this process for the interactions between Earth's mantle and exosphere are profound. For example, consider the potential effects of bend-fault serpentinization on water and carbon cycling into the mantle. Offshore Nicaragua where bend-fault serpentinization is best measured to date, seismic observations suggest that a ~10-15km thick layer beneath the Moho has been partially serpentinized by ~10-20%. Where serpentinites have been found in mid-ocean ridge median valley settings, they contain a ~1% carbonate fraction by weight, and in ophiolite exposures serpentinized mantle often contain much more.than ~1% carbonate fraction by weight. This



Suggested 2-drillhole transect strategy to first find crustal and mantle effects of spreading center processes with hole 1 and then find bend-faulting effects and net composition of subducted slab with hole 2.

volume of serpentinized mantle, if created and subducted globally by bend-faulting of subducting plates, will recycle more water into the mantle than overlying crust and mantle, and would recycle a comparable magnitude of CO2 into the mantle as has been inferred to be emitted by plate spreading and consumed by crustal alteration linked to weathering and mountain building — in simpler words, we will need to completely rethink our basic understanding of Earth's global carbon and water cycles.

If both ridge and subduction-linked processes strongly shape the chemistry of the oceanic crust and mantle, then we will need to study this system by drilling a two (or more) hole transect consisting of a site on off-axis seafloor prior to subduction (to constrain the extent of ridge and off-axis processes in shaping the crust and uppermost mantle, and a site on bend-faulted crust between the outer rise and trench axis that constrains the actual material being recycled into the mantle. The chemical differences between these sites will constrain how much additional chemical modifications are associated with bend-fault hydration processes and what volatiles actually subduct back into the mantle. Of course it would be ideal to drill several such transects if at all possible. At least one — on the Cocos Plate through the outer rise offshore Nicaragua contains an area with observed bend-fault serpentinization in ~3100-3300m water depth.

As a final note, mantle serpentinization has been linked to hydrogen and methane-generating reactions that are favorably used for chemosynthetic activity by Archaea. If bend-fault serpentinization is associated with hydrogen and methane production, then this region may be a major unrecognized reservoir for deep life, and may have been in fact the first and safest place for deep-life to flourish on early Earth because deep-sea trenchs would retain an ocean cap in preference to shallower ridges during large-scale Hadean impact events.

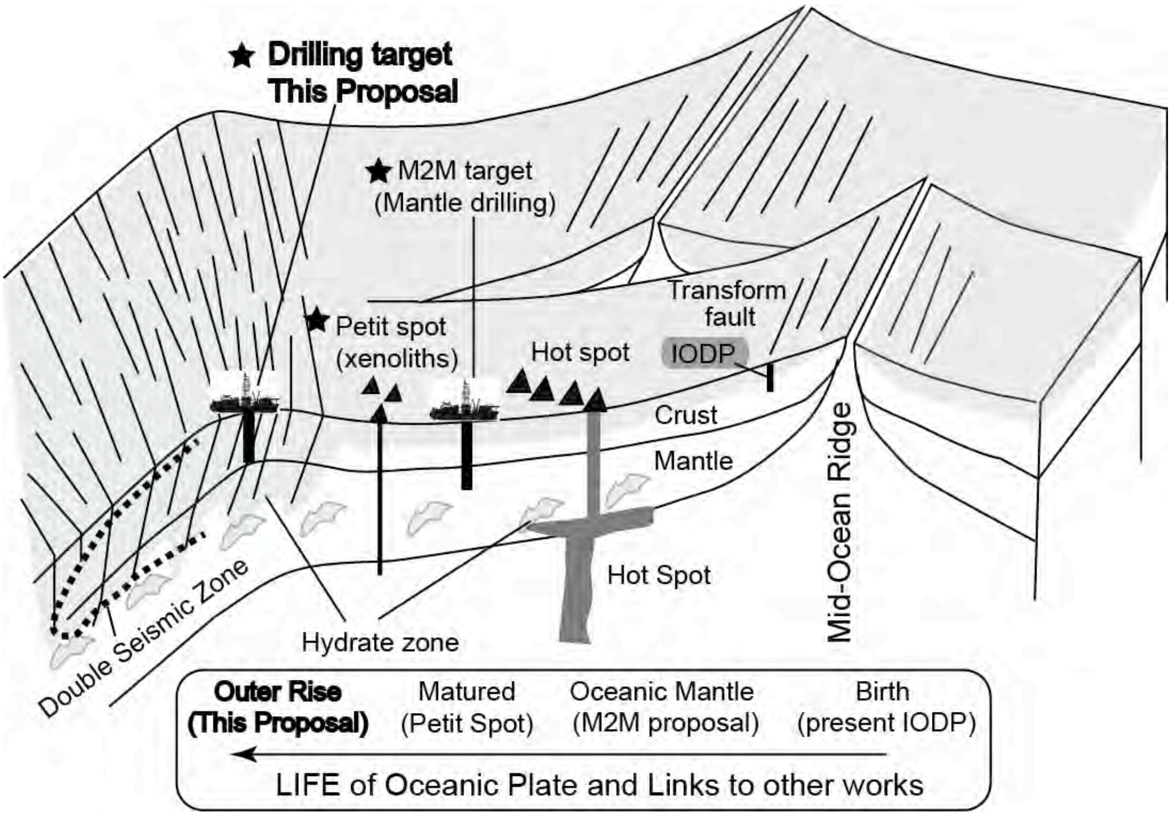
Ultra-Deep drilling into the Tohoku Outer Rise

Tomoaki Morishita[1], Katsuyoshi Michibayashi[2], Shuichi Kodaira[3] and Biswajit Ghosh[4]

[1]Kanazawa University, [2]Shizuoka University, [3]JAMSTEC, [4]Calcutta University

Keywords: Tohoku Outer Rise, Fault, Hydration, subducting oceanic plate, Ultra-Deep Drilling, Ultra-deep water depth

Target of the Proposal: We would like to propose to drill into the Tohoku Outer Rise as the deepest as possible (up to 4,000 m) at ultra deep water depth (6,000 m from the sea surface). The major objective is to recover the materials of the outer rise of the subducting Pacific plate, where trenchward-dipping multichannel seismic reflections are expected to be imaged, in order to understand the igneous stratigraphy and its modification of the oceanic plate due to faulting coupled with water percolation at the outer rise. The outer rise is expected to be bending just before the subduction. This, combined with the present ODP/IODP results (e.g., Wilson et al., 2006 *Science*), the future ultra-deep mantle drilling project (middle of the Oceanic Plate) (the present active M2M proposal) and the study on xenoliths in petit-spot magmas (just before the outer rise) (Hirano et al., 2006 *Science*), will provide us complete material sets of subducting Pacific plate, i.e., the life of the Pacific plate (Figure).



It is well known that water derived from subducting oceanic plates plays a major role in several phenomena linking to natural disasters, such as intra-slab seismicity and arc magmatism.

Scientific background: Seismicity in subduction zones is usually referred to as shallow (< 70 km) intermediate-depth (70-350 km) or deep focus (> 350 km). Intermediate- and deep-focus earthquakes might be linked to metamorphic dehydration reactions in the subducting plate (e.g., Kirby et al., 1996 *Geophys. Monograph.*; Omori et al., 2002 *Bull. Earthq. Res. Inst. Univ. Tokyo*, 2004 *PEPI*; Hacker et al., 2003 *JGR*). Jiao et al. (2000 *JGR*) examined the Tonga subduction zone and found that an asymmetric fault system, which might be corresponded to that found for outer rise events, persists down to about 450 km. They suggested that intermediated- and deep-focused earthquakes were caused by the reactivation of pre-existing faults in the oceanic plate before subduction. **However, it is not clear yet where and how much faults and water are distributed in crust and mantle in the subducting oceanic plate.**

Faults, fissures and fractures are generally created at spreading centers (e.g., Carbotte & Macdonald, 1994 *JGR*). Their alignments are usually parallel to mid-ocean ridges. Seno & Yamanaka (1996 *Geophys. Monograph.*) examined double seismic zones and pointed out that dehydration embrittlement in the subducting plate. They suggested a possibility that the hydration in the deeper part of the oceanic plate was originally caused by the magmatic effects of plumes. Omori et al. (2002 *Bull. Earthq. Res. Inst. Univ. Tokyo*) pointed out the existence of serpentinized peridotite in the subducting pate at a depth of 50-80 km based on the Poisson's ratio in the Northeast Japan. They suggested that transform faults and faults at the Outer Rise might be hydration sites of the oceanic mantle. Ranero et al. (2003 *Nature*) reported multichannel seismic reflection images across the oceanic trench slope show two main sets of reflections beneath the sediments: one is subhorizontal reflections which occur at the base of the crust, and the other appears as trenchward-dipping reflections across the crust and mantle, which extend at least to depths 18-20 km beneath the sea floor. The reflectivity of the small-offset, i.e., deep faults imaged in the seismic data, can be best explained by water percolation and alteration of oceanic lithosphere along the fault planes.

Why the Tohoku Outer Rise?: Many large interplate earthquakes frequently occur at the Japan Trench convergent margin. The recent detailed seismic data around the 2011 off the Pacific Cost of Tohoku earthquake area suggest that one of aftershock activities might be a result of reactivation of a buried hydrated fault in the subducting plate (Nakajima et al., 2011, GRL). Numerous horsts and grabens were identified in the subducting plate at the northwestern Pacific ocean based on bathymetric data (Ludwig et al., 1966 *JGR*; Kobayashi et al, 1998 *Geophys. J. Int.*; Nakanishi, 2011 *Modern Approaches in Solid Earth Sciences*), and were also confirmed by multichannel seismic reflection surveys (Tsuru et al., 2000 *JGR*). Bending-related faults in the outer rise-trench region might be cutting through the crust and mantle, and might have been extensively hydrated by water percolation and mineral alteration. Recently Fujie et al. (2013 *GRL*) demonstrates, off the Kuril trench, reduction of seismic velocity as well as increase of Vp/Vs ratio in the crust toward trench from the outer rise. Those observations interpreted to be formed by hydration of the oceanic crust due to bending related fault. **Here we emphasized again, however, that we do not know where and how much faults and water are distributed in crust and mantle in the subducting oceanic plate. Direct drilling into the outer rise is the only way to get the answer.**

The outer rise deep-drilling should be a technically challenging drilling proposal in terms of ultra-deep drilling at ultra-deep water depth. However, if it would be succeeded, the deep drilling hole would be strongly linked to the results of other deep drilling project (e.g., Mantle Drilling: M2M proposal), and would be used for the monitoring of geophysical signals which allow us to collect lines of information related to earthquakes in this region, one of the highest population density areas in the world.

