JOIDES Resolution Assessment Report

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Executive Summary

The International Ocean Discovery Program (IODP), which was launched in the autumn of 2013, is the latest iteration of an international, collaborative program of scientific ocean drilling that has spanned almost 50 years. It succeeds the Deep Sea Drilling Project (1968-1983), the Ocean Drilling Program (1985-2003) and the Integrated Ocean Drilling Program (2003-2014). The workhorse of the IODP is the *JOIDES Resolution*, whose operationally diverse capabilities and regional planning model provide the scientific community with a vital platform for implementing the program. Since the beginning of IODP, the *JOIDES Resolution* has enabled researchers to make significant progress on every science theme in the 2013-2023 IODP Science Plan, *Illuminating Earth's Past, Present, and Future*.

This *JOIDES Resolution* Assessment Report represents the results of a multi-phased, year-long community review of the performance of the *JOIDES Resolution* in implementing IODP science. Our conclusions incorporate the input of the 876 scientists who participated in an extensive survey about the vessel and its scientific potential and accomplishments, and the 81 participants who distilled and analyzed the survey data and expedition results at a September 2017 meeting in Denver, Colorado.

Overall, the survey results underscore the scientific community's deep satisfaction with the *JOIDES Resolution* and its ability to continue to fulfill IODP objectives. Responses were strongly positive with respect to the ship's drilling systems, analytical systems, and logging systems, with each receiving favorable ratings from over 90% of the respondents. The *JOIDES Resolution* continues to effectively drill and core in many different environments and rock types to address a myriad of scientific objectives.

IODP science has greatly benefited from recent operational and technological improvements to the *JOIDES Resolution*. Drilling and coring advances, such as half-length advanced-piston coring, have significantly improved core quality, and the vessel's regional planning model, unique among IODP drilling platforms, enables complex, multi-expedition investigations of Earth systems. It has also minimized transit times between expeditions and contributed to substantial fuel savings. Coupling those advances with efficiencies realized by the *JOIDES Resolution* Science Operator and income from co-sponsored complementary project proposals, the vessel's operational time has recently increased from 8 to 10 or more months per year, positioning IODP to achieve high-priority science goals at an accelerated rate. Finally, regional planning has also served as a catalyst for improvements in the IODP proposal review process, significantly reducing the time between the submission of drilling proposals and their implementation. This has in turn allowed IODP to be increasingly flexible and responsive to recent drilling results and to societal needs.

As outlined in the National Research Council's report *Sea Change: 2015-2025 Decadal Survey of Ocean Sciences*, scientific ocean drilling is critical to the future success of ocean and earth science research because of the unique types of samples and data collected by IODP. During the first years of the program, IODP expeditions conducted with the *JOIDES Resolut*ion have contributed to five of the eight *Sea Change* research priority questions, and future expeditions will provide insight into two more.

The scientific community unwaveringly supports the continued use of the *JOIDES Resolution* to fulfill the remainder of the 2013-2023 IODP Science Plan and seeks continued utilization of its singular research capability.

Section I: Introduction

In 2016, the U.S. scientific ocean drilling community was asked by the National Science Foundation (NSF) to review and assess the role of the *JOIDES Resolution* in meeting the challenges of the 2013-2023 International Ocean Discovery Program (IODP) Science Plan, *Illuminating Earth's Past, Present and Future*. This assessment focuses on the period beginning with the start of the International Ocean Discovery Program (Expedition 349 in January 2014) and includes both an inventory of facility accomplishments and a description of the relationship between specific 2013-2023 Science Plan challenges and the use of the *JOIDES Resolution* to accomplish the science related to those challenges. (The International Ocean Discovery Program succeeded the Integrated Ocean Drilling Program—which also used the acronym "IODP"—in autumn of 2013; for the purposes of this report, "IODP" refers specifically to the International Ocean Discovery Program.)

The assessment process was developed and led by the *JOIDES Resolution* Assessment Steering Committee, members of which were invited to serve by the U.S. Science Support Program (USSSP) based on nominations from the U.S. Advisory Committee for Scientific Ocean Drilling (USAC), the *JOIDES Resolution* Facility Board (JRFB), and the Science Evaluation Panel (SEP) co-chairs. Nominations were evaluated based on each candidate's ability to represent and steer the U.S. IODP community through the assessment process. Care was taken to assure a balance of scientific specialty, career level, institution type, and familiarity with past IODP assessment processes. The Steering Committee has final responsibility for the contents of this report.

As part of the *JOIDES Resolution* evaluation, we conducted a broad online survey to solicit feedback from the global IODP community on individual experiences with, and priorities for, the *JOIDES Resolution* facility. The survey results were used to compile both expedition-specific and program-wide accomplishments, which were in turn used to inform workshop planning and, eventually, report conclusions. Detailed discussion took place at the in-person workshop, which was held on September 26-27, 2017 in Denver, CO. Workshop participants were charged with: 1) evaluating the specific merits of the *JOIDES Resolution* and how the facility will continue to accomplish the goals of the 2013-2023 IODP Science Plan; 2) determining if the *JOIDES Resolution* requires enhancements or modifications to accomplish these goals; 3) reviewing outcomes from multi-expedition, regionally-focused operations; and 4) summarizing the community's perspective on the overall science that has been accomplished to date by the *JOIDES Resolution*.

Day 1 of the workshop focused on the analysis and integration of results from previous expeditions (the Expedition Evaluation reports) and the *JOIDES Resolution* Community Survey. The majority of the discussion occurred in breakout sessions by theme groups. Day 2 discussion included both breakout and plenary sessions and focused on the broader preliminary assessment of the *JOIDES Resolution* as well as evaluation and consideration of regional operations. The conclusions in this report are based on the Community Survey, the Expedition Evaluation Reports, and the detailed discussions of the workshop participants.

Section II: *JOIDES Resolution* Community Survey

The first stage of the *JOIDES Resolution* assessment was to conduct a comprehensive online survey to solicit the community's experiences, opinions and priorities for the *JOIDES Resolution* facility. The community responses to the survey formed the foundation of the workshop's evaluation of the *JOIDES Resolution*'s successes in meeting the objectives of the 2013-2023 IODP Science Plan, as well as its capacity to continue to do so.

The Steering Committee developed the survey questions in concert with USSSP and USAC. An independent consultant, Ms. Beth Rabin, reviewed the validity of the questions. The survey solicited demographic and background information from the respondents, including country of residence, career level, past involvement with scientific ocean drilling, scientific expertise, involvement with other large Earth science research programs, geographic interest, and thematic interest (i.e., the theme(s) of the IODP Science Plan with which the respondent most closely identifies). Respondents were asked to identify new technical or scientific developments that the *JOIDES Resolution* has facilitated since the start of IODP; how these developments have helped address the IODP Science Plan themes; the most important scientific accomplishments to which the *JOIDES Resolution* has contributed since the beginning of this phase of ocean drilling; the most critical scientific challenges for the *JOIDES Resolution* to address over the next 5 years; and other questions to elicit opinions about the ability of the *JOIDES Resolution* to address the critical science themes of the IODP Science Plan.

The survey was launched during the 2016 American Geophysical Union (AGU) Fall Meeting and was promoted widely at the conference and thereafter through USSSP's electronic and social media (e.g., website, newsletters, Twitter, Facebook). All scientists with an interest in scientific ocean drilling were encouraged to participate through the survey's closing date in early May 2017. In total, the community survey received 967 responses, 37 of which were duplicates and were thus removed from the response pool. An additional 54 responses were deemed insufficiently complete to contribute meaningfully to the results. Thus, the final total of valid responses was 876.

The community survey received responses from scientists in 37 countries, with the U.S. comprising by far the largest group of respondents (46% of total responses, Figure 1). Of the U.S. responses, more than 44% of total participants were either graduate students or early career (defined as being less than ten years post-Ph.D.), indicating that the U.S. IODP community continues to be successful in recruiting young scientists into its pipeline. Among all respondents, both U.S and international, it was notable that scientists in the Biosphere Frontiers theme tended to be younger than their counterparts from other IODP themes, reflecting the fact that this field is somewhat newer than other traditional areas of research in scientific ocean drilling.

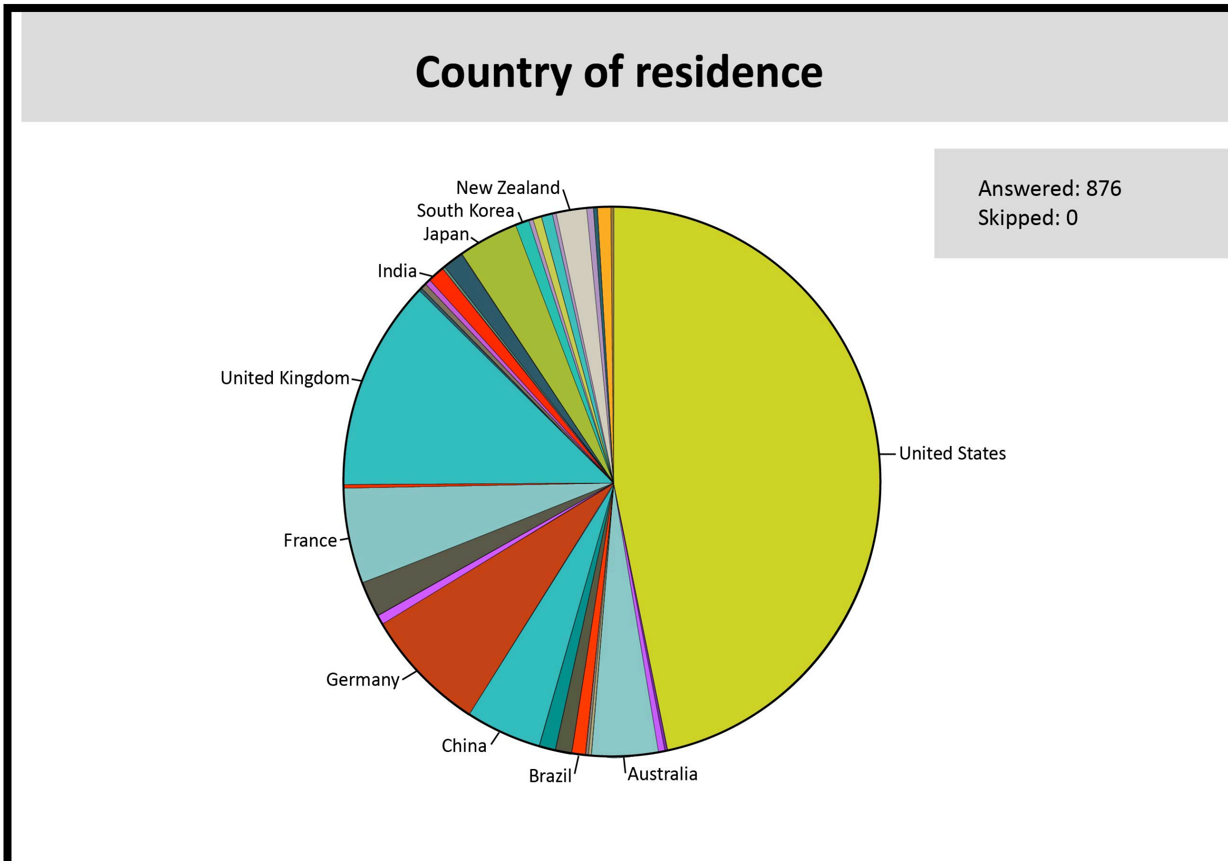

Figure 1: Distribution of responses by country of residence.

The survey did not require respondents to provide identifying information, but 234 of the 410 U.S. respondents chose to identify their home institution. According to these responses, scientists from at least 84 unique institutions participated in the survey, with the actual number of institutions likely to be significantly higher, given that only 57% of U.S. respondents included this information. It is clear that a broad array of U.S. institutions participate in IODP.

Among all respondents, both U.S. and non-U.S., 66% had sailed on at least one *JOIDES Resolution* expedition, and 16% had sailed on at least three (Figure 2). Fifteen percent of respondents had sailed as co-chief scientists. Respondents most frequently self-identified as paleoceanographers/paleoclimatologists; the next most common discipline cited was stratigraphy, followed by Earth and planetary surface processes, tectonophysics, volcanology/geochemistry/petrology, global environmental change, and biogeosciences/microbiology (Figure 3). (Respondents were allowed to include more than one discipline.)

The geographic focus of IODP science interests is extremely broad, with each of the following geographic areas attracting interest from at least 35% of respondents: North Atlantic Ocean,

Number of times sailed on the *JOIDES Resolution*

Answered: 876
Skipped: 0

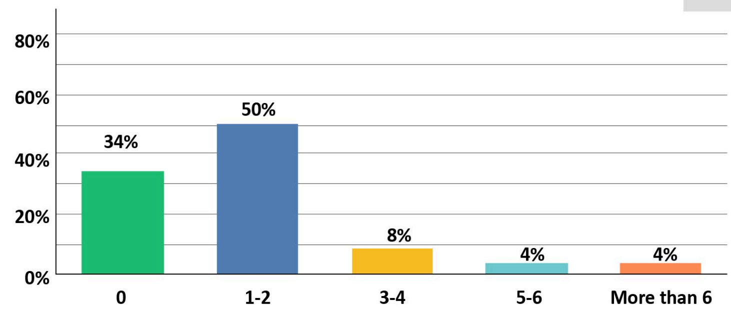

Figure 2: Distribution of responses by number of times sailed on the *JOIDES Resolution*.

Primary disciplines

Answered: 872
Skipped: 4

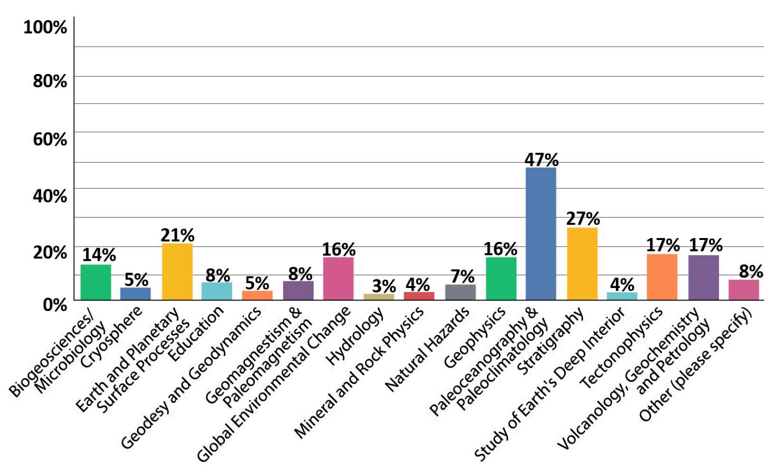

Figure 3: Distribution of responses by primary discipline(s).

South Atlantic Ocean, North Pacific Ocean, South Pacific Ocean, Indian Ocean, and Southern Ocean. In addition, the Arctic Ocean, Gulf of Mexico, Mediterranean Sea, and the South China Sea each attracted interest from at least 15% of respondents (Figure 4).

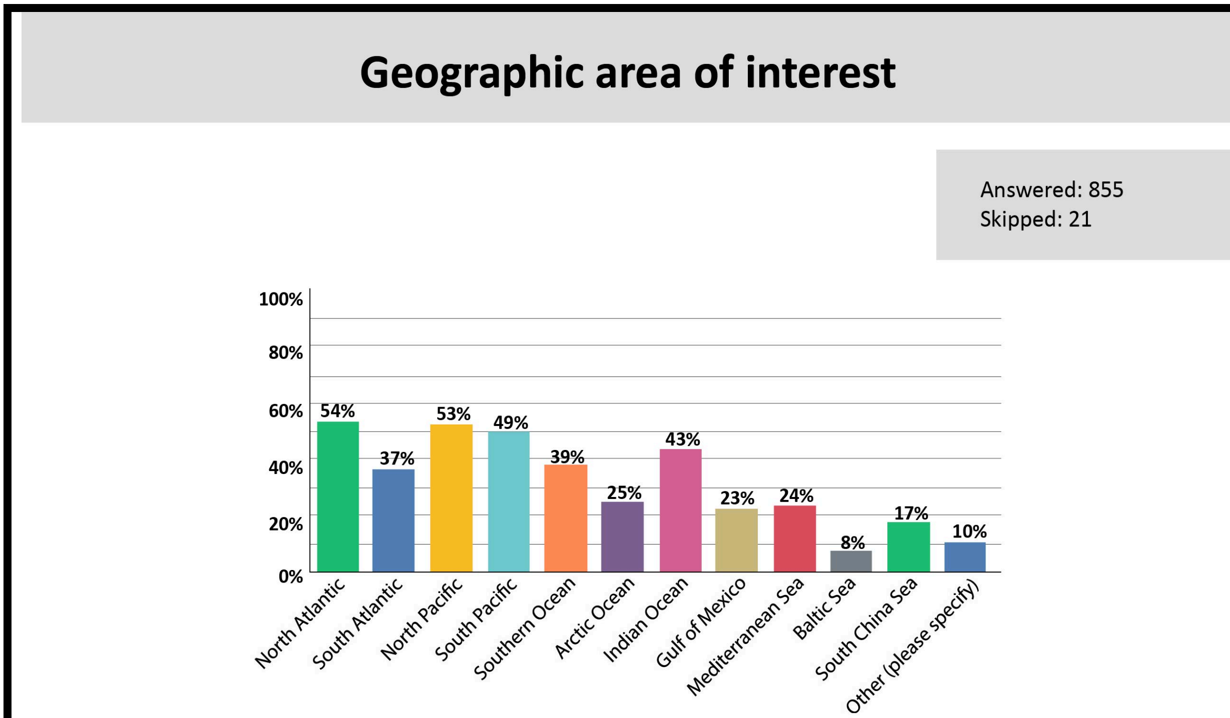

Figure 4: Distribution of responses by geographic interest(s).

Among scientists who use IODP samples and data, cross-pollination with other scientific programs is also common. Among all respondents, the participation rate of IODP scientists exceeded 15% for each of the following: Center for Dark Energy Biosphere Investigations (C-DEBI), Deep Carbon Observatory, GeoPRISMS, the International Continental Scientific Drilling Program (ICDP), and InterRidge (Figure 5).

When asked which IODP science theme respondents most closely identified with, 53% selected Climate and Ocean Change, 20% selected Earth Connections, 18% selected Earth in Motion, and 9% selected Biosphere Frontiers (Figure 6). Respondents were also given the opportunity to select one or more secondary themes related to their research interests. Encouragingly, each of the four themes was identified as a secondary interest by at least 26% of respondents, indicating that all themes are broadly represented within the IODP community.

Participation in other initiatives or community groups

Answered: 433
Skipped: 443

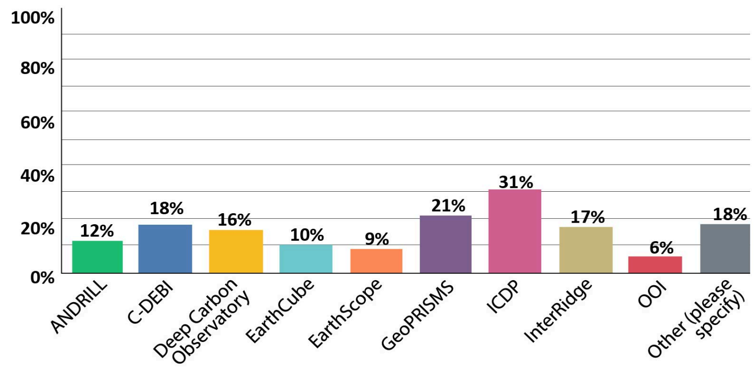

Figure 5: Involvement of respondents in other scientific initiatives.

Primary science theme identification

Answered: 754
Skipped: 122

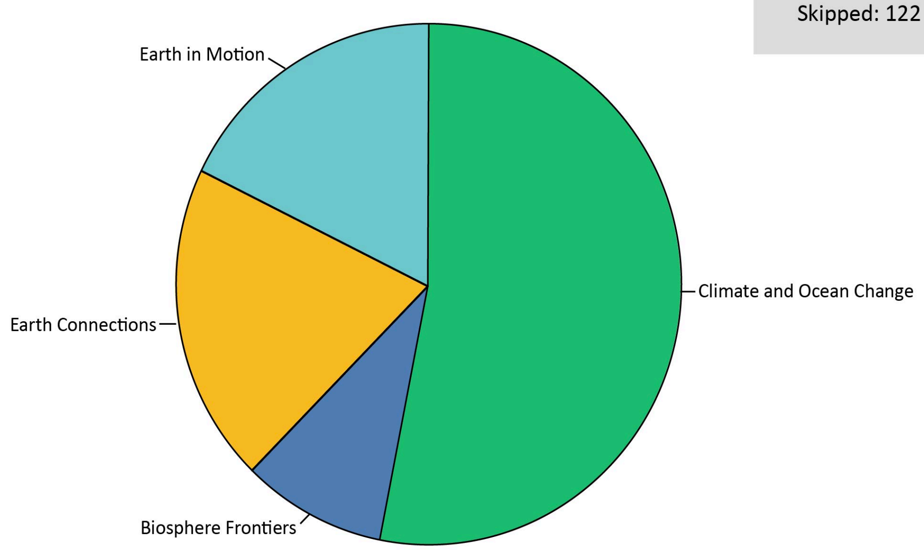

Figure 6: Primary IODP science theme identification among all respondents.

Respondents were specifically asked to assess the capabilities of the *JOIDES Resolution* for addressing the challenges of the 2013-2023 IODP Science Plan. The survey asked respondents to rate the drilling, logging, and analytic system separately, with the option of choosing whether each of these systems was "suitable" or "not suitable." Satisfaction with the facility was extremely high across all systems, with **95.6% of respondents rating the drilling systems as suitable**. Analytical and logging systems were rated as suitable **by 91.5% and 91.9%, respectively**. This finding underscores the community's deep overall satisfaction with the facility and its ability to pursue the objectives of the IODP Science Plan over the next five years.

The most commonly cited shortcomings of the facility were the limited X-ray fluorescence (XRF) core scanning capabilities, lack of computed tomography (CT) core scanning, the need for further technology development to improve recovery in challenging core environments (e.g., hard rock, sands, alternating hard and soft sediments, high temperature settings, high latitude areas with abundant ice rafted debris, etc.), and the limited internet bandwidth. Respondents also expressed interest in riser capability, increased ice-strengthening, and large-volume coring systems, none of which are financially feasible. Even among respondents who were highly satisfied with the facility capabilities, some concerns were expressed about the age of the vessel and its infrastructure.