EXPLORING THE DEEP CRUST OF MESOZOIC PACIFIC OCEANIC PLATEAUS

Masao Nakanishi[1], Maria Luisa Tejada[2], Takashi Sano[3], Takeshi Hanyu[2], Kenji Shimizu[2], Seiichi Miura[2], and Daisuke Suetsugu[2]

[1]Chiba University, Chiba 263-8522, Japan; [2]JAMSTEC, Yokosuka, 237-0061 Japan; [3]National Museum of Nature and Science, Tsukuba 305-0005, Japan

Keywords: oceanic plateau, large igneous provinces, plate boundary, Pacific Ocean, mantle evolution

Drilling Targets

We propose the deep drilling of Mesozoic Pacific oceanic plateaus, Shatsky Rise and Mid-Pacific Mountains (MPM). Knowledge about large igneous provinces (LIPs) has played a fundamental role in shaping the prevailing view of mantle geodynamics. A widely accepted explanation for plateaus is the plume head hypothesis (e.g., Richards et al., 1989; Griffiths and Campbell, 1990). Many existing data are indirect indicators of eruptive rate and magmatic volume and could be explained by alternative hypotheses. A growing debate about the number, characteristics, and even existence of mantle plumes (e.g., Foulger, 2002; Courtillot et al., 2003) makes it desirable to consider alternative explanations for plateaus. In order to address the plume head vs. alternative hypotheses, it is necessary to study a plateau for which the relation of the plateau to contemporaneous mid-ocean ridges is known. Shatsky Rise and MPM are suitable for this issue because both oceanic plateaus formed during a time of magnetic reversals. Magnetic anomaly lineations from Late Jurassic to Early Cretaceous around the Shatsky Rise and MPM were identified by Nakanishi et al. (1999) and Nakanishi et al. (1992), respectively (Figures 1 and 2). Magnetic reversals recorded in the deep crust of the plateaus provide a vital control on their structure and original tectonic setting. Magnetic anomaly lineations can be used not only to date the plateau and surrounding lithosphere, but also to understand how plateau morphology is related to ridge tectonics. Systematic sampling of the deep crust offers the chance to test plume head and alternative hypotheses.

Results of previous ocean drilling

Shatsky Rise

IODP Expedition 324 obtained volcanic samples from the deeper part of the crust than previous cruises, but the mystery of how Shatsky Rise formed is still an open question (Sano et al., White Paper).

Mid-Pacific Mountains

Mean radiometric age of the basements under Resolution Guyot is 127.6 ± 2.1 Ma (Winterer and Sager, 1995). That of alkalic basalt sills at the bottom of Hole 865A on Allison Guyot is 110.7 ±1.2 Ma. Age data of the Mid-Pacific Mountains generally support the hypothesis that the chain contains an age progression, from Late Jurassic to Early Cretaceous on the western end, to Late Cretaceous on the eastern end (Winterer and Metzler, 1984; Duncan and Clague, 1985, Winterer and Sager, 1995).

Fig. 1.Magnetic anomaly lineations around the Shatsky Rise (Nakanishi et al., 1999) and selected ODP/IODP drilling sites.

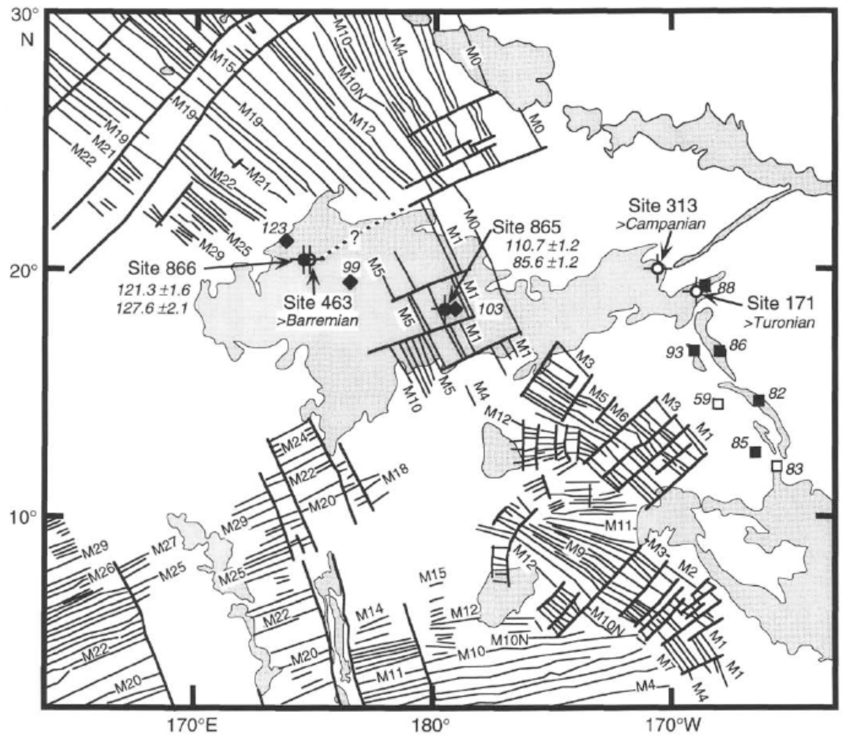


Fig. 2. Magnetic lineations (Nakanishi et al., 1992) and radiometric and paleontologic dates from the Mid-Pacific Mountains (Winterer and Sager, 1995).

How (NOT) to Drill to the Mantle
(Chikyu Workshop White Paper)

James H. Natland
Rosenstiel School of Marine and Atmospheric Science, University of Miami
Miami, FL 33149 USA

From the start, construction of *Chikyu* opened the possibility of drilling through entire ocean crust into the mantle. Drilling a Mohole was the original goal of scientific ocean drilling, and has been highlighted as a major objective of every proposal for renewing drilling ever since. Nevertheless, after more than 50 years, this goal has not been achieved. The reasons for this have varied over the years, but began with the Deep Sea Drilling Project, which was first formulated in response to the demise of Project Mohole as the United States National *Sediment* Coring Program, and which more or less retained that posture through the first 44 legs of drilling. A single ship, at first dedicated to that single objective, and then to many, never could become the vehicle for truly deep ocean-crust drilling. Beginning with the International Phase of Ocean Drilling and Leg 45, however, a new emphasis was placed on ocean-crust drilling, with the idea that experience gained would eventually lead to the capability of mounting a full-fledged program of reaching the mantle.

Since then, ships have changed and some passably deep holes have been drilled, but none as yet to more than 2 km of penetration into igneous rock. A program of offsetsection ocean crust drilling was initiated following ODP Leg 118, which began drilling into gabbro at Hole 735B on the Southwest Indian Ridge. The hole was deepened more than 10 years later, but this underscores one of the chief difficulties that have bedeviled deep crustal drilling. Scientific ocean drilling overall caters to a broad community of geoscientists and has many objectives. Over half of the program has been devoted to the problems of ocean history and climate change. Attention has been paid to passive margins, active margins, large igneous provinces, hot-spot migration, sediment drifts, high-resolution stratigraphy, fluid flow at continental margins and biogeochemistry. Of the original objectives for drilling offset sections in the ocean crust in 1990, several of the major ones, such as drilling long sections through the dike-gabbro and gabbro-peridotite sections, or obtaining a long section in peridotite, have not been attained. Some of these have never been attempted, and at no place have we obtained the composite section originally envisioned for this program.

With one ship to serve all objectives, this is understandable. *JOIDES Resolution* has been a workhorse. With two ships, there is a better chance, but probably only if one of them, *Chikyu*, becomes dedicated for a period of time to the one principal objective, as it has been for NanTroSEIZE drilling. *JOIDES Resolution* simply has to become the allpurpose vehicle for EVERY OTHER objective in the program. The purpose of this would primarily be to clear the decks for a dedicated *Chikyu* program that will require much time, single-minded dedication and great perseverance. We simply cannot make much progress if two ships are spread around among multiple programs. The ten-year hiatus in returning to ODP Hole 735B exemplifies the problem. It required approval of a completely new proposal and separate approval of an attendant separately funded site survey before it could happen. The survey finally happened *after* the drilling expedition, which was approved by the JOIDES planning structure solely because a hole had already been started, and did not formally need a *site* survey. Similarly, each return to DSDP/ODP Hole 504B required a separate proposal, and only took place with some alacrity because the hole is strategically located close to the Panama Canal. Holes in the Indian Ocean have virtually no chance of frequent revisits because all other scientific objectives are so far away.

In short, this type of drilling cannot proceed on the basis of a series of continuing resolutions. The full program – surveys, drilling, logging, post-drilling activities – needs to be set in place from the outset, milestones established, and budgets approved. There will be considerable extra expenses. In the case of Mohole drilling, has anyone yet considered that a 2-km casing assembly should be installed through shattered basalts and dikes and into gabbros before proceeding into deeper rocks? Will it not require the control of closed circulation and weighted muds to keep stress-related breakouts from occurring below that?

Through successive improvements in platform capability, we have discovered that we are making progress. Both penetration into and recovery of fractured basalt have improved from the days of *Glomar Challenger*, and even since the last dry-dock and refit of *JOIDES Resolution*. The improvements have been in dynamic positioning and heave compensation. *Chikyu* doubtless will be an even better platform, but in terms of crustal drilling it is still an untested vessel. An intangible factor is crew experience, but this goes by the board if expeditions are infrequently scheduled. Emerging from past drilling experience is the knowledge that holes, so far at least, eventually fail because difficulties add up. Holes wear out. Segments with a narrow annulus widen. Fractured rock fails, ledges form, and the more horizons of these that a hole penetrates, the likelihood is that eventually difficulties will become impossible to surmount.

What is the ticket to success? It is to minimize at all stages the chances for failure. It means to reduce heave by using a proper platform and adequate heave compensation. It means to drill during optimum conditions of wind and sea, not in the winter, in compensation for a high-latitude ocean history expedition during the summer. It means to start rather modestly, obtaining experience in drilling each principal lithology – basalt, dikes, gabbro and peridotite, before taking on the entire ensemble in a single hole. This means that *Chikyu* should be dedicated at first to some portion of the offset-section drilling program that has been on the books for two decades. It means to *design* the eventual very deep hole, as any oil company does when planning a hole for production. It means to characterize fully the upper crustal characteristics of a principal target by a combination of surveys, preliminary drilling of pilot holes, and downhole measurements. It means at each stage to install a proper hard-rock base and uppermost casing assembly on as decent an outcrop as possible, not a talus ramp or fault surface. It means to anticipate when and where difficulties might arise, and plan for them, as with, e.g., the installation of casing. It means eventually to use well control. It means going back to the drawing board when difficulties are encountered. It means ten years of effort, with perhaps 3 drilling legs each year.

The first step, as I believe, is to declare *Chikyu* the crustal drilling platform of the future, and to design that ship and all its appurtenances with that in mind. Without that initial step, we will not drill a Mohole.

Formation and Environmental Impacts of Oceanic Large Igneous Provinces

Clive R. Neal[1]

[1]Dept. of Civil & Env. Eng. & Earth Sciences, University of Notre Dame, Notre Dame, IN 46556, USA.

Key terms: Large igneous provinces, eruptions, syn-LIP sediments, environmental impact.

During 2007, the Large Igneous Province (LIP) community met in Coleraine, Northern Ireland to discuss how scientific ocean drilling could advance our understanding of the origin, evolution and environmental impact of these magmatic constructs. Four of the key findings of this workshop were that ocean drilling could: 1) advance our understanding of the mode(s) of eruption during LIP formation; 2) better define the duration of LIP volcanism; 3) examine LIP source variability over time; and 4) establish relationships between oceanic LIPs, Oceanic Anoxic Events (OAEs), and other major environmental changes [1]. Using a combination of riser and non-riser drilling over the next decade, the Chikyu could make great advances in addressing each of these findings. For the purposes of this white paper, I focus on the Greater Ontong Java Plateau (OJP) in the SW Pacific, which is reported to be comprised of the Ontong Java, Hikurangi, and Manihiki Plateaus because they have similar ages and compositions [2,3]; all three may have formed during the same event and subsequent plate movements have split them apart [4,5] (**Fig. 1**). The OJP occupies an area about the size of Western Europe and ≤35 km thick with an anomalous mantle root (seismically slow) that extends to 300 km below the plateau [6,7]. All previous OJP sites but one (Site 1184 on the Eastern Salient) recovered pillow lavas erupted at least 1 km below sea level [8]. Chikyu drilling can address each of the four findings highlighted above in the following ways:

Fig. 1: Greater OJP breakup [5].

1) Recent multichannel seismic results from the high plateau of the OJP have shown reflectors present in the basement lava pile on the high plateau [9]. These have been interpreted as representing alternating pillow lava-massive flow sequences representing alternating low- and high-eruption rates, respectively, originating from the crest of the high plateau. A deep (3-5 km) riser hole on the high plateau could answer a number of questions, including the alternating modes of eruption, as well as investigating the evolution of magma composition (i.e., source variability) over time. Non-riser drilling on the Eastern Salient of the OJP could test whether this portion was emergent, as it would be approximately in the center of the OJP-Manihiki-Hikurangi "super plateau" if they were originally formed as one entity [4,5] (Fig. 1).
2) The duration of LIP volcanism can be accomplished in a number of ways: (a) drilling at the feather edge of the plateau to capture the last and first large flows (i.e., those that flowed a long distance) and drill into underlying basement/sediment. Recent MCS data can be used to determine sites for non-riser drilling to achieve this objective. Another way to achieve this goal is coring of syn-LIP sediments to age date ash layers or determine the geochemistry of the sediments to identify significant volcanic inputs. The latter method has been used to demonstrate correlations between OAE-2 and LIP events (e.g., [9]) as well as the onset on volcanism associated with the Izu-Bonnin arc [10]. Syn-LIP sediment drilling sites are the Magellan Rise (drilled by DSDP Leg 17, Site 167 but core recovery was low) and the Nauru Basin (see Figs. 6 & 7 of [11]). Increasing recovery in sequences of hard-soft rock transitions (i.e., chert-limestone) is critical for recovering the syn-LIP sediment sequences and ash layers that represent subaerial eruption(s). Riser drilling at either/both sites will enhance recovery could enable a major leap forward in our understanding of LIP construction by identifying major volcanic events in syn-LIP sediments. The importance of coring of syn-LIP sediments is also addressed in the white paper by Elisabetta Erba.
3) Examination of source variability over time requires either a deep hole to be drilled into the lave pile [see 1) above] or use the structure of the plateau to initiate drilling in a deeper part of the lava pile. For example, sites amenable to such drilling include: the conjugate rifted margins of the Hikurangi and Manihiki plateaus (Fig. 2); the Danger Islands Troughs of the Manihiki Plateau (Fig. 2); in Kroenke Canyon and on the conjugate rifted margins of the OJP bordering the Stewart Basin (Fig. 2).

4) The environmental impact of oceanic LIPs is difficult to estimate because of the poor age constraints on LIP formation (low-K tholeiites produce relatively imprecise Ar-Ar age dates). OAE-1a (the Selli Event) has been correlated with the formation of the OJP (e.g., [12,13]). However, correlations have been made on limited sites of OAE-1a. Other OAE events have also been correlated with LIP formation events (e.g., [14]). Detailed geochemical analyses of OAE and bounding sediments from various sites are required to conclusively attribute oceanic anoxic events with LIP formation. Recovery of OAE intervals at multiple locations around an oceanic LIP also allows directionality of fluxes to be evaluated. Knowledge of the duration of the LIP event is required for these studies (see above). Sites where these intervals can be cored are on Shatsky and Magellan Rises, as well as on the Manihiki, Ontong Java, and Hikurangi plateaus. The importance of coring of such intervals is also addressed in the white paper by Elisabetta Erba.

Summary. Use of the Chikyu over the next decade of scientific ocean drilling can make significant contributions to the IODP Science Plan in the areas of geodynamics and environmental (climate & ocean) change. With deep riser holes into plateau basement, advancing the deep biosphere goals can also be entertained. By getting a better understanding of LIP formation, results can be used to more thoroughly evaluate how other terrestrial planetary bodies have evolved, where LIP magmatism rather than plate tectonics appears to be the norm (e.g., Mars, Moon, Venus, Mercury).

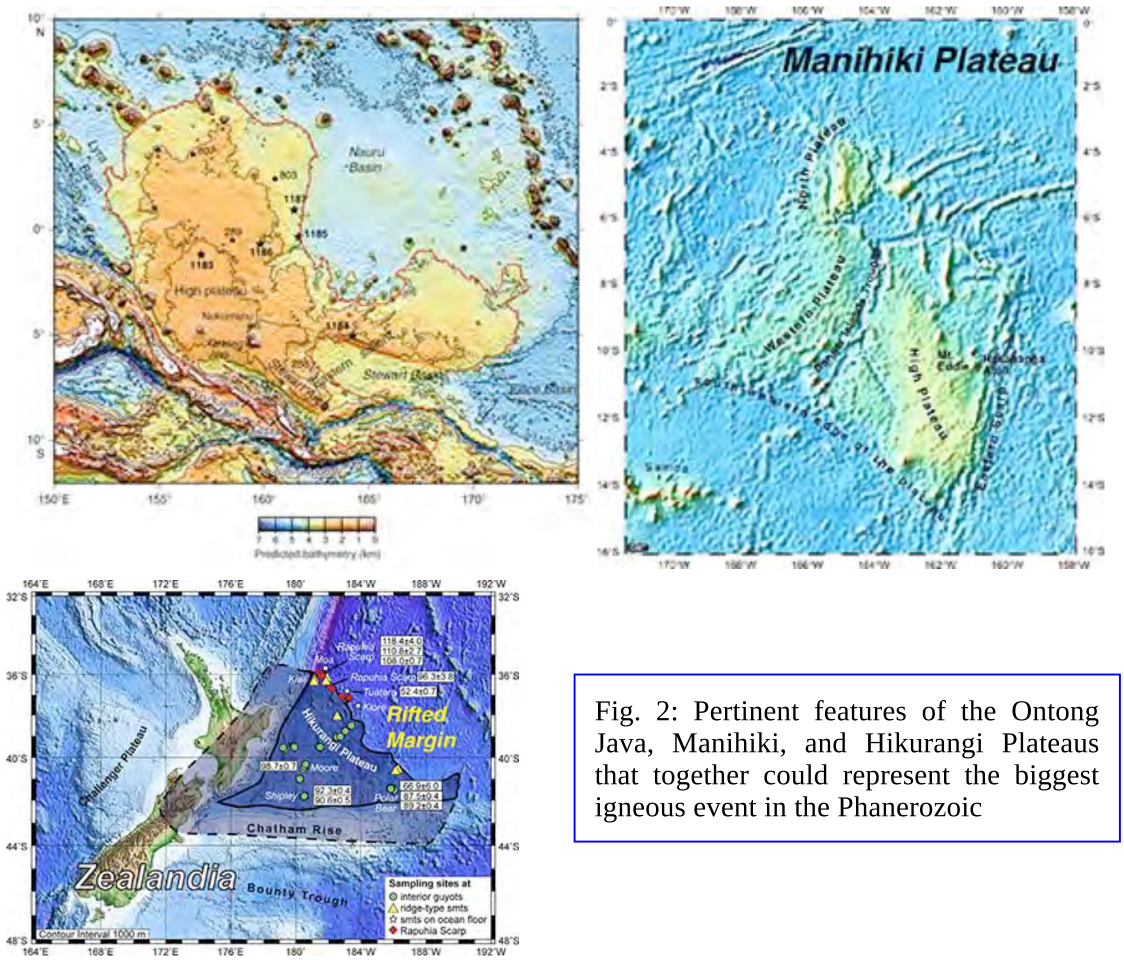


Fig. 2: Pertinent features of the Ontong Java, Manihiki, and Hikurangi Plateaus that together could represent the biggest igneous event in the Phanerozoic