Section III: Workshop

The *JOIDES Resolution* Assessment Workshop was held on September 26-27, 2107 in Denver, CO and was attended by 81 participants, most of whom were selected on the basis of their familiarity with IODP, their recent participation on IODP expeditions, and/or their ability to offer comprehensive perspective on the facility. The workshop participants were charged with reviewing the performance of the JOIDES Resolution facility in carrying out the 2013-2023 IODP Science Plan to date, and assessing the facility's ability to complete the science plan over the next five years.

The first day of the workshop focused on analyzing and integrating results from the Community Survey and the 16 IODP expeditions completed by the time the workshop was convened. The majority of the analysis and integration occurred in breakout sessions organized by the themes identified in the IODP Science Plan. The second day focused on synthesizing the preliminary assessments of the *JOIDES Resolution* and evaluating regional operations.

Each thematic breakout group accomplished the following:

- Group members contextualized and synthesized comments from the open-ended questions of the Community Survey into summary statements for each challenge. These statements were used in the thematic assessment of the *JOIDES Resolution*.
- Participants reviewed the Expedition Evaluation Reports for evidence of the capabilities of the *JOIDES Resolution* and any limitations in carrying out the IODP Science Plan by expedition. The Expedition Evaluation Reports, developed by selected watchdogs in each thematic group, were completed prior to the workshop and reviewed by the Steering Committee and the *JOIDES Resolution* Science Operator (JRSO) for accuracy.
- An assessment of the ability of the *JOIDES Resolution* to carry out the IODP Science Plan. Comments and other data from the Community Survey were used to support the conclusions for each challenge.

Day 2 plenary sessions were devoted to a discussion of the thematic assessments. In Plenary Session I, each group was charged with presenting responses to the following questions, which were then synthesized into a summary spreadsheet:

- What is the relationship between the IODP Science Plan and the *JOIDES Resolution*'s contributions to date in addressing your theme and challenges? Synthesize the Expedition Evaluation Reports, supported by Community Survey results and comments.
- What are the specific merits of the *JOIDES Resolution* for your theme and how will the facility continue to help accomplish your theme's goals in the IODP Science Plan? Outline why the *JOIDES Resolution* is successful at what it does using specific examples, but consider too its limitations.

- Outline possible enhancements/modifications to the *JOIDES Resolution*, if needed, directly referencing the above question, but with guidance from JRSO on feasibility. Consider how the *JOIDES Resolution* might improve its ability to realize your theme's goals from the IODP Science Plan in the next 5 years.
- Regional operations: Describe ways in which this innovation enhanced the science outcomes for your theme.
- What exciting science is still left to fulfill in your theme from the IODP Science Plan? Identify potential expeditions, by challenge, that could be addressed in the next 5 years, focusing on the likely ship track of the *JOIDES Resolution*.

In Plenary Session II, participants reviewed the following questions and summarized the results for incorporation into the appropriate theme group review of the facility. The Day 2 plenary sessions benefited from discussions in both the theme breakout and cross-thematic (all participants) groups.

- What are the specific merits of the *JOIDES Resolution* facility and how will it continue to help accomplish the goals of the IODP Science Plan?
- Outline possible enhancements/modifications to the *JOIDES Resolution* facility, if needed.
- Evaluate the scientific benefits of regional operations.
- Are there other innovations such as regional operations in our standard operating procedures that could lead to economies of resources like this?
- Given the projected *JOIDES Resolution* ship track for the next five years and gaps identified in completing the challenges to date, what should the role of the facility be in addressing these challenges?

Climate and Ocean Change

The Climate and Ocean Change theme in the 2013-2023 Science Plan addresses questions involving atmospheric and ocean interactions and history, including the regional and systemic responses to changes in CO_2, warming climate and chemical perturbations. All four Science Plan challenges within this theme have been addressed by the expeditions in the first years of the program, and the recent focus on the Indo-Pacific Basin has resulted in an exceptional opportunity to evaluate monsoons, their climate controls, and associated weathering and tectonism. With few exceptions, highly successful coring activities positioned the science parties to achieve the expedition objectives. Recovered cores also led to unanticipated discoveries and developments. In addition to the nine expeditions that had a primary focus on Climate and Ocean Change, four expeditions devoted to the Earth in Motion and Earth Connections themes recovered sediments suitable for paleoclimate and paleoceanographic investigations.

Contributions to date of the *JOIDES Resolution*

Challenge 1: How does Earth's climatic system respond to elevated levels of atmospheric CO_2? Recent expeditions provided high-quality material for reconstructions related to this challenge, including records of atmospheric CO_2 from the Plio-Pleistocene (Expedition 353, 361, 363) and potentially the Miocene (Expedition 363). Future scheduled drilling is expected to recover appropriate Miocene sequences to fill this temporal gap. More general reconstructions of climate, including but not limited to sea surface temperature, precipitation, and ocean circulation/water mass structures, will soon emerge from Expeditions 353, 355, 356, 359, 361, and 363.

Expedition 353 explored the relationship between monsoon circulation and insolation, Southern Hemisphere latent heat export, global ice volume, and greenhouse gas concentrations, in addition to providing verification targets for climate models. Expedition 355 sought to determine the amplitude and direction of environmental change at ~8 Ma and other times of major climatic variation during the Cenozoic (Challenges 1 and 3), and was greatly aided by use of the half-length Advance Piston Coring (HLAPC), allowing for examination of the erosional response to monsoon changes at a millennial-scale resolution. Coring during Expedition 355 yielded the unexpected bonus of encountering an extensive mass transport deposit that likely represents the second largest known deposit of this type in the geological record on a passive margin.

Expedition 356 explored Challenge 1 by targeting the timing and variability of the onset of Indonesian Throughflow, the extent of Indo-Pacific Warm Pool, and the onset of the Leeuwin Current to understand the controls on Quaternary extra-tropical carbonate and reef deposition. A complementary objective was to obtain an ~5 m.y. orbital-scale tropical to subtropical climate and ocean archive. This would be directly comparable to deep-ocean oxygen isotope and ice-core archives, allowing the community to chart the variability of the Australian monsoon and the onset of aridity in northwestern Australia.

Expedition 361 had multiple objectives that focused on Challenge 1 both directly and indirectly, including the opportunity to identify continental climate change under changing CO_2 levels. These objectives were to: 1) assess the sensitivity of the Agulhas Current to changing climates of the Pliocene and Pleistocene; 2) reconstruct the dynamics of the Indian–Atlantic gateway circulation during such climate changes; and 3) constrain the temperature, salinity, and density structure of the Last Glacial Maximum (LGM) deep ocean from the bottom of the ocean to the base of the main thermocline.

Expedition 363 recovered 6900 m of exceptional core to explore Challenge 1 details such as: 1) the millennial-scale climate variability in the Western Pacific Warm Pool; 2) the orbital-scale climate variability through the Neogene; 3) the Miocene to late Pleistocene evolution of the Australian monsoon; 4) changes in the Indonesian Throughflow through the Neogene; and 5) the density structure of the western equatorial Pacific.

Challenge 2: How do ice sheets and sea level respond to a warming climate? Materials recovered during Expeditions 356 and 359 provide unique opportunities to contribute to Challenge 2. Results from drilling on the Maldives during Expedition 359 will document sea level fluctuations in the Miocene. A related question, the development of time scales at the resolution of ice sheet expansion and contraction, was addressed by Expedition 353, which recovered a record of Oligocene-present sediments that will yield an astronomically-tuned time scale with integrated high-resolution calcareous and siliceous microfossils, to be used in global compilation studies of paleoclimatic and biotic evolution. The upcoming circum-Antarctic expeditions will contribute significantly to documenting the temporal influence and response of this region to Cenozoic climate change. Future Southern Ocean expeditions will provide an unprecedented addition to the reconstruction of Antarctic climate, ocean circulation, and ice sheet dynamics, complementing ANDRILL and previous deep-sea drilling expeditions.

Challenge 3: What controls regional patterns of precipitation, such as those associated with monsoons or El Niño? The monsoon dimension of this challenge was addressed for monsoon systems in Africa (Expedition 361), India (Expeditions 353 and 355), Asia (Expeditions 353 and 354) and Australia (Expeditions 356 and 363). Other regional climate features, including those related to tropical ocean circulation, will be explored with records recovered during Expeditions 353, 361, and 363.

Expedition 353 has established the sensitivity of monsoon circulation to climatic controls, and will help determine the extent of coupling between Indian and East Asian monsoon winds and precipitation over temporal and geographic scales. Complementary goals focused on separating the effects of climate change and tectonics on runoff and erosion; understanding the timing and conditions in which monsoon circulation developed; and understanding the relationship of the Indian monsoon to major Cenozoic climate events.

Expedition 354 targeted Himalaya erosional history and Asian monsoon development in the Neogene and the timing of Himalayan uplift. Expedition 355 focused on the exhumation of the Greater Himalayan region and the resulting enhanced erosional flux and intense chemical weathering, although termination of drilling above the onset of this event renders its timing equivocal. The use of the half-length APC enabled recovery of sandy sediments that will allow for examination of the erosional response to monsoon changes at millennial-scale resolution. Objectives to define the start of fan deposition were not met because of shallower drilling than planned, but the sediments nonetheless revealed important information about fan sedimentation.

Expedition 356 targeted the variability of the Australian monsoon and determined the timing of the onset of aridity in northwestern Australia. Expedition 363 recovered 6900 m of exceptional core with which the team will reconstruct the Miocene to late Pleistocene evolution of the Australian monsoon. Expedition 359 sought to relate the timing of sequence boundaries in drift sediments to oceanic current changes linked to the Indian monsoon. Expedition 361 focused on the relationship of the Agulhas Current to changing climates of the Pliocene and Pleistocene, in association with transient to long-term changes of high-latitude climates, tropical heat budgets, and the monsoon system, as well as addressing the impact of Agulhas variability on southern Africa terrestrial climates, rainfall patterns and river runoff.

Challenge 4: How resilient is the ocean to chemical perturbation? Challenge 4 is addressed in some capacity by all expeditions recovering sediments for climate reconstructions. Emphasis on specific processes, such as the role of tectonic uplift and erosion on carbon burial, will come from the Asian monsoon-related expeditions. Questions related to ocean anoxic events will be explored with materials recovered during drilling into Cretaceous black shales (Expedition 369, underway at the time of report preparation).

Expedition 354 objectives focus on the impacts of high preservation and burial of organic matter on the deep biosphere, in the context of Himalayan uplift and erosion. Expedition 361 objectives included constraining the temperature, salinity, and density structure of the LGM deep ocean from the bottom of the ocean to the base of the main thermocline. Expedition 363 objectives focused on understanding the ocean structure and circulation related to opening of the Indonesian Throughflow, assessing the associated changes in density structure of the western equatorial Pacific, and evaluating the influence of those changes on diagenetic processes.