References: [1] Neal C.R. et al. (2008) *Scientific Drilling* **6**, 4-18. [2] Hoernle K. et al. (2011) *Geochim. Cosmochim. Acta* **74**, 7196-7219. [3] Ingle S. et al. (2007) *Geology* **35**, 595-598. [4] Taylor B. (2006) *Earth Planet. Sci. Lett*. **241**, 372-380. [5] Chandler M.T. et al. (2012) *Earth Planet. Sci. Lett.* **331-332**, 140-151. [6] Richardson W.P. et al. (2000) *Phys. Earth Planet. Int*. **118**, 29-51. [7] Klosko E.R. et al. (2001) *Earth Planet. Sci. Lett*. **186**, 347-361. [8] Mahoney J.J. et al. (2001) *Proc. ODP Init. Rpts.*, **192**, 75p. [9] Snow L.J. et al. (2005) *Paleoceanography* **20**, PA3005, doi: I 0.1 029/2004PAOO I 093. [10] Scudder R.P. et al. (2009) *Earth Planet. Sci. Lett*. **284**, 639-648. [11] Mochizuki K. et al. (2005) G^3 **6**, Q10003, doi:10.1029/2004GC000867. [12] Jones C.E. and Jenkyns H.C. (2001) *Amer. J. Sci*. **301**, 112-149. [13] Tejada M.L.G. et al. (2009) *Geology* **37**, 855-858. [14] Erba E. (2004) *Marine Micropaleo*. **52**, 85-106.

DEEP CRUSTAL ARCHITECTURE OF A DYING BACKARC SPREADING SEGMENT AT GODZILLA MEGAMULLION

Yasuhiko Ohara[1, 6], Jonathan E. Snow[2], Henry J.B. Dick[3], Katsuyoshi Michibayashi[4], Yumiko Harigane[5], Kenichiro Tani[6], Oasamu Ishizuka[5, 6], Wendy Nelson[2], Matthew Loocke[2], Alessio Sanfilippo[7] and Kyoko Okino[8]

[1]Hydrographic and Oceanographic Department of Japan, [2]University of Houston, [3]Woods Hole Oceanographic Institution, [4]Shizuoka University, [5]Geological Survey of Japan/AIST, [6]Japan Agency for Marine-Earth Science and Technology, [7]University of Pavia, [8]University of Tokyo

[Keywords] Godzilla Megamullion, oceanic core complex, backarc basin, oceanic lithosphere, ophiolite

1. Godzilla Megmaullion: an Oceanic Core Complex in a dying backarc spreading segment

Oceanic Core Complexes (OCC) provide a valuable opportunity to directly study the architecture of oceanic lithosphere, together with the tectono-magmatic processes associated with its formation and evolution. The following major questions regarding mid-ocean ridge processes can be best addressed by drilling at tectonic windows such as OCCs:

(1) Lithospheric architecture
(2) Mantle dynamics and melt migration at spreading ridges
(3) Fluid circulation in oceanic lithosphere
(4) Physical properties in serpentinized lower crust.

The Godzilla Megamullion is the largest known OCC, and is located in an extinct backarc basin in the Philippine Sea: the Parece Vela Basin (PVB). Earlier, based on poorly constrained magnetic data, the basin was believed as an intermediate-spreading ridge (8.8–7.0 cm/year full-rate) from 26 to 12 Ma (Okino et al. 1998; Ohara et al. 2001, 2003). Although a higher magmatic budget is expected for a fast- to intermediate-spreading ridge, the PVB shows features indicating a smaller magmatic budget, including OCCs and abundant peridotites and gabbros (Ohara et al., 2001; 2003). Many peridotites in the PVB are significantly less depleted than those exposed at comparable spreading rates on other mid-ocean ridge systems (Loocke et al., submitted; Ohara et al. 2001, 2003; Ohara 2006; Snow et al., submitted), the tectono-magmatic characteristics were thus thought to be unusual and paradoxical. Zircon U-Pb dating of gabbroic and leucocratic rocks from Godzilla Megamullion now reveals that exhumation of the 125 km long detachment surface lasted for ~4 m.y., with continuous magmatic accretion at the spreading axis (Tani et al., 2011). The estimated denudation rate of the OCC was ~2.5 cm/y; significantly slower than the previous estimate based on magnetic data. The latest magmatism occurred at ~7.9 Ma or later, significantly younger than a previous estimate of 12 Ma. The new age data indicate that the terminal phase of PVB spreading was not at intermediate spreading rates, with a significant decline and asymmetry accompanying formation of Godzilla Megamullion in a “dying” backarc spreading segment (Snow et al., submitted).

Several lines of evidence indicate the presence of a large mantle component in the Godzilla Megamullion footwall. First, demonstrable mantle peridotites occur in nearly every region of the OCC. Second, they are generally affected by crystal plastic deformation to produce porphyroclastic textures typical of abyssal peridotites everywhere (Harigane et al., 2011), but are not extensively mylonitized to talc-serpentine schists typical of detachment surfaces. This suggests that significant rooted mantle peridotite is exposed along the OCC surface.

Abyssal peridotite in backarc basin setting has only been known from the few localities in the Philippine Sea (Ohara et al., 2003, Ohara, 2006). Among these, the Godzilla Megamullion is unique by its vast area of the exposed mantle peridotite, being the best place to study architecture of backarc basin lithosphere.

2. Architecture and evolution of backarc lithosphere and ophiolites: our research focus and expected new outcomes

A significant fraction of the ocean floor is created in backarc basins. The opportunity to explore the formation of the backarc basin lower crust and upper mantle is, therefore, an important contribution to the overall geology of the ocean basins. At the same time, much of our understanding of all ocean crust comes from ophiolites, most of which are thought to have at least some arc/backarc component (e.g., Dewey and Bird, 1971; Miyashiro, 1973; Pearce, 2003). A better understanding of the construction of backarc basin crust and its relationship to the upper mantle will thus greatly aid in the interpretation of the results of ophiolite analog studies and their relevance to the creation of the oceanic crust.

3. Achieving our goals: drilling with and without a riser

We propose substantial riserless and riser drilling at Godzilla Megamullion that will provide an excellent opportunity to address the issues noted above. Riserless drilling (Chikyu or JR) can reasonably be expected to provide cored holes of ~200 m depth in most parts of Godzilla Megamullion, providing direct access to stratigraphically coherent intervals of the middle and lower crust of the PVB. These will be used to site a future riser hole in the accessible part of the Godzilla Megamullion that will explore the deeper structure of the backarc basin oceanic lithosphere. Although the Moho in this area is likely to be beyond drilling capabilities, the proposed drilling strategy will accomplish several related goals of understanding the nature of this important geologic boundary in a dying backarc spreading environment, and will prepare the way for drilling a future total penetration hole elsewhere, giving a preview of the mineralogy, structures, hydrology and drilling conditions to be encountered at the lower levels of the oceanic crust.

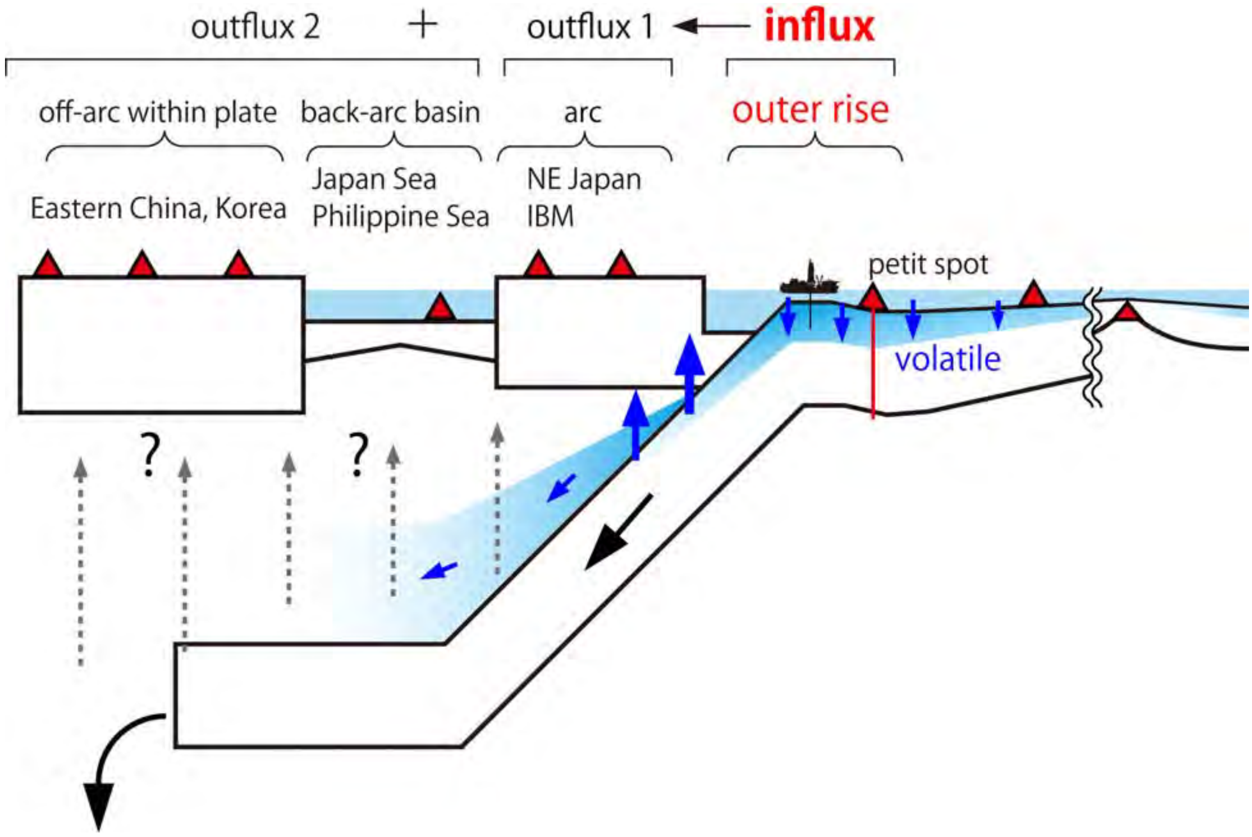
BEHAVIOR AND MASS BALANCE OF THE VOLATILE COMPONENTS IN THE OCEANIC PLATE: SAMPLING FROM OUTER RISE