Theme-wide accomplishments: Expeditions conducted on the *JOIDES Resolution* to date have significantly addressed all four Climate and Ocean Change challenges, and have also integrated Climate and Ocean Change drilling targets into challenges within other themes. The community agreed that the onboard analytical capabilities and the dedicated technical crew have been and continue to be critical to the theme group's success. The community confirmed that recovery of new sedimentary sequences in pursuit of hypothesis-driven objectives facilitates the discovery of unexpected results and processes. Discovery on an expedition is not usually limited to only one theme; it regularly spans different areas of the program. For example, Expeditions 367/ 368 were focused on development of the southeast Asian margin, but the sediments recovered in that campaign allowed for investigation into the Climate and Ocean Change theme. There are also scientific links between themes, such as Climate and Ocean Change Challenge 4 (chemical perturbation), Biosphere Frontiers Challenge 7 (ecosystem sensitivity), and Earth in Motion Challenge 13 (subseafloor carbon).

Merits of the *JOIDES Resolution*

The Climate and Oceans community consensus is that the *JOIDES Resolution* is the tool of choice for recovering high-quality, continuous sedimentary records used for reconstructing climate and ocean histories. Since the implementation of the IODP Science Plan, technical developments in Advanced Piston Coring (APC) drilling are allowing drilling to greater depths than previously available. In particular, the adoption of the half-length APCs allows for better recovery of sediment from depths where it is typically too stiff for full APC but too soft for Extended Core Barrel (XCB) drilling without severe disturbance. It has enabled recovery of sandy layers that were not recoverable previously. It also allows for the undisturbed recovery of targeted sections needed for high-resolution time-series reconstructions of climate evolution.

Several analytical advancements have improved our ability to recover excellent quality climate records. Technical improvements within the shipboard laboratories include the addition of a new magnetometer, updated software, orientation tool/capability, and a desktop SEM. Better scanning and imaging capabilities, and database speed and accessibility, have facilitated data generation and sharing shipboard. The implementation of post-cruise, programmatically-supported X-ray fluorescence (XRF) scanning is providing non-destructive high-resolution chemical records to facilitate stratigraphic correlation and sampling. The success of this technique is affirmed by the many comments from the community asking for shipboard capability.

Coring of extended, high-quality sediment sequences has provided datasets that are critical to meeting Challenges 1-4 in a variety of settings and sediment type. Expedition 361 achieved excellent core recovery (102%), from which was developed a continuous stratigraphic splice from triple-cored APC holes, and thus a complete sedimentary record of paleoceanographic conditions. The high recovery of quality APC cores on that same expedition also meant that interstitial pore water sampling goals were met with high-resolution sampling that can address oceanic water chemistry and circulation during the LGM ocean. High core recovery and quality on Expedition 353, aided by use of the half-length APC, resulted in sampling across a salinity gradient and geographic range in the Bay of Bengal and Andaman Sea. The half-length APC used in conjunction with XCB were key in providing a flexible coring system for recovery of alternating lithologies on Expedition 356. The flexibility of the platform also enabled recovery of hemipelagic sediments in this region, allowing for both marine and continental systems to be examined simultaneously. The complete recovery of high-quality core facilitates ongoing geochemical proxy development, validation, and refinement.

The fact that the *JOIDES Resolution* is able to core both sediments and hard rock well allows for added value when both types of material are recovered on an expedition. Expeditions 349, 350, 351 and 362 did not have primary Climate and Ocean Change-related objectives, but the sediments recovered are or could be employed in paleoclimate investigations.

Although the *JOIDES Resolution* is an exceptional vessel for Ocean and Climate Change science objectives, it is recognized that the exploratory nature of scientific drilling is not without its surprises. Expedition objectives are sometime frustrated by the sedimentary record itself. For example, Expedition 359 had only partial recovery of carbonate platform strata, which makes it harder to test hypotheses for why the platforms drowned. It should be stressed that the missing section is not related to deficiencies in the facility but to the patterns of deposition of the carbonate sediments. Equally noteworthy is serendipitous discovery. The unplanned recovery of hemipelagic and coarse-grained sediments from the mid-Bengal Fan, recovery of turbidite records in the Bay of Bengal and Andaman Sea, and discovery of evidence for gas hydrates in thin silt beds on the Indian margin (Challenge 3) were all facilitated by the unique capabilities of the *JOIDES Resolution* facility.

Impact of Regional Operations

This theme has uniquely benefitted from regional operations. The community is actively working to generate data since Expedition 349. Anticipated accomplishments, based on materials recovered, include increased coverage of sea surface temperature and chemical gradients from previously unexplored or underexplored regions of the ocean, including the Indian Ocean and western Pacific warm pool, estimates of sea level variability and rates of change, organic carbon burial rates, reconstructions of terrestrial hydroclimate from nearshore and river influenced localities, and improved reconstructions of pCO_2 across the Plio-Pleistocene. The temporal and spatial distribution of sites will provide data to inform Earth system climate models exploring a range of processes, including ice sheet dynamics, sea level change, and climate sensitivity to radiative forcing in the past.

Potential Facility Implementations

The next five years of *JOIDES Resolution* operations will address aspects of each of the four challenges under the Climate and Oceans Change theme. Recovery of high-accumulation-rate sediment will provide records to address abrupt climate change and biogeochemical feedbacks. The scheduled expeditions to the Southern Ocean will provide material to study high latitude processes, ice sheet dynamics, and any consequent (or coincident) changes in ocean circulation and ocean chemistry. Older continuous records, extending to the pre-Pliocene, will be used to study the response of the climate system to higher CO_2 and constraints on deep ocean hydrology and intermediate water-mass structure and chemistry (e.g., Atlantic Meridional Overturning Circulation, or AMOC) along meridional gradients (tropics-poles). Broad spatial coverage will allow pole-to-equator scale investigations of ecosystem responses to climate change.

Challenge 1: Future expeditions can focus on recovering optimal materials that yield the best marine CO_2 proxies in stratigraphic intervals that are to date poorly represented. Because locations that provide unaltered carbonates (boron proxy) and organic rich sediments (alkenone proxy) are generally mutually exclusive, developing robust CO_2 reconstructions will require multiple legs based on sedimentary criteria. In addition, mapping climatic and ecological consequences of variable CO_2 levels in the Earth's past requires improved geographic coverage, particularly in high latitude regions that are presently under-sampled. Planned expeditions in the Southern Ocean and anticipated expeditions in the North Atlantic Ocean will provide this coverage.

Challenge 2: The *JOIDES Resolution* can contribute to separating various influences on sea level change by recovering records from particular regions where each influence is thought to be most important and/or evident. More specifically, the upcoming expeditions in the Southern

Ocean will investigate ice sheet instabilities in the past and their potential causes, which includes both improved recovery and improved dating of those instabilities, and the linking of proximal and distal records (e.g., drifts), recovered from both *JOIDES Resolution* and mission-specific platform (MSP) operations, and deep-water circulation and deep-water chemistry (e.g., CO_2). Complementary northern hemisphere records are needed in the Atlantic and Pacific basins to discern global leads-lags in the response of the cryosphere. Records from the Maldives and Southern Ocean sites will establish rates and magnitudes of sea level changes during rapid (suborbital) climate changes (e.g., during Heinrich events and Marine Isotope Stage 3). The suite of records from all thematic drilling efforts could investigate mechanisms and rates of Cenozoic open-ocean responses to changes in the cryosphere. The anticipated data will reconstruct ice sheet behavior and address questions related to the role of ocean circulation and ocean chemistry in ice sheet growth and decay, and will be used to inform models, including those that seek to understand the response of ice sheets to warm climates.

Challenge 3: Work from already-drilled expeditions will provide excellent histories of precipitation from the Indian Ocean. Future expeditions could provide unprecedented deep time records of global precipitation, including the West African, South American and North American monsoons, and Mediterranean climate.

Challenge 4: Exploring the ancient chemistry of the ocean would lead to improved constraints on deep ocean hydrology and intermediate water-mass structure and chemistry (e.g., Atlantic Meridional Overturning Circulation, extending to the pre-Pliocene), including latitudinal gradients (tropics-poles). Proxy development will continue to be essential to understanding ocean chemistry.

The community has identified some areas for improvements to the *JOIDES Resolution* that could advance scientific outcomes over the next five years. Improvements in software (e.g., Correlator), correlation sensors (e.g., smaller diameter magnetic susceptibility loops, color reflectance), and training for stratigraphic correlators are critical to the ability to take advantage of the multiple-hole approach and to facilitate real-time shipboard coring in sections focused on climate change science. The community suggests that correlator training should be conducted in advance of sailing. Similarly, continued evaluation of additional analytical capabilities for shipboard use could improve high-resolution core characterization (e.g., computed tomography (CT) scanner, XRF).

The community also advocates for continued efforts to improve core recovery and quality in sediments typically cored with the XCB tool, or further improvement in range of the APC tool. This is particularly of concern in difficult lithologies, such as interlayered ooze and chert. An associated concern is the preservation of carbonate and organic matter in organic-rich sediments after splitting. This is critically important for cores that are not sampled until several months post-cruise. A systematic study is recommended to explore better core storage options.

Biosphere Frontiers

Biosphere Frontiers addresses fundamental yet largely unanswered questions, including the origin and distribution of microbial life in the sub-seafloor, limits and challenges to life in that environment, and ecosystem responses, including evolution, to change. One of the reasons there has been an explosion in deep biosphere research in recent years is the advent of highly sensitive DNA sequencing, which allows generation of high quality data with low biomass samples, such as those typical for deep biosphere work. This has allowed for production of outstanding data from recent expeditions, as well as exciting discoveries using new techniques from samples collected as far back as Ocean Drilling Program Leg 201.

Contributions to date of the *JOIDES Resolution*

Challenge 5: What are the origin, composition, and global significance of deep subseafloor communities? Since the expeditions in the first few years of the International Ocean Discovery Program have been regionally focused, it is premature to report on the global significance element of Challenge 5. Yet this challenge has been partially addressed, setting some bounds on composition and global significance of the subseafloor microbial biosphere, although there are many remaining questions about origins of life and community sensitivity to change, both throughout Earth history and in the future. Participation of biosphere researchers as single participants or in pairs on expeditions that are not specifically biosphere-oriented has greatly aided this effort, although expeditions in which biosphere objectives are primary are required to assess hypotheses at a deeper level than cataloging the extent and diversity of the deep biosphere.

Challenge 6: What are the limits of life in the subseafloor realm? The *JOIDES Resolution* has helped researchers develop some estimates on the limits of life by looking where cells are sparse and inactive, but more work is needed to understand the mechanisms underlying the limits of life. For example, drilling into the high pH Mariana mud volcanoes on Expedition 366 supplied one version of limits to life that is different from the extremely low energy limit tested on Expedition 329 (South Pacific Gyre). As new realms such as the lower oceanic crust are explored, as was done on Expedition 360, theories and understanding about limits of life may change.

Challenge 7: How sensitive are ecosystems and biodiversity to environmental change? Challenge 7 spans geomicrobiology, micropaleontology (e.g., foraminifera), and even terrestrial realms. For example, Expedition 361 examined pollen and terrestrial indicators in Africa that document the impact of early human existence in the area. This particular challenge is so fundamental to traditional micropaleontology that it was not included in the specific outcomes for Expeditions 361, 353, 354, 356, 362, 363, although Challenge 7 was addressed in all of these.

Among the surface biosphere community, recent expeditions have provided great insight into human evolution by providing records proximal to the origin of humanity in eastern Africa for the first time (Expedition 361 drilled on two deltas off east Africa). Expedition 361 site U1477 also provided excellent LGM records. Finally, Expeditions 353, 354, 356, 361 and 363 all provided an understanding of the monsoon system and the response of the surface biosphere to its development.