Tetsuya Sakuyama[1], Takeshi Hanyu[1], and Jun-Ichi Kimura[1]

[1] Japan Agency for Marine-Earth Science and Technology

outer rise, oceanic crust, downhole variation of volatile conponents

Dehydration of a subducting oceanic plate and melting of the wedge mantle induced by infiltration of the fluid released from the oceanic plate are the key processes to invoke arc magmatism and produce geochemical heterogeneity of the whole-mantle of the earth. Petrologists and geochemists have used volcanic rocks in arcs to characterize fluids and to estimate amount of the supply from the subducting slab in order to reveal a material recycling process at subduction zone. Meanwhile, instead of considerable amount of studies on volcanic rocks in arcs, petrological and geochemical studies on subducting materials including sediments, oceanic crust basalts, and peridotites, are still limited because of more difficulty in sampling than subaerial rocks. Petrological and geochemical studies on both the pristine and mature oceanic plates should provide the most important constraint on hydration and carbonation processes of the oceanic crust and lithosphere. Ocean drilling in the eastern Pacific Ocean in Hole 1256D has reached ~1500 mbsf and successfully sampled an intact sequence of young oceanic crust through lavas, sheeted dikes, and gabbros. Sampling of mature oceanic plate in Site 843 and Site 801 is, however, only limited to the ~70 m and ~600 m of the upper oceanic crust, respectively. Alt & Teagle (1999) measured the distributions and abundances of alteration types and carbonate minerals in samples from Site 843 and Site 801 as well as those from relatively young samples from Site 504B and Site 896. They revealed that upper oceanic crust can be an important sink of carbon for global carbon budget, even though their estimation is only the minimum due to plausible selective loss of carbonate during drilling and limited depth of drilling. At outer rise, normal faults are developed due to bending of the oceanic plate before subduction starts. Recent seismological study has shown an existence of a zone with high Vp/Vs ratio in the upper oceanic crust beneath a crest of outer rise. Hence, much more amount of volatile components is expected to be introduced to the deep oceanic plate through the normal faults than at normal seafloor, although hydration and carbonation processes and amount of them are still unknown. Downhole variation of volatile contents in deeper oceanic crust and consequently upper peridotitic layer of the oceanic plate particularly at outer rise is, therefore, necessary to estimate influx rate of volatiles into the earth.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Deep Drilling on Cretaceous Oceanic Plateaus in the Western Pacific

Takashi Sano[1], Masao Nakanishi[2], Takeshi Hanyu[3], Seiichi Miura[3], Kenji Shimizu[3], Daisuke Suetsugu[3], Maria Luisa G. Tejada[3], Ichiro Kumagai[4], and Akira Ishikawa[5]

[1]National Museum of Nature and Science, Tsukuba 305-0005, Japan; [2]Chiba University, Chiba 263-8522, Japan; [3]JAMSTEC, Yokosuka 237-0061, Japan; [4]Meisei University, Hino 191-8506, Japan; [5]The University of Tokyo, Tokyo 153-8902, Japan

Key words: oceanic plateau, large igneous province, western Pacific, plume, magma genesis

Superplume origin of the western Pacific plateaus?

Large Igneous Provinces (LIPs) are massive magmatic episodes that distinct from those forming oceanic crust at spreading ridges (e.g., Coffin & Eldholm, 1994, *Rev Geophys*, 32, 1-36). The largest LIPs, oceanic plateaus and continental flood basalts, reach volumes of several 10^6 to several 10^7 km^3 and are characterized by anomalously high rates of mantle melting that represent the largest volcanic events in the Earth's history. There is currently a lively debate about the LIPs volcanism: whether they are built by plume heads from the lower mantle, changes in plate stress, or even meteor impacts (e.g., Saunders, 2005, *Elements* 1, 259-263). One difficulty with their research is that several of oceanic plateaus (e.g., Kerguelen Plateau) and all of continental flood basalts were erupted on continents or their remnants where assimilation of continental lithosphere can obscure the primary mantle signature of the lavas. In contrast, Cretaceous oceanic plateaus in the western Pacific (Ontong Java Plateau, Shatsky Rise, and so on) have no effect of the crustal assimilation, permitting its primary origin in mantle to be resolved. The time of productions of the western Pacific plateaus coincides with increases in climate warming, resulting oceanic anoxic event, and eustatic sea level change; and therefore, its origin receives attention from paleo-environment aspects, too. It is proposed that the western Pacific plateaus were formed by the upwelling of very large plume head of mantle material, superplume, that erupted beneath the Pacific basin (Larson, 1991, *Geology*, 19, 547-550). The crustal thickness of the oceanic plateaus are estimated to be $\geq$30 km (e.g., Miura et al., 2004, *Tectonophys*, 389, 191-220). The present-day South Pacific superswell is probably the nearly exhausted remnant of the original upwelling. Moreover, the remnant of the superplume is likely detected by a wide-angle slice of the P-wave tomographic model of the Earth's mantle (e.g., Fukao et al., 2009, *Rev Earth Planet Sci*, 37, 19-46).

The plume head phenomenon occurs naturally in numerical and laboratory experiments, but there is currently no unequivocal geological evidence proving that a starting plume head in convecting mantle has operated with Earth. Thus several alternative explanations (described above) or more complex plume head models are proposed to explain origin of the oceanic plateaus.

Results of previous ocean drilling

To test the plume head model, petrological and geochemical data from igneous rocks are important. Although a small number of dredges have recovered basalts from the western Pacific plateaus, almost of all such samples were highly altered. The best way to obtain fresh samples is by drilling of holes. Thus, operations during Ocean Drilling Program (ODP) Leg 192 and Integrated Ocean Drilling Program (IODP) Expedition 324 drilled Ontong Java Plateau and Shatsky Rise, respectively, seeking evidence that would test the plume head hypothesis (Mahoney et al., 2001, *Init Rep ODP*, 192; Sager et al., 2010, *Proc IODP*, 324). Based on drilling of several holes in the oceanic plateaus, both expeditions have extended our knowledge of the compositions and origin of the plateaus magmas considerably (e.g., Fitton and Godard, 2004, *J Geol Soc Lond Spec Pub* 229, 151-178; Tejada et al., 2004, *J Geol Soc Lond Spec Pub* 229, 133-150; Sano et al., 2012, *G-cubed*, 13, Q08010). However, both expeditions uncovered complications that do not fit the simple model, so debate over plume head hypothesis continued.

Deep drilling of the oceanic plateaus

One of the main reasons for the previous failure to test the plume head model is that the previous drilling holes in the oceanic plateaus were too thin; only <300 m basement lavas were recovered among the thick oceanic plateaus ($\geq$30 km). Figure 1 shows that only uppermost part (<1%) of the oceanic plateaus were researched by the previous ocean drilling expeditions. The information of such thin drilling holes is difficult to evaluate the plume head model that is proposed by numerical and laboratory experiments. The laboratory experiments of "thermo-chemical" plumes containing both thermal and chemical density anomalies are characterized by a strong time-dependence and could develop for mantle density anomalies lower than 2% (e.g., Kumagai et al., 2008, *Geophys Res Lett*, 35, L16301). Such thermal or chemical density anomalies would be detected by geological researches of long drilling cores (e.g., ~3000 m basement lavas which construct ~10% of total thickness of the oceanic plateaus).

To date, such long cores were difficult to recover, but a riser drilling vessel *Chikyu* has made drilling >3000 m basement lavas technically feasible. Sites for oceanic plateaus drilling have not been selected yet, and thus, suitable target plateaus await additional site surveys. Although recent studies suggested that the simple plume head model cannot explain age, distribution, and P-wave tomographic model observations of the LIPs, research of the long drilling cores will break through the scientific problem and propose new-type plume head model. Observations of the thick basement lavas in oceanic plateaus will advance understanding of not only the evolution of our planet but also environment effects of the oceanic plateaus activities.

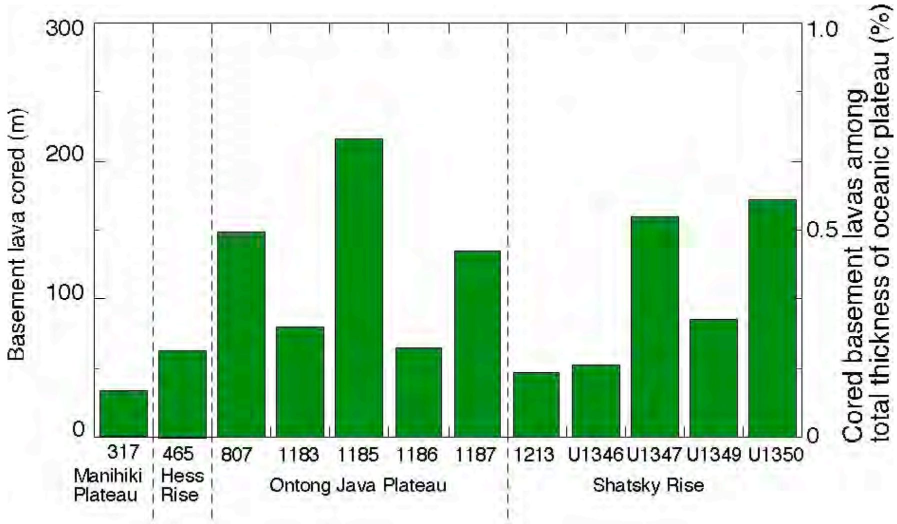


Figure 1. Depth (left axis) and percentage (right axis) of basement lava penetration for scientific drill sites deeper than 30 m drilled into oceanic plateaus in the western Pacific. The percentage of basement lava penetration was calculated by assuming that crustal thicknesses of the oceanic plateaus are 30 km (e.g., Miura et al., 2004; Korenaga and Sager, 2012, *J Geophys Res*, JB009248).

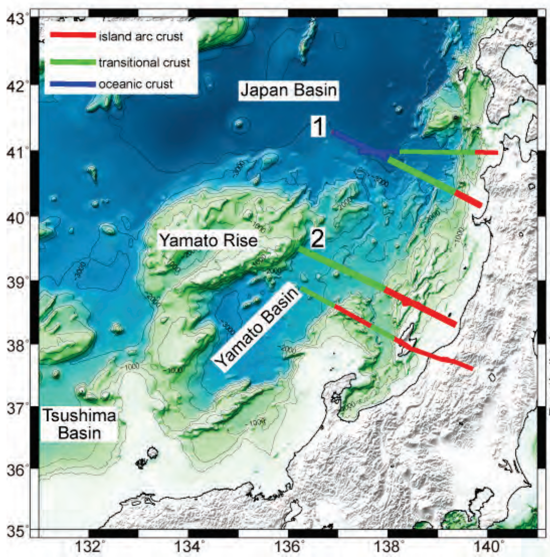
Verification of the formation process in the Japan Sea and interaction between the crust and the mantle

[Author (s)] Takeshi Sato[1]

[Institution (s)] [1]IFREE, Japan Agency for Marine-Earth Science and Technology (JAMSTEC)

[Keywords (six or less)] marginal sea, Japan Sea, crustal structure, mantle condition, formation process

The Japan Sea is one of marginal seas all over the world. Based on results of the ODP drilling, and previous geophysical and geological surveys, Tamaki et al., (1992) proposed that the Japan Sea was formed by the separation between the Japan islands and Asian continent, the continental rifting, the crustal extension, and the ocean floor spreading between about 30 and 12 Ma. However, the Japan Sea was not completely formed by the process of the ocean floor spreading (Tamaki et al., 1992). Actually, the Sea has various crustal types; the Japan Basin, which locates in the northern and northwestern parts, has an oceanic crust, on the other hand, in the Yamato and Tsushima Basins which locate in the southern part, the crustal structure is neither a typical oceanic nor continental crust, and the Yamato Rise has the continental crust (e.g., Tamaki et al., 1992). Recently, in the Yamato and the Japan Basins along the eastern margin of the Japan Sea, the seismic survey deployed dense ocean bottom seismographs (OBSs) were conducted, so that the Yamato Basin partly has the thick crust with the high velocity lower crust (Vp>7.2 km/s) (HVLC) (Fig. 1). This HVLC may show the underplating of mantle materials with the high mantle temperature during the formation. On the other hand, the Japan Basin has thinner crust and lower velocity compared with the Yamato Basin (Fig. 1). The difference of the crustal structure between the Japan and the Yamato Basins seems to be the cause by that of



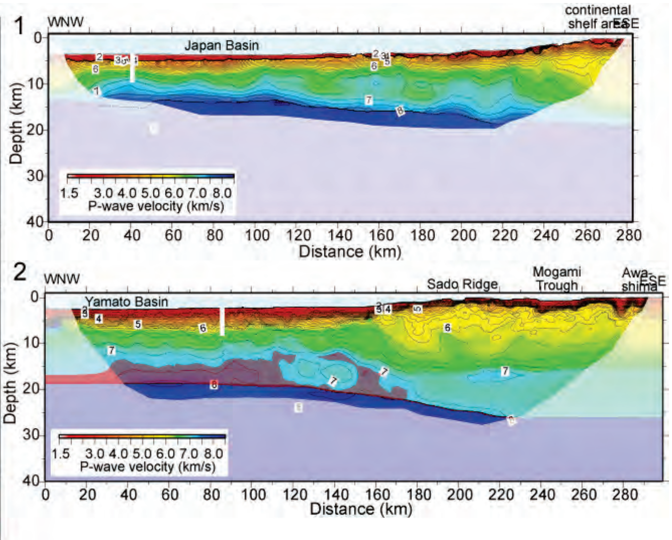


Fig.1: (left) Topographic map of the Japan and the Yamato Basins in the Japan Sea. (right) Velocity structures in the Japan Basin (1) and Yamato Basin (2)

mantle condition during the formation of both Basins. Moreover, it is likely that the difference of the mantle condition during the formation has the influence on not only the lower crust but also the shallow part of the crust (sediments, the upper and middle crust), so that it is expected that the upper and middle crust deformed by the mantle condition. Therefore, to understand the implication between the formation process and the mantle condition of these Basins in this Sea, it is important to clarify the nature, the origin and the age of the shallow crust in these Basins. For the drilling, I should get directly rocks composed the shallow crust in the basin region where the characteristics of the lower crust and mantle condition may differ. Moreover, if this drilling will be conducted, then we will promote the understanding about the detail formation processes of the Japan Sea which has the mature and immature stage concerned with the different mantle condition in the Sea.

References:

Tamaki, K., K. Suyehiro, J. Allan, J. C. Ingle Jr., and K. A. Pisciotto, Tectonic synthesis and implications of Japan Sea ODP Drilling, In Tamaki, K., K. Suyehiro, J. Allan, M. McWilliams, et al., *Proc. ODP, Sci. Results, 127/128*, Pt.2 College Station, TX Ocean Drilling Program, 1333-1348, 1992.

To the Moho and Beyond!
Public engagement and understanding of drilling to Earthôs mantle

Damon A.H. Teagle[1], Malcolm J. Wright[2], Mark T. Frank[3], Dominic J. Hobson[3], Margie Comrie[2], Doug Ashwell[2] and the MoHole to Mantle (M2M) proponents.

[1.] Ocean and Earth Science, National Oceanography Centre Southampton, University of Southampton, UK; Damon.Teagle@southampton.ac.uk
[2.] School of Communication, Journalism, and Marketing, Massey University, New Zealand
[3.] EPSRC WebScience Doctoral Training Centre, Electronics and Computer Science, University of Southampton, UK.

The US National Academy of Sciences celebration of the fiftieth anniversary of the pioneering operations of Project MoHole[1], coinciding with a forward-looking commentary in Nature[2] about direct sampling of Earthôs mantle, has led to unprecedented public interest in ultra-deep scientific ocean drilling. The MoHole to Mantle (M2M)[3] proponents have recently updated and developed the scientific justifications for drilling to directly sample fresh peridotites that in the recent geological past were part of the convecting upper mantle. Fresh mantle rocks will provide previously unattainable information on the concentrations and isotopic compositions of many of our key tracers of planetary evolution and differentiation (e.g., noble gases or fluid mobile heat producing elements such as U and K), the abundances of volatiles such as sulfur and water, or the state of carbon (C, CO_2 vs CH_4), and the scale of chemical and physical heterogeneities within the uppermost mantle. During the journey to the mantle, cores and observations will test models of the magmatic accretion of the lower crust, the vigor of deep hydrothermal circulation of seawater, the geological nature of the Mohoroviļ iĺ Discontinuity (The Moho), and the limits of life within the crystalline ocean crust[3]. Assessments by oil industry consultants now consider that drilling to the mantle is within the realm of technical feasibility with only moderate improvements in existing technology[4].

The scale, technical challenges, potential cost, and exploratory nature of the MoHole Project has inspired print, video, radio, and television journalists from around the globe. There have been recent articles and interviews of M2M proponents on US National Public Radio (Science Friday), BBC Radio 4 and 5, as well as radio in Australia, New Zealand, Canada, France and Costa Rica. Print articles include National Geographic[5] and New Scientist[6], with video interviews in The Times[7], Huffington Post[8], and ThomsonReuters[9]. Many of the articles generate large number of comments from the interested public including direct correspondence with the M2M proponents. For example, a recent CNN article that appeared on television as well as the CNN-website[10] resulted in more than 15k Facebook ñLikesò, more than a thousand Tweets, and almost 2700 individual comments within a few days of publication. Although many of the comments are favorable, others display clear misunderstanding of the aims and risks or the project, and a significant number range from hostile to abusive.

Many large scientific have failed to adequately explain to the public the purpose of the endeavor, the scientific questions, the technical challenges, the nature of hazards, and the consequent risks. Mistrust and negative sentiment can have serious deleterious impact on large-scale scientific experiments without proper public engagement and support, for example the fear of black holes from the ignition of the Large Hadron Collider. Before a billion-plus dollars are invested in deep drilling to the mantle, it would be prudent to undertake a major public engagement exercise to explain the science and the risks involved. The recent intense media interest already provides significant data about the public perception of drilling to the mantle.

There are many approaches to measuring public engagement with science. We report and compare pilot results for several of these, including web-metrics (e.g., Google trend analysis, Facebook engagement, unique visitors, time on site), content analysis (e.g., use of positive and negative adjectives, thematic analysis of open ended responses), and automated sentiment analysis to identify, quantify, and better understand common concerns and misconceptions. Using network analysis we have identified and monitored the most important actors and conversations about the mantle drilling program on the web, and compared the levels of positive and negative recommendation with the norms found in other fields[11].