Expedition 353 sought to establish an Oligocene-present astronomically-tuned time scale and to integrate high-resolution calcareous and siliceous microfossils into global compilation studies of paleoclimatic and biotic evolution, although the sediments are likely Miocene age. Expedition 354, which assessed the impacts of high preservation and burial of organic matter on the deep biosphere, also has a link to Challenge 7.

Theme-wide accomplishments: During IODP, Expeditions 360 and 366 both had primary biosphere objectives, as do upcoming drilling programs in Guaymas Basin and the Gulf of Mexico (Expeditions 385 and 386). As evidence for enthusiasm within the field, the successful integration between the deep biosphere communities involved in IODP, including the NSF-funded Center for Dark Energy Biosphere Investigations (C-DEBI), and the Keck-funded Census of Deep Life (CoDL), have helped to greatly advance science in the field over the past eight years.

Biosphere frontiers research is a newer addition to the *JOIDES Resolution*, and it has taken time for researchers to develop methods for sampling and analyzing samples while minimizing potential contamination from drilling fluid. Thus, many high-profile papers in recent years have focused on expeditions that occurred towards the end of the Integrated Ocean Drilling Program (2004-2013). Among those highlights are: 1) the discovery that oxygen likely penetrates to basement for up to 37% of seafloor sediments (Expedition 329, South Pacific Gyre); 2) characterization of microbial communities and their activities in young, cool and oxic ridge-flank basement (CORKs installed during Expedition 336, Mid-Atlantic Ridge Microbiology), rates of oxygen consumption in basement (Expedition 336, Mid-Atlantic Ridge Microbiology); and 3) the discovery that subseafloor microbial communities are dynamic over time (from CORK observatories installed during Expedition 327, Juan de Fuca Ridge-Flank Hydrogeology). Microbiology as a field within the IODP community is blossoming and there have been several recent expeditions focused on microbiology on the *Chikyu* (Expedition 370, Temperature Limit of the Deep Biosphere off Muroto) and on mission-specific platforms (Expeditions 347, 357 and 364).

Respondents to the community survey noted the importance of including microbiology and biogeochemistry on IODP expeditions in which biosphere objectives are not primary, to allow work with live samples on board. This approach has allowed the community to begin to obtain a faster and more accurate understanding of the extent, characteristics and activities of the deep biosphere, while more biosphere-focused expeditions allow for tackling in-depth hypotheses. One respondent noted, "Probably the most exciting [scientific development] to me has been the identification of fungi in the deep subsurface - I would not have predicted that, and would certainly like to see these investigations continue, and that those investigations address Challenges 5 and 6 and perhaps 7, although it would be a stretch to relate any proven fungi found now to conditions that might have prevailed when they were buried. That relatively complex life can apparently exist at depth is really something new."

Merits of the *JOIDES Resolution*

Many technical developments and improvements related to Biosphere Frontier challenges have occurred since the initiation of IODP. Improvements in the quality of cores, especially from half-length APC, now provide better orbital chronologies, thus allowing for calculations of rates of change of a variety of processes and proxies. Half-length APC has reduced contamination of cores in deep sediments by allowing sample recovery from depths previously requiring XCB coring, which is known to be highly susceptible to drilling fluid contamination. It has also improved core-log integration, enabling improved biostratigraphy and benefitting microbiologists as well as the paleoceanographers and stratigraphers working on biosphere questions. Improved high-temperature sampling, fluid sampling in rocks, and techniques that improve recovery of hard rock, will be useful to researchers pursuing Biosphere Frontiers challenges, as well as those related to other themes.

As stated, contamination is an ongoing challenge for microbiology on the *JOIDES Resolution*. Along the lines of technical developments that improve contamination control, a different contamination tracer, perfluoromethyldecaline (PFMD), has been tested on Expeditions 360 and 366 as a potential replacement for the standard perfluoromethylcyclohexane (PMCH). This tracer is less volatile and potentially easier to measure, but further testing will be required before it is fully implemented. In addition, construction of an overpressured sampling area with HEPA filtered air for Expedition 360 provided a cleaner working environment for microbiology sampling, although there were problems with the same system during Expedition 366. This unit may prove valuable for future expeditions if it can be standardized.

The *JOIDES Resolution* recently purchased and installed a scanning electron microscope (SEM), which has provided outstanding images of forams and other microscopic fossils. These are important for research, enabling fossil identification and documentation of preservation, but perhaps more so for outreach and communication with the public. There has also been an improvement in imaging systems overall, resulting in outstanding images of core sections and also microbial isolates growing on solid agar in petri dishes.

The CORKs installed during earlier phases of IODP have continued to yield transformative science with subsequent cruises. While the follow-up cruises are not with the *JOIDES Resolution*, the community notes the value of the *JOIDES Resolution* in drilling the original boreholes and installing the CORKs and the newer, lower-cost CORK-Lites. For deep biosphere work, CORKs installed during Expeditions 301, 327, and 336 have provided numerous high-profile publications, and we look forward to results from the recently installed CORK-Lites on Expedition 366.

The *JOIDES Resolution* can operate in a broad range of water depths globally, providing a flexible platform to address a remarkable range of science goals. However, there are some barriers that cannot be breached. For example, a limitation of the *JOIDES Resolution* is its inability to drill in more than 6 km of water. Another limitation is berth space and staffing of technicians with appropriate technical knowledge for quick microbiology equipment repair. Several cruises were significantly impacted due to issues with running the gas chromatograph used for contamination testing.

Impact of Regional Operations

In general, regional drilling facilitates possible comparative studies that reveal larger biogeographical and biostratigraphic patterns and provide much more information about a given region than sporadic drilling efforts. Regional drilling allows the community to reach this end result sooner. Knowing where the ship is scheduled to operate also simplifies planning for proposal development, and this is especially effective for asking questions that are not location-specific (looking at sediments under gyres versus the continental shelf, etc.). It is also possible that the regional drilling will help attract new countries to participate in IODP if the *JOIDES Resolution* will be in geographically proximate waters for some time.

Perhaps the largest benefit to the Biosphere Frontiers theme from regional drilling resulted in a realization that accepted biostratigraphic chronologies from the Atlantic and Pacific are not readily applied to the Indian Ocean. Multiple expeditions detected similar anomalies in the Indian Ocean, which were detected and fixed. Because of this effort, an improved regional biostratigraphy emerged. Regional Indian Ocean drilling has also provided an understanding of the monsoon system and surface biosphere response to its development as a whole; single expeditions can observe one of its many regional dynamics, but multiple expeditions are required to synthesize a basin scale analysis. For deep biosphere studies, regional drilling also allows for planning to revisit previously drilled sites to install or service a CORK for borehole experiments.

Potential Facility Implementations

The movement into new ocean basins will surely impact Challenge 5 by increasing the geographic coverage of the ship. Upcoming drilling in the Southern Ocean and South Atlantic will enrich our knowledge, especially with expanded age ranges of basement sampling planned. The marine-terrestrial interaction can be advanced by drilling in the Amazon regime. Guaymas Basin drilling (Expedition 385) will impact all biosphere objectives, including limits of life. The crustal biome needs further investigation and remains behind the sedimentary deep biosphere community in terms of sites studied.

The Biosphere Frontiers community has expressed interest in exploring several broad scientific themes to achieve science plan objectives 5 through 7: 1) the ecology of organic-rich margin sediments; 2) metabolic rates in diverse subsurface environments; 3) comparing ecosystems subsisting on refractory versus labile carbon; 4) the microbiology of polar ecosystems; 5) microbiology across crustal ages (the majority of data are from young, <11 Ma, crust, with the exception of Expedition 330, mostly 65-80 Ma); 6) further investigation in gyres, including clay-rich sediments; 7) exploring the lower oceanic crust (including at Atlantis Bank); and 8) connections between the terrestrial and marine deep biosphere. Sampling for census work is needed in more regions in general, but the regional drilling plan will help fill in gaps in regions over the long term.

There is an overall interest within the Biosphere Frontiers community to learn about fundamental ecosystem structure, including metabolic processes, networks and interactions. The community views this as progress as it moves from determining not just "who is there," which remains an important question but is the one on which the most progress has been made, to "what they are doing" and how subsurface communities interact. There is a desire to synthesize data about microbial communities with reactive transport modeling for a deeper understanding of subsurface ecosystems.

There is also excitement about the development of high-pressure sample collection tools for the upcoming methane hydrate work in the Gulf of Mexico (Expedition 386), which may be valuable for deep biosphere work. The expedition includes the use of instruments that are not be standard on the *JOIDES Resolution*, but are in development and likely to yield exciting results.

Many of the Biosphere challenges will be addressed in the upcoming expeditions. The impact of acidification and history of oceanic productivity can all be addressed when the ship enters the Atlantic Ocean basin. The Southern Ocean ecosystem evolution will be addressed soon. Future drilling into Paleogene and Neogene in the northern Atlantic would be helpful to expand records from the Pacific. The influence of dust delivery can also be addressed in the equatorial Atlantic, as can investigations of seeps and hydrates, as well as overall carbon cycling. The metabolic web of subsurface ecosystems is still not well understood, nor is the potential for preservation of biomaterials amidst an active ecosystem.

Integrating biosphere objectives with other themes during drilling allows for successful serendipitous discoveries. It is still not well understood how the deep biosphere in the broadest sense is linked to regional and global scale processes and cycles, including volcanism, subduction, seismicity, sea level change and climate change. These processes all include volumetrically large and temporally long physical and chemical processes that may impact microbial communities known to survive for long time periods. *JOIDES Resolution*-supported research can help to understand these Earth system processes.

While improvements have been made to the *JOIDES Resolution* since 2013 for Biosphere Frontiers investigations, the community recognizes the pace of innovation is challenging for incorporation into standard operations on the facility. Acquiring high-quality samples for deep biosphere work benefits from the rapid evolution of sampling techniques and protocols, especially those that reduce contamination from all aspects of drilling. New chemical tracers for contamination control are being tested, but a single tracer may not be appropriate for all sample types. Increased training of geochemistry and microbiology technicians for running these different tracers may be required, and additional support staff may be needed for cruises with extensive tracer programs. The shipboard protocols to deal with contamination are improving as geomicrobiology becomes more common across all expeditions, but implementation of these tracers requires routine inspection and operation of equipment, including assuring that the gas chromatograph is working prior to leaving port. The maturation of protocols for dealing with contamination is evident by the recent purchase of a KOACH Instant cleanroom system. This portable system allows for clean sampling of cores once they are taken from the catwalk or core-splitting room.

Biosphere Frontiers science stands to benefit from drilling innovations for challenging settings. Investigating high-temperature limits to life requires tools that can collect samples from these extreme environments. These tools may also be useful for work outside of Biosphere Frontiers in the study of hydrothermal vents and deep basement, where temperatures are challenging for current equipment. Similarly, advances in drilling techniques that improve recovery in fractured rocks, and the development of tools to sample liquid in fractured rock, would likely be valuable across disciplines.

A desired enhancement to the facility is the expansion of storage systems essential to the long-term curation of microbiological samples. For dedicated biosphere expeditions, the addition of a -80°C freezer in the core repository would significantly enhance the value of an expedition, enabling the ability to generate results for many years post-expedition. Long-term curation would greatly benefit from deploying a Cells Alive Freezing System on the *JOIDES Resolution* to freeze samples to -80°C without damage from ice crystals, a common complication when samples are placed directly in a -80°C freezer.

For improvements in biostratigraphy, which are of value to both microbiology and surface biosphere objectives, there were multiple responses requesting on-board core-scanning XRF analyzers, as well as a high-resolution magnetic susceptibility tool. These would allow for better correlations between cores and borehole logging. There is also a desire for shipboard CT scanning, with the acknowledgement that it may be prohibitively expensive. However, CT scanning would improve analysis of core integrity and allow for determination of core sections of value because of interfaces, transitions, or other features of interest for microbiology.

A recent development affecting expedition planning has been the Convention on Biological Diversity's 2014 adoption of the Nagoya Protocol, which promotes the "fair and equitable sharing of benefits arising out of the utilization of genetic resources" to its signatories. In response, the JRSO has accelerated the expedition staffing schedule, in order to determine if members of the deep biosphere community will be participating on expeditions and performing experiments that are relevant to the Nagoya Protocol. The earlier staffing process will enable the JRSO to include such information when submitting clearance documents.

Earth Connections

The Earth Connections theme of the IODP Science Plan includes four challenges related to deep Earth processes and their impact on Earth's surface environment. The community survey and workshop recognized that all four of the Earth Connections challenges had been addressed by the *JOIDES Resolution* in the first phase of IODP. This reflects the high proposal pressure to study this theme in the Indio-Pacific region. Substantial advances on the theme's challenges have been made through multiple drilling expeditions to the South China Sea and the Izu-Bonin-Mariana (IBM) arc regions, highlighting the value of regional operations in IODP.

Contributions to date of the *JOIDES Resolution*

Challenge 8. What are the composition, structure, and dynamics of Earth's upper mantle?
Progress towards Challenge 8 has been made by recovering peridotite samples from serpentine mud volcanoes in a subduction forearc setting and from inferring mantle composition from basalt and gabbro samples. Drilling through the Moho and recovery of *in situ* mantle has not been achieved by the *JOIDES Resolution* in the current phase of IODP, although considerable progress was made in achieving drilling to the crust-mantle boundary at Atlantis Bank during Expedition 360. Mantle compositions and temporal variations were indirectly inferred from basalt compositions at several other locations (e.g., Expeditions 349, 351, 352, 367, 368).

South China Sea Expeditions 349, 367, and 368 drilled basaltic basement and overlying sediments, providing age constraints and samples for determining the origin of the igneous rocks during the transition from rifting to seafloor spreading. The samples suggest that igneous oceanic crust can form shortly after breakup even without evidence for a volcanic margin, although an alternate interpretation is that basalt overlies serpentinized mantle. Additionally, drilling reveals that off-axis seamount volcanism initiated after spreading stopped and lasted for ~4 m.y.

IBM Expeditions 351 and 352 recovered basement samples of forearc basalt and a variety of boninites related to subduction initiation and establishment of the early volcanic arc. All three northern IBM expeditions (350, 351, and 352) recovered volcaniclastic rock and ash sequences, which provide a detailed record of volcanism over the history of the arc.

Mantle science was also accomplished on individual expeditions. Expedition 360 drilled nearly 800 m of gabbroic rocks on the Atlantis Bank, and is the first of a planned multiple-expedition program to drill through the crust-mantle boundary at this location. Peridotites were recovered from drilling at serpentine mud volcanoes in the Mariana forearc during Expedition 366 that will reveal information about the sources of mantle related to subduction initiation, as well as deformation in the mantle in a forearc setting. Shipboard results suggest Australia experienced rapid subsidence and uplift as evidenced by biotic and sedimentological analyses during Expedition 356 on the northwest Australian shelf.

Challenge 9. How are seafloor spreading and mantle melting linked to ocean crustal architecture? Progress has been made in continental margin, proto-arc, and mid-ocean ridge settings in characterizing ocean crustal architecture and its relationship to mantle melting and tectonic setting. Expedition 360 recovered a long gabbro section that shows that magmatic accretion took place in a highly dynamic environment, beginning while the gabbros were partially molten and continuing as they cooled and were exhumed tectonically from beneath the rift valley floor. Overall, the gabbros are generally too fractionated to be in equilibrium with the mid-ocean-ridge basalt (MORB) hanging wall, reflecting a complex evolution beyond initial intrusion of basaltic melt. The section of oceanic gabbroic crust drilled by Expedition 360 will be compared to similar sections drilled elsewhere (e.g. Atlantis Massif and the Eastern Equatorial Pacific). This comparison is crucial for understanding variations in middle and deep crust related to variations in sea-floor spreading rates. IBM Expeditions 351 and 352 recovered basalts and dikes related to seafloor spreading in a subduction initiation setting for comparison to those related to sea-floor spreading at mid-ocean ridges. South China Sea Expeditions 349, 367, and 368 recovered basement samples addressing the rift-to-seafloor spreading transition.

Challenge 10. What are the mechanism, magnitude, and history of chemical exchanges between the oceanic crust and seawater? The chemical exchange between oceanic crust and seawater was directly addressed by sampling serpentine mud volcanoes in a subduction forearc setting, by unexpectedly drilling and recovering a deep section through a major fault zone in gabbro at Atlantis Bank, and through analysis of hydrothermal assemblages in igneous basement acquired during this phase of IODP.

Expedition 360 at Atlantis Bank drilled and successfully sampled a major fault zone that extended from 411 to 469 mbsf that appears to control an active hydrologic system. Three serpentine mud volcanoes were drilled during Expedition 366 with the goal of examining processes of mass transport and geochemical cycling within the forearc of the Mariana non-accretionary convergent margin. The emplacement of screened casing at the summits of three active mud volcanoes will provide sites for emplacement of CORK-Lites to allow monitoring of episodes of eruption at the mud volcanoes, determining the response to seismicity, and evaluating whether variations in fluid composition, rate of flow, and temperature/pressure changes affect subsurface microbial populations. Expeditions 349, 367, and 368 in the South China Sea, and Expeditions 350, 351, and 352 in the IBM region recovered hydrothermal assemblages in basement and volcaniclastic sediment samples that also will be used to address this challenge. Ongoing analyses of these samples are addressing the causes of subduction initiation as well as the evolution of fluid-fluxes in the early arc.

Challenge 11. How do subduction zones initiate, cycle volatiles, and generate continental crust? Considerable progress was made towards understanding subduction initiation in the Izu-

Bonin and Tasman Sea regions, and volatile cycling was addressed in a subduction forearc setting. The genesis of continental crust was investigated through the volcaniclastic record in the Izu-Bonin region. The three IBM Expeditions (350, 351 and 352) contributed significantly to our understanding of subduction initiation, the evolution of elemental recycling through subduction zones, and ultimately, how and when crust with continental affinities is generated in an island arc. A robust volcaniclastic record was collected during the IBM expeditions, which will document changes in lava composition as the magmatic arc evolved from infancy through maturity and dissection, and thus how the nature of the arc crust changed through time. Drilling of serpentine mud volcanoes during Expedition 366 addresses volatile cycling in the Mariana forearc. Drilling during Expedition 371 in the Tasman Sea also addresses subduction initiation; this expedition was not discussed during the workshop as it was completed the first day of the meeting.

Merits of the *JOIDES Resolution*

The Earth Connections theme benefits tremendously from having a highly flexible drilling and analytical platform. Two new procedures have been implemented in IODP that have significantly improved drilling efficiency. The first was drilling in the casing and reentry system using an under-reamer and mud motor. The second was the use of a drill-in guide base to directly drill into hard rock. These engineering advances during the first phase of IODP save ~3-4 days of drilling time at each site compared to the standard procedure of drilling and then casing. This capability has been a major advancement in efficiency in this phase of the program. Core recovery was improved during this phase through use of the half-length APC in sedimentary sections. Core recovery for hard rock drilling is variable and dependent on rock conditions, especially faulting, but has been adequate to address all proposed scientific objectives.

Onboard analytical equipment facilitates decision making during expeditions for both drilling and sampling. Essential equipment includes the handheld XRF, the Inductively Coupled Plasma Atomic Emission Spectrometer (ICP-AES), the scanning electron microscope (SEM), petrographic microscopes and image-capturing capabilities, and core loggers for physical property measurements. Equipment improvements in the lab areas have markedly increased the analytical capability of the *JOIDES Resolution* and decreased the turnaround time for data collection. Many community members considered the addition of the SEM to be valuable, although energy dispersive spectroscopy (EDS) would enhance its value. The community also appreciated the enhancement in equipment and protocols for imaging core and core samples (e.g. thin section scans, optical and SEM photomicrographs). The addition of a handheld XRF for near real time chemical analysis was considered crucial in some expeditions for operational decision-making and targeting sample collection. The replacement of the ICP-AES in July 2017 has improved onboard bulk core compositional analysis. The new cryogenic magnetometer and broader implementation of non-magnetic core barrels has improved the capability of the *JOIDES Resolution* to study magnetic properties of core samples. The JRSO and the technical and shipboard staff are capable and professional, and are willing to work prior to and during expeditions to make sure that drilling is successful and scientific objectives are accomplished.

The new Deep Crustal Drilling Engineering workgroup will review the results of Expeditions 360 335 (Superfast Spreading Rate Crust 4) and make recommendations on how to successfully achieve drilling, coring, and logging deeper than 1.5 km into ocean crust hard rock environments. Drilling at single sites to these depths is essential for addressing challenges related to oceanic crust architecture and the upper mantle.

Impact of Regional Operations

Regional operations have been critical in advancing the Earth Connections theme by devoting substantial drilling effort to studying ocean basin development from expeditions in the South China Sea and oceanic island arc development from expeditions in the IBM. Regional operations have facilitated integrated expedition proposals and more science days. Key examples are IBM Expeditions 350, 351, and 352, which drilled the rear arc, back arc, and forearc of the IBM system. Some scientific objectives were shared between expeditions, such as determining the nature of the pre-existing crust and mantle prior to and after subduction. Planning for a Chapman Conference to integrate results from the three expeditions is underway. This approach should lead to a meaningful regional synthesis, and will be a component in a global synthesis of subduction initiation. The most progress in the Earth Connections theme was made on Challenge 11, largely because of the regional approach.

Regional workshops bringing together scientists from many disciplines allowed formulation of individual or related proposals addressing first-order problems from a multi-disciplinary viewpoint. Such workshops were critical in planning the regional operations in the South China Sea, the IBM system, and the South Atlantic. This approach led to detailed and integrated drilling plans and acquisition of site survey data. For example, following a workshop about drilling during ship transits, a South Atlantic seismic survey proposal was developed and funded in support of multidisciplinary drilling of paleoclimate, evolution of oceanic crust, and biosphere objectives along a South Atlantic transect.

Potential Facility Implementations

The Earth Connections workshop participants evaluated the potential science that could be accomplished along the proposed *JOIDES Resolution* ship track and modifications to the facility that would enhance these scientific targets. The community feels that the most critical scientific challenges are to synthesize results from past regionally or thematically related expeditions, which remains a challenge across all themes and challenges.

Challenge 8. There are locations where mantle can be drilled in the next five years, including exposures on the Southwest Indian Ridge and in the IBM back-arc and forearc. Advances in understanding mantle dynamics should be achieved by drilling hot spot seamount chains and large igneous provinces (LIPs) within the context of the new paradigm of large low shear velocity provinces (LLSVPs). Locations that might be drilled in the next five years include Agulhas-Transkei transect and Walvis Ridge hotspot.