Although most public response is positive there are clearly concepts that are not yet adequately explained. Further, the relative ferocity of some negative reactions may be an ongoing cause for concern. Some issues are scientific, such as a general misconception that the mantle is molten. Others are technical misunderstandings, such as statements that deeper holes have been drilled. They have (e.g., the 12,262 m Kola Superdeep Borehole, or very long lateral hydrocarbon exploration wells in Qatar (12,289 m) and off Sakhalin Island, Russia (12,345 m)), but these holes are into continental crust or sedimentary basins and are less than a third of the way to the mantle in these environments. Other common concerns are about magma eruption, gas explosion (e.g., Deepwater Horizon-like disaster), the draining of the oceans, or the release of Satan. Especially when the potential cost of the project has been headlined in the news article, there is considerable concern that resources could be better spent, even though the cost, although significant, is a small fraction of any space mission or armed conflict.

Clearly there is an urgent need for a comprehensive and compelling mantle drilling web-presence that will engage and educate a generally enthusiastic public in this most ambitious Earth science project, as well as an active program of public engagement to proactively set the public agenda for discussion. In each case a program of measurement is required to enable the impact of these activities to be assessed. In this paper we report the first steps towards such a program for measuring public engagement with, and reaction to, the MoHole project.

References:

[1] http://www.nas.edu/history/mohole/

[2] Teagle, D.A.H., and Ildefonse, B. (2011), Journey to the mantle of the Earth, Nature 471:437-439

[3] Umino S., Ildefonse, B., Kelemen, P.B., Kodaira, S., Michibayashi, K., Moroshita, T., Teagle, D.A.H., and the MoHole proponents (2012), MoHole to Mantle (M2M); IODP Proposal 805-MDP

[4] Blade Energy Partners (2012), Project Mohole initial Feasibility Study for 2017 drilling; prepared for Integrated Ocean Drilling Program, 110p; http://www.iodp.org/mantle-drilling-preliminary-resources

[5] Berwald, J., (2012), NEXT: Drilling to the Mantle, National Geographic January, 2012, p33.

[6] Osman, J. (2012), Driller Thriller, New Scientist 30 June 2012, p38-41.

[7] The Times (5 Sep, 2012): Video: The real secrets of the deep. Deep Range: A story of the mid-ocean ridge. http://www.thetimes.co.uk/tto/public/article3528070.ece and http://www.thetimes.co.uk/tto/science/eureka/article3528237.ece

[8] Santa Maria, C., (29 Oct, 2012): Video: Mantle Drilling Project aims to dig deep to understand Earthôs past Huffington Post ñTalk Nerdy to Meò http://www.huffingtonpost.com/2012/10/29/earth-mantle-drilling_n_1967846.html?utm_hp_ref=science&ncid=edlinkusaolp00000008

[9] Drury, J. (8 Jan 2013) Billion-dollar drilling project aims for the Earthôs mantle http://uk.reuters.com/video/2013/01/08/billion-dollar-drilling-project-aims-for?videoId=240350714&videoChannel=4000

[10] Levitt, T. (2 Oct, 2012) The $1 billion mission to reach the Earthôs mantle, CNN. http://edition.cnn.com/2012/10/01/tech/mantle-earth-drill-mission/index.html?iref=allsearch

[11] East, R., Hammond, K. and Wright, M. (2007), The Relative Incidence of Positive and Negative Word of Mouth: A multi-category study, International Journal of Research in Marketing, 24 (2), 175-184.

PROBING DEEPER INTO PACIFIC OCEANIC PLATEAUS

Maria Luisa Tejada[1], Takashi Sano[2], Takeshi Hanyu[1], Masao Nakanishi[3], Kenji Shimizu[1], Seiichi Miura[1], Akira Ishikawa[4] and Katsuhiko Suzuki[1]

[1]JAMSTEC, Yokosuka, 237-0061 Japan; [2]National Museum of Nature and Science, Tsukuba 305-0005, Japan; [3]Chiba University, Chiba 263-8522, Japan; [4]The University of Tokyo, Tokyo 153-8902, Japan

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The Opportunity

In the last 10 years, two major Pacific oceanic plateaus, Ontong Java Plateau (OJP) and Shatsky Rise (Shatsky) had been drilled during the Ocean Drilling Program (ODP) 192, 198 and Integrated Ocean Drilling (IODP) Expedition 324. For the OJP, the geochemical studies yielded lava compositions that have limited variation, which contrast very well with the results for the older Shatsky. Whether or not this difference is due to sampling artifact because OJP's earliest volcanic products are inaccessible, or due to sampling only the very limited skin of its >30 km crust, is poorly understood at present. Unlike the OJP, the earliest to the latest volcanic products of Shatsky are more accessible for study, which may lead to a better understanding of the processes of oceanic plateau formation. To this end, further geophysical and geochemical study of the rise by deep drilling, especially the youngest massif and its northern arm, is desirable.

Chikyu can drill deeper into the basement and, possibly with technological innovations, at greater water depths. This gives us an opportunity for enhanced and more systematic drilling into oceanic plateaus, most of which are concentrated in the Pacific Ocean. So far, only limited sampling has been done on these plateaus due to their massive thickness and location at greater water depths. However, Chikyu has a potential advantage to be used for drilling deeper in time and depth into Pacific oceanic plateaus in order to: 1) resolve differences between geochemical variations, i. e., OJP vs. Shatsky, and 2) determine whether the geochemical variation is a function of tectonic setting or change in mantle composition with time, e.g., dominance of normal ocean ridge composition earlier (Shatsky) and ocean island composition later (OJP).

Drilling deeper into Shatsky Rise and Mid-Pacific Mountains

To understand the origin of the Pacific oceanic plateaus better, a holistic approach is necessary. This means considering them as parts of a spectrum of products of a huge magma-tectonic system possibly related to the low seismic velocity region beneath the Pacific Ocean. As such, all the Pacific oceanic plateaus may have been products at different times of this widespread mantle upwelling above this low seismic velocity region, with Shatsky and Mid-Pacific Mountains possibly representing the initial magmatic activity, the combined Ontong Java, Manihiki, and Hikurangi plateaus (Taylor, EPSL 2006) could represent the peak, whereas the Papanin Ridge and Hess Rise could represent the later stages (Fig. 1). Together with deep drilling on OJP (Neal, White Paper), it is possible to acquire ages and paleolatitudes of initial magmatic products, the temporal evolution, and the origin of this major magma-tectonic event in the Pacific Ocean (e.g., Larson, Geology 1991).

At Shatsky, volcanism started with TAMU Massif, at M20 time (~147 Ma) and waned through time with the formation of two other massifs, ORI and Shirshov, until M13 time (~139 Ma). Radiometric dating of basalts cored at ODP Site 1213 gave an age of 144.6 ±0.8 Ma (Mahoney et al., Geology 2005) for the southwest flank of TAMU Massif. IODP Expedition 324 d rilled five sites (U1346-U1350) on Shatsky recently (Sager, EOS 2011). Four magma types were identified: 1) normal, 2) low-Ti, 3) high-Nb, and 4) U1349 types (Sano et al., G-cubed 2012). Stratigraphic and geographical distribution of magma types indicate that most (~94%) of the lavas on the oldest volcano, TAMU Massif, are composed of normal oceanic floor basalt (N-MORB). In contrast, more than half (~57%) of lavas on younger ORI Massif consist of low-Ti, high-Nb, and U1349-type basalts, implying that magma compositions became heterogeneous with time. The thin lava pile at Site U1346 on the youngest Shirshov Massif is of normal type basalt but this may not be representative because recovered thickness of basement lavas is very thin (<50m) at only one site (Site U1346). The dominance so far of N-MORB-like lava compositions contrasts with expectations for a mantle plume origin of the rise. However, the tendency of some lavas of ORI and Shirshov Massifs (Sites U1350 and U1346) to exhibit more enriched isotopic and geochemical signatures suggest a possible mixed source (OJP+MORB, Geldmacher et al., AGU 2012) for Shatsky. Further study is needed to fill in the data gap in the geochemical evolution of Shatsky Rise and the best way to do it is to deepen U1350 and U1346 sites, and drill its possible tails, Papanin Ridge and Hess Rise.

Not much is known about the Mid-Pacific Mountains because previous drilling on this edifice recovered samples from guyots only (Sites 463 and 866). Yet, the recovery of Barremian age sediments suggests that the main edifice might have formed since the late Jurassic, like Shatsky. If more geophysical, geochemical, and age data are obtained from this edifice, together with results from deep drilling on Shatsky, we could learn more about the earliest initiation of oceanic plateau-forming magmatism in the Pacific Ocean. However, Chikyu should have the capability to drill into at least 3.5 km water depths to reach the older basement, which presents a challenge for planning in the next ten years.

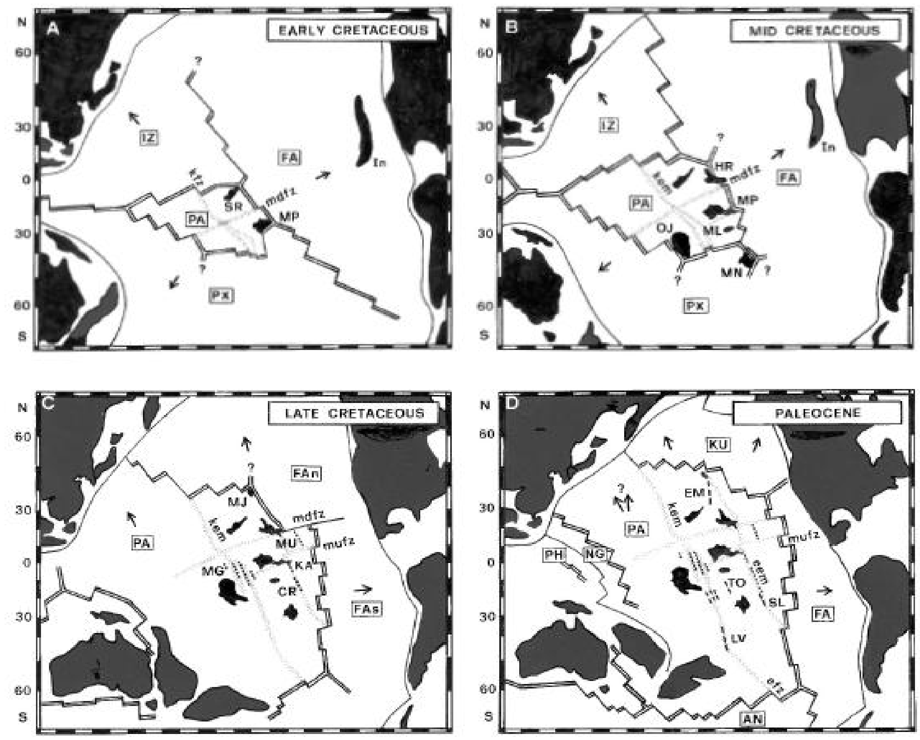

Figure 1. Paleotectonic reconstruction of Pacific oceanic plateaus (adapted from Wilde, AGU 2010).

MoHole to the Mantle (M2M)

Susumu Umino[1], Benoît Ildefonse[2], Peter B. Kelemen[3], Shuichi Kodaira[4], Katsuyoshi Michibayashi[5], Tomoaki Morishita[1], Damon A.H. Teagle[6], Natsue Abe[4], Olivier Alard[2], Shoji Arai[1], Gary Acton[7], Jeffrey C. Alt[8], Ryo Anma[9], Wolfgang Bach[10], Chris Ballentine[11], Neil R. Banerjee[12], Juan Pablo Canales[13], Mathilde Cannat[14], Richard L. Carlson[15], Rosalind M. Coggon[16], Laurence Coogan[17], Henry J. B. Dick[13], Toshiya Fujiwara[4], Yoshio Fukao[4], Jeffrey S. Gee[18], Kathryn Gillis[17], Marguerite Godard[2], Saskia Goes[16], Takeshi Hanyu[4], Alistair Harding[18], Yumiko Harigane[19], Erik Hauri[20], Eric Hellebrand[21], Ikuo Katayama[22], Jeffrey A. Karson[23], Hiroyuki Kimura[5], Jun-ichi Kimura[3], Juergen Koepke[24], Hidenori Kumagai[3], C. Johan Lissenberg[25], John Maclennan[26], Jinichiro Maeda[27], Christopher J. MacLeod[25], D. Jay Miller[28], Sumio Miyashita[29], Gregory F. Moore[21], Antony Morris[30], Kentaro Nakamura[4], James H. Natland[31], Toshio Nozaka[32], Mladen Nedimovic[33], Yasuhiko Ohara[34], Eiji Ohtani[35], Ian J. Parkinson[36], Philippe Pezard[2], Mark Rehkamper[16], Tetsuya Sakuyama[4], Vincent Salters[37], Takeshi Sato[4], Matthew O. Schrenk[38], Nobukazu Seama[39], Jonathan E. Snow[40], Eiichi Takazawa[29], Masako Tominaga[41], Takeshi Tsuji[42], Peter E. van Keken[8], Jessica M. Warren[43], Douglas S. Wilson[44]

[1]Kanazawa University (Japan), [2]CNRS, Montpellier University (France), [3]LDEO, Columbia University (USA), [4]JAMSTEC/IFREE (Japan), [5]Shizuoka University (Japan), [6]NOCS, Southamption (UK), [7]University of California, Davis (USA), [8]University of Michigan (USA), [9]University of Tsukuba (Japan), [10]Bremen University (Germany), [11]University of Manchester (USA), [12]University of Western Ontario (Canada), [13]WHOI (USA), [14]CNRS, IPG (France), [15]Texas A&M University (USA), [16]Imperial College London (UK), [17]University of Victoria (Canada), [18]Scripps, UCSD (USA), [19]AIST (Japan), [20]CIW (USA), [21]University of Hawaii (USA), [22]Hiroshima University (Japan), [23]Syracuse University (USA), [24]Hannover University (Germany), [25]Cardiff University (UK), [26]University of Cambridge (UK), [27]Hokkaido University (Japan), [28]IODP, TAMU (USA), [29]Niigata University (Japan), [30]University of Plymouth (UK), [31]University of Miami (USA), [32]Okayama University (Japan), [33]Dalhousie University (Canada), [34]HODJ (Japan), [35]Tohoku University (Japan), [36]The Open University (UK), [37]Florida State University (USA), [38]East Carolina University (USA), [39]Kobe University (Japan), [40]University of Houston (USA), [41]Michigan State University (USA), [42]Kyushu University (Japan), [43]Stanford University (USA), [44]University of California, Santa Barbara (USA)

[Keywords] Mantle, Moho, oceanic lithosphere, oceanic crust, Mid-Ocean Ridge processes, hydrothermal cooling, carbon cycle

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For the first time, the MoHole to the Mantle (M2M) project will sample upper mantle peridotites that in the near geological past resided in the convecting mantle, and recently (~20 to 100 Myrs) underwent partial melting at a fast-spreading mid-ocean ridge. This will be achieved by drilling through intact fast-spread oceanic crust and ~500 m into the mantle lithosphere. This first in-situ sampling of fresh upper mantle rocks will provide hitherto unattainable information on the chemical and isotopic composition (including fluid mobile components K, U, C, S, H_2O, CO_2, noble gases), physico-chemical conditions (e.g., fO_2, fS), seismic velocities and other physical properties, paleomagnetic and rock magnetic properties, deformation and rheology, and the scales of chemical, magnetic, and physical heterogeneity of the uppermost mantle. This information is essential to understand the formation and evolution of Earth, its internal heat budget, planetary differentiation and reservoir mixing by mantle convection, mantle melting, and melt focusing and transport at mid-ocean ridges.

Fast spreading ocean crust is targeted because it exhibits relatively uniform bathymetry and seismic structure, and is representative of the great majority of crust recycled back into the mantle by subduction during the past 200 Myrs. The M2M project echoes long-term goals of Earth scientists since the late 1950's, to understand the oceanic lithosphere. To date, the elusive frontier at the Moho, and the enormous mantle domain beneath, have been symbolic, unattainable goals. However, with the riser-drilling vessel Chikyu, the aspirations of generations of Earth scientists to drill completely through the oceanic crust and into the upper mantle, ~6 km below seafloor, have moved into the realm of technical feasibility. The ultradeep hole (MoHole) will reach a zone which has been more inaccessible and less well known than the surface of the Moon, to address first-order questions about the composition and structure of the Earth's convecting mantle, the geological nature of the Mohorovičić Discontinuity (Moho), the formation and evolution of oceanic crust, and the deep limits of life.

The M2M proposal provides the scientific justification for drilling a >6000 m borehole to the mantle. This rationale has been developed by six workshops since 2006 and integrated into the proposal, which summarizes the current state of the art and vision for engineering, technology, and operations necessary to achieve the objective. M2M directly addresses Challenges 6, 8, 9 and 10 of the 2013-2023 IODP Science Plan. Drilling the first MoHole will be a challenging enterprise requiring space-mission-levels of detailed planning and engineering. The depth of the required borehole is far beyond depths reached so far in ocean crust using conventional non-riser drilling. Industry commonly drills deeper beneath the seafloor, but the required water depth, the hardness of the formations encountered, and the temperature at the MoHole exceeds current industry thresholds. However, new technology exemplified by ongoing development of the Chikyu ultra-deep drilling vessel is arguably at the point where a framework for the operations can be constructed. A site for mantle drilling has yet to be selected; three potential target regions await additional site surveys.

Drilling into the mantle will be the most ambitious undertaking ever achieved on Earth by the geoscience community, comparable in both scope and impact to the Moon and Mars missions, and must engage the full spectrum of scientific expertise. Observations of pristine upper mantle will transform our understanding of the evolution of our planet and challenge the fundamental paradigms that are the foundations of Earth Science.

The M2M proposal (IODP 805-MDP), reports from workshops held since 2006, and other information is available at **www.mohole.org** (in Japanese: **www.ipc.shizuoka.ac.jp/~s-moho**).

Deep drilling into Ontong Java Plateau basement using Chikyu's riser drilling system

Xixi Zhao
Department of Earth and Planetary Sciences, University of California Santa Cruz, USA

Keywords: Large igneous province, Ontong Java Plateau, Riser drilling system

Exploring the lateral heterogeneity of oceanic lithosphere is one of the primary objectives defined by the IODP science plan. Oceanic plateaus are thought to be the most important targets to elucidate the link between the dynamics in the Earth's deep interior and their impact on the Earth's surface through volcanic activity. Three enormous Pacific oceanic plateaus (Ontong Java, Manihiki and Hikurangi) formed at ~122 Ma and coincided with Oceanic Anoxic Event 1a. Interestingly, the Earth's magnetic field also stopped reversing during this time interval (the Cretaceous Normal Superchron from Aptian to Santonian, 124-84 Ma). Models for the origin of the Ontong Java Plateau such as a surfacing plume head, bolide impact, or mantle melting related to plate configuration cannot account for all of the observations made for the world's largest igneous province.

Drilling of the plateau basements during past DSDP and ODP cruises, using one drilling platform of JR-type non-riser ship, have significantly increased our knowledge of their structure, composition and age. However, the origin of oceanic plateaus is still controversial mainly due to the difficulty in drilling to depths of more than a few hundred meters into igneous basements. To develop models that satisfy existing data, new samples of Lower Cretaceous sediment and basement both on and off the Ontong Java Plateau are required. Basement rocks, especially from the Plateau's eastern salient, are key targets to understand the origin and evolution of the plateau. Future drilling into the igneous basements using Chikyu riser drilling system, would provide important information on the vertical and lateral variations in the lithospheric structure beneath the plateau, and may provide major breakthrough in understanding the enigmatic origin of the Ontong Java Plateau. Deep drilling should also provide unique and continuous archives and legacy data (such as the Earth's magnetic field intensity in Cretaceous) for understanding the physical and geological processes in the core and lithosphere and the formation of the large igneous provinces.

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Japan Agency for Marine-Earth Science and Technology
2-15 Natsushima-cho, Yokosuka, Kanagawa 237-0061, Japan

Integrated Ocean Drilling Program Management International
2-1-6 Etchujima, Koto-ku, Tokyo 135-8533, Japan