Challenge 9. Deep drilling of gabbro and mantle on Expedition 360 and lower crust at Hole 1256D (Expedition 335, Superfast Spreading Rate Crust 4) would make progress on this challenge. Establishing the nature of the Moho is fundamental to advancing our understanding of this challenge – is it the crust-mantle boundary or an alteration front? Understanding the architecture of oceanic crust requires knowledge of the depth of serpentinization in oceanic plates and its impact on their seismic velocity structure.

Drilling of hot spot seamount chains and LIPs, and plume-related oceanic crust, could address this challenge. Drilling at Walvis Ridge, the Agulhas Plateau, and V-shaped ridges in the north Atlantic Ocean developed through interactions of the Iceland hot spot and the Mid-Atlantic Ridge could be carried out during the next five years.

Challenge 10. Upcoming scheduled drilling at Brothers Arc Flux (Expedition 376) and the Guaymas Basin (Expedition 385) will address this challenge. The crust-fluid interactions recorded in drill core are often not given a high priority during hard-rock expeditions. Fluid-rock interaction will be robustly studied during the upcoming Brothers Arc expedition. Additional progress could be made by drilling a transect of holes at different ages along oceanic crust formed at the southern Mid-Atlantic Ridge, and by deeper drilling at Atlantis Bank and Hole 1256D.

Challenge 11. Volatile cycling will be addressed by Expeditions 372 and 375 at the Hikurangi margin (hydrologic processes related to slow slip events), as well as during Expedition 376, to study fluid flux out of subduction zones. Additional progress could be made in the next five years by studying bend faulting and hydration at subduction zones in the Pacific Ocean basin. Drilling deep crust and mantle at the IBM forearc could further sample the crustal architecture associated with subduction zone initiation and provide additional insight into ophiolite genesis.

With regard to modifications to the *JOIDES Resolution* facility, the Earth Connections community commented on adjustments that primarily focus on the importance of better core recovery and deeper penetration while drilling hard rock, which would enhance success of many Earth Connections-related expeditions. The community urges upgrading the SEM to include energy dispersive X-ray spectroscopy (EDS) capability, which would allow rapid determination of solid phase compositions. Adding routine shipboard XRF core scanning to the *JOIDES Resolution* was also considered valuable by the Earth Connections community, but this needs to be evaluated against the cost in space and expedition resources. This request might be mitigated by more routine use of the hand-held XRF.

Earth in Motion

The Earth in Motion theme of the 2013-2023 IODP Science Plan addresses questions involving fundamental Earth system processes, including those underlying major geologic hazards that occur at timescales of seconds to years. The community survey and workshop recognized that some of these challenges had been addressed by the *JOIDES Resolution* during IODP, and that additional advances will be made as the facility moves into additional ocean basins. The workshop participants noted that upcoming scheduled expeditions and regions along the proposed ship track have the strong potential to significantly advance this theme.

Contributions to date of the *JOIDES Resolution*

Challenge 12: What mechanisms control the occurrence of destructive earthquakes, landslides, and tsunami? This challenge was addressed on Expedition 362, whose primary objective was to examine how the material on the incoming plate influences the seismogenic properties of a subduction zone. This objective was met by coring incoming lithologies and characterizing incoming material properties. Here, input materials are thick and warm such that dewatering and temperature-controlled diagenetic reactions have led to sediment strengthening prior to crossing the deformation front.

Challenge 13: What properties and processes govern the flow and storage of carbon in the subseafloor? Expeditions 354, 359, and 362 in the Indian Ocean documented stored carbon in sediment cores that are critical for better understanding the global carbon cycle. Expedition 366 documented carbon stored in the serpentinite mud volcanoes. These expeditions led to significant advances in our understanding of the properties and processes governing the flow and storage of carbon in the subseafloor.

Challenge 14: How do fluids link subseafloor tectonic, thermal, and biogeochemical processes? This challenge has been addressed on several expeditions. Expedition 366 confirmed deeply sourced fluids in serpentinite mud volcanoes. Expedition 362 documented the importance of dehydration reactions in modifying the physical properties and lithology of incoming sediments. Temperature measurements, lithology, mineralogy, and geochemistry of input sediments has led to a better understanding of dehydration, compaction, and diagenetic processes that are key players in controlling frictional properties along subduction zone faults. Expedition 354 discovered salinity anomalies revealing isolated flow paths in the subseafloor. Expedition 359 found pore water profiles suggesting advection of seawater into sediments is more complex than assumed in commonly accepted models.

Theme-wide accomplishments

The community survey and workshop participants both note that the most significant Earth in Motion accomplishments by the *JOIDES Resolution* during IODP are the knowledge advancements in subduction zones and subduction zone processes. These include characterization of input material (e.g., Exp 362) and the physical and chemical properties (e.g., compaction, diagenesis, pore pressure, *in situ* stress state) of those materials and fluids, leading to advanced understanding of subduction zone hazards and subduction initiation, and their relation to fluid flow.

Additional advances link Challenges 13 and 14. Expedition 366 characterized active mud volcanoes in a sediment-starved margin, and examined the relationship of the volcanoes and the serpentinization of those volcanoes to the fluids moving through the system. Finally, targeting Challenge 13, the *JOIDES Resolution* facilitated the significant discovery that considerable carbon is stored in the Bengal Fan organic matter (Expedition 354) and in the Bengal-Nicobar Fans (Expedition 362), and that subduction zones can act as significant carbon sinks. This was an unexpected discovery, since these expeditions were not specifically targeting Challenge 13 objectives.

Merits of the *JOIDES Resolution*

The Earth in Motion community was in agreement that specific merits of the *JOIDES Resolution* cut across all challenges within the theme. The *JOIDES Resolution* is the most cost-effective vessel in the world capable of recovering and analyzing continuous cores to target depths. Complete recovery of cores at relatively low cost is essential for achieving many of the scientific challenges of this theme. The *JOIDES Resolution* is nimble in its ability to effectively core in many different environments that address a myriad of scientific objectives. Essential drilling capabilities for Earth in Motion challenges include fault zone drilling and drilling for the installation of observatories. The community was in agreement that measurements of physical properties and fluid chemistry in near real time is an important capability for achieving scientific challenges. One example of the effectiveness of the *JOIDES Resolution* in this regard is illustrated by the recovery of the full stratigraphy and characterization of subduction zone inputs at the Sumatra sites during Expedition 362. The community also emphasized the importance of outreach and education from the *JOIDES Resolution*.

The community feels that scientific and technical developments facilitated by the *JOIDES Resolution* span the full range of challenges within the Earth in Motion theme. For Challenges 12 and 14, the most important developments have been technological efficiencies and improvements to the operation of the facility. These developments include, but are not limited to, the ability of the *JOIDES Resolution* to drill-in casing, coupled with the hydraulic release tool, which facilitates access to deeper sediments without the need for separate casing drilling. These developments in turn have improved the ability of the *JOIDES Resolution* to install observatories such as CORKs and have made the *JOIDES Resolution* the most efficient and successful observatory-installing facility. Drill-in casing and the half-length APC have also improved core recovery and logging abilities in deep holes. This capability has allowed recovery of detailed stratigraphy and mass transport deposits that allow assessment of carbon storage in submarine fans. Also, deep-sea cameras have allowed easier re-entry to the sites, which similarly improves core recovery at depth as well as efficient and cost-effective installation of the observatories. The community also recognizes the notable advances in *JOIDES Resolution* operations, which have not yet been fully tested but which represent significant leaps forward in the ability of the community to sample and work in overpressured regimes. These tools include pressure-coring tools, the motion decoupled hydraulic delivery system (MDHDS), and the temperature-2-pressure (T2P) tools, which will be deployed by the *JOIDES Resolution* on upcoming expeditions and further enhance the efficiency and the ability of the *JOIDES Resolution* to address the themes in the IODP Science Plan.

Impact of Regional Operations

The Earth in Motion community was in agreement that regional operations have enhanced the scientific outcomes relating to this theme. One benefit is longer planning periods for expeditions, particularly important in light of the complex drilling and engineering often encountered in subduction zone environments. This increases planning ability for specialty tools (e.g. Expeditions 372 and 375 on the Hikurangi margin), such as logging-while-drilling (LWD) tools, and emplacement of observatories. Science party interactions and collaborations with set resources have also benefitted from the long planning periods. A regional approach also fosters an increased number of proposals in a given area because proponents know where the ship will be, and longer-term planning is therefore possible to acquire site characterization data. This aspect builds strong communities that can cross science themes, leading to a better understanding of integrated Earth systems and enhanced in-reach and outreach. A regional approach also encourages the participation of the smaller IODP member nations and consortia. The community also recognized the increased ease of adding Ancillary Project Letters (APLs) to integrate and synthesize with other expeditions (e.g., the integration of carbon cycle questions with paleoceanography expeditions).

Regional planning does have some trade-offs; important science might not be accomplished quickly and/or the *JOIDES Resolution* might move out of a region before objectives can be fully realized. An example of this is Expedition 360, where the target drilling depth was not reached and it will likely be some time before the *JOIDES Resolution* returns to the area to complete deep drilling. Importantly, the community noted that although relatively few Earth in Motion-themed expeditions have been drilled thus far in IODP, upcoming expeditions in the Hikurangi area (in 2018) and elsewhere (in 2019-20) will begin to alleviate this issue.

Potential Facility Implementations

The community and workshop participants evaluated the potential science that could be accomplished along the proposed ship track and modifications to the facility that would enhance these scientific targets. The community feels that the most critical scientific challenges are to understand the spectrum of slip behavior and hazards (**Challenge 12**) and to be able to take *in situ* and time-series measurements to understand seismogenesis, tsunamigenesis, marine volcanism, hydrothermal circulation, and ore formation.

Within **Challenge 12**, there is a need to evaluate the range of slip behavior observed at convergent margins, including Cascadia, the Caribbean, the Aleutians, the Mediterranean, and Mexico); Scheduled drilling at the Hikurangi margin with its emphasis on slow slip events addresses part of the range of slip behavior. Active APLs target slip behavior at Costa Rica (e.g., proposal 908-APL) and a full proposal is in the system to better understand at the Kanto region (proposal 770-Full3). Landslides are an important geohazard and active proposals include targeting the Cape Fear Slide (proposal 811-Full). Other important landslides are in the Aleutians, Sahara slide, and Lesser Antilles. A priority within all of these is investigating the preconditioning and driving mechanisms for slope instability that generates mass transport deposits and larger slides. Lastly, the community commented on the need to engage and excite the public, particularly when the science results relate to geohazards (Challenge 12).

The critical scientific challenges for the *JOIDES Resolution* under **Challenge 13** are to investigate the storage and flow of carbon in gas hydrates and their relationship to the biogenic carbon factory. Upcoming exciting science addressing the flow and storage of carbon in the subseafloor includes *in situ* subsurface monitoring with CORKS at the Hikurangi margin. The biogenic factory, gas hydrate systems, and other parts of carbon cycles will be addressed during Expedition 386 in the Gulf of Mexico, which is focused on large-scale fluid flow between sands and shales and how it couples to the biogenic factory. An additional challenge is to investigate the role of the lower crust in the carbon cycle and to study the carbonation potentials of peridotites and serpentinites. Active proposals addressing this challenge include methane cycling generally (e.g., 791-APL, 836-APL) and those targeting the Beaufort margin (e.g., 797-Pre, 806-Pre) and Argentine margin (910-Pre). Other proposals within this theme address the role of hydrothermal fluids in carbon cycling (833-Full2) and serpentinization at bend faults (876-Pre).

Within **Challenge 14**, upcoming exciting science will include drilling at Hikurangi (Expeditions 372 and 375) and exploring the relationship between fluid pressure and slow slip. *In situ* subsurface monitoring of fluids with CORKs is an important component of this research and the installation of CORK-Lites, enabled by the *JOIDES Resolution* at Mariana, and the potential for such installations at, for example, Cascadia, Alaska and the Caribbean, is exciting. Active proposals addressing this challenge include 633-Full2, which targets the Costa Rica mud mounds and is designed to provide insights into deep fluid processes and their links to tectonics. Proposal 769-APL targets the role of upper lithosphere structure in governing fluid flow and chemical flux at the Costa Rica Rift. Other exciting science includes the role of bend faults in the chemical hydration-linked reactions in cold lithospheric mantle and overlying ocean crust. Bend-faults appear to play a key role by providing high-permeability pathways for seawater to flow into the oceanic crust and uppermost mantle. These processes hydrate the lithosphere just prior to subduction and may influence the tectonics of convergent margins.

With regard to modifications to the *JOIDES Resolution* facility, the Earth in Motion community commented on adjustments that spread across the specific challenges, primarily focusing on the importance of measuring *in situ* properties. Development of tools beyond CORKS for *in situ* measurements (e.g., pressure, temperature, and fluids) and preparing holes for measurements (e.g., mud program) is needed. Community members also commented on the importance of oriented cores for APC, half-length APC, and XCB nonmagnetic coring equipment. Quality core depends on good heave compensation and the community was in agreement that heave compensation was an area where ongoing investment would keep core quality high. Other community members noted better partnerships with industry could be developed; that an ROV for re-entry, wide diameter logging tools, and other inexpensive logging tools could be investigated. The community also felt that the ability to image cores was important (e.g., by CT scanner) to allow identification of faults, slip zones, 3D structure, and orientation, and to obtain porosity data and guide cutting of cores.

Section IV: Increased Efficiencies and Effectiveness in IODP

IODP has a more efficient, cost-effective and rigorous evaluation process than its predecessor programs for reviewing proposals from the community. The panel structure has been streamlined, reducing the number of advisory panels to just two—the Science Evaluation Panel (SEP) and Environmental Protection and Safety Panel (EPSP), both of which report to the *JOIDES Resolution* Facility Board (JRFB). By combining broad expertise in IODP science and site survey data, the SEP effectively merges science evaluation and site characterization into a single peer-review process while including input from the *JOIDES Resolution* Science Operator. This combination provides direct evaluation of the proposed scientific objectives in the context of available site data and the drilling capabilities of the *JOIDES Resolution*. New guidelines allow flexibility in required data, with specific requirements tailored to the objectives. This process provides more effective guidance to proponents, who now receive input from one evaluation panel, improving communications between the SEP review process and the community. As a result, this new system not only enhances the nurturing and development of proposals, it also provides increased efficiencies in the evaluation of proposals and reduction of time between submission and sailing. Typical proposal residence times in the system are now approximately four years from initial submission until the actual expedition on the *JOIDES Resolution* for excellent proposals, compared to approximately ten years during the Integrated Ocean Drilling Program. The increased efficiency and flexibility of the review process has allowed expediting of proposal reviews, without decreasing quality, to fit within the regional ship track. Some proposals have moved through the system in fewer than three years, which has enabled more efficient and cost-effective ship operations.

SEP and the JRFB have developed a mechanism for the influx of non-IODP funds to the program via Complementary Project Proposals (CPPs). CPP customers, which have included industry, international partners, and other governmental agencies, are provided with extra berths and an opportunity to propose expeditions that focus on specific, scientifically relevant areas that may not have been targeted through the routine IODP proposal submission process. These proposals must address objectives of the IODP Science Plan and they receive the same rigorous evaluation and peer review as all other IODP proposals. The addition of the CPP mechanism has allowed for the inclusion and funding of several expeditions in recent years, and is expected to fund additional expeditions and tool development in the future.

SEP and the JRFB have also developed a new mechanism to synergize with onshore drilling supported by the International Continental Drilling Program (ICDP), via the implementation of Amphibious Drilling Proposals (ADPs). ADPs address scientific objectives that can only be accomplished by drilling both onshore and offshore. Currently, there is one active ADP in the IODP system that uses the *JOIDES Resolution* (proposal 895-Pre), and additional submissions are anticipated in the future.

Ancillary Project Letters (APLs) have increased the flexibility of the program to implement short but highly relevant, and often time-sensitive, topics. These proposals constitute less than 15%

of the time of a typical expedition (fewer than nine days, including additional transit time) and have provided high profile, efficient use of the *JOIDES Resolution* without significantly impacting the primary expeditions. An excellent example of this is the Agulhas LGM Density Profile drilled as part of Expedition 361. In addition to encouraging the submission of APLs, IODP also encourages other proposals that may require less or more time than the conventional 61-day length expedition. The JRFB has exhibited considerable flexibility in integrating multiple objectives into expeditions.

Effectiveness of regional operating model toward understanding regional to global-scale science

In 2012, seventy-three representatives of the U.S. scientific community assembled for a workshop in Denver, Colorado. That workshop, entitled "Building U.S. Strategies for 2013-2023 Scientific Ocean Drilling," served to prioritize the 14 scientific challenges outlined in *Illuminating Earth's Past, Present, and Future*, the 2013-2023 IODP Science Plan; to identify new approaches for more efficient planning of scientific ocean drilling expeditions; and to encourage drilling proposals that would achieve the goals of the IODP Science Plan while saving costs and enhancing science return through an efficient ship track.

Based on recommendations from the 2012 workshop, new operational and programmatic approaches have been implemented that make the *JOIDES Resolution* Facility more efficient and cost effective in planning expeditions. Since the inception of IODP, significant progress has been made toward addressing the highest priority scientific challenges of the IODP Science Plant and additional critical expeditions using the *JOIDES Resolution* have been scheduled for execution up to mid-2020 (http://iodp.tamu.edu/scienceops/index.html). The *JOIDES Resolution* is now scheduled based on a regional ship track that projects the ship track five years into the future and will circumnavigate all ocean basins during the 2013-2023 IODP Program. The *JOIDES Resolution* ship track is widely advertised and its early announcement, along with the commitment to visit every ocean basin in this current phase of ocean drilling, has aided the scientific community in developing cooperative, regional and inter-disciplinary strategies early in the planning process. Extending the IODP planning horizon also has allowed for the scheduling of more multidisciplinary and technically challenging expeditions (e.g., Hikurangi margin), which require longer lead times for technology development and site characterization, and more opportunities to seek external funding or other resources.

Regional planning has also minimized transit time between expeditions, resulting in significant savings in fuel costs while maximizing the time that the ship is conducting science operations. Together with the new source of additional income ($30M) from co-sponsored CPPs by *JOIDES Resolution* international partners and the Department of Energy (DOE), as well as significant cost saving efficiencies realized by the JRSO, the operation time of the *JOIDES Resolution* has been increased from 8 months per year to 10 or more. This has allowed the JRSO to achieve the budget reductions requested by NSF in response to the recommendations from the National Research Council's report, *Sea Change: 2015-2025 Decadal Survey of Ocean Sciences.*

Unrecognized efficiencies

Unexpected efficiencies have also resulted from the decision-making progress of *JOIDES Resolution* operations, where daily operational decisions are mostly decentralized and entrusted to the ship-based scientific party and JRSO staff. This is largely attributable to the work of the SEP and EPSP in pre-approving numerous alternate sites, and the JRSO in securing requisite and often challenging clearances. Thus, an expedition leaves port with a set of defined scientific objectives and a deep portfolio of pre-approved primary and secondary drilling sites, allowing for a high degree of decision making entrusted to the scientific party without the need for renewed shore-based review. The scientific staff have the freedom to adapt the drilling plan with the advice of the Expedition Project Manager and *JOIDES Resolution* support staff in order to maximize the scientific return based on the knowledge gained from early drilling and operational considerations that develop over the course of the expedition. This efficient management and decision-making structure is congruent with and perhaps essential for continuing to achieve "more with less."

Section V: *JOIDES Resolution* Contribution to Addressing Priorities Identified in the *Sea Change* Report

In 2015, the National Academy of Sciences published *Sea Change: The 2015-2025 Decadal Survey of Ocean Sciences*, a report that included eight priority ocean research questions for the coming decade. Ordered from the ocean surface to the seafloor, the following questions were identified:

- What are the rates, mechanisms, impacts, and geographic variability of sea level change?
- How are the coastal and estuarine ocean and their ecosystems influenced by the global hyrodrologic cycle, land use, and upwelling from the deep ocean?
- How have ocean biogeochemical and physical processes contributed to today's climate and its variability, and how will this system change over the next century?
- What is the role of biodiversity in the resilience of marine ecosystems and how will it be affected by natural and anthropogenic changes?
- How different will marine food webs be at mid-century? In the next 100 years?
- What are the processes that control the formation and evolution of ocean basins?
- How can risk be better characterized and the ability to forecast geohazards like mega-earthquakes, tsunamis, undersea landslides, and volcanic eruptions be improved?
- What is the geophysical, chemical, and biological character of the subseafloor environment and how does it affect global elemental cycles and understanding of the origin and evolution of life?

The *JOIDES Resolution* is ideally suited to address *Sea Change* Priority Questions 1 and 3. Understanding sea level and ocean-climate variability both require long, continuous sediment records to evaluate environmental change. Other ships are capable of addressing some elements of these fields using piston and Calypso-type cores, especially over the last few glacial-interglacial cycles (e.g., generally < 1 Myr), but cannot provide information on the operation of the ocean-climate system on longer time scales. Similarly, cabled Ocean Observatory Initiative (OOI) and submarine vehicles, particularly gliders, focus more on data collection in real time than on collection of sediments and samples from deep time. Only scientific ocean drilling can recover deep (>100m) records of the operation of the global ocean-climate systems under various climate states, including intervals of past great warmth and high CO_2. Similarly, only drilling can obtain pre-Pleistocene records and an understanding of the evolution of the cryosphere and sea-level change from an ice-free state with small global sea-level changes (< 25 m) to a bipolar world with large (> 100 m) sea level change.

***Sea Change* Priority Question 1: What are the rates, mechanisms, impacts, and geographic variability of sea level change?** Sea level change was addressed on Expeditions 356, 359, 361 and 363. Sea level change was a primary objective of Expedition 359, which has provided a record of the changes in a carbonate platform in response to large Neogene (past 23 Myr) sea level change. Drilling on Expedition 356, 361, and 363 provided additional insights to the record of sea level change. In particular, Expedition 356 recovered exceptionally thick (i.e., higher temporal resolution) Pleistocene sediments that record glacial-interglacial cycles on the western Australia margin and aid in understanding the regional response. The identification of orbital scale variation in planned high-resolution cores helps determine controls on ice sheet volume, and also contributes to data/model iterations and the relationship to climate-weathering links (Expedition 363). Recovery of cores from low-latitude sites with high sedimentation rates and temporal resolution comparable to high latitude ice cores (Expeditions 356, 361, and 363) fleshes out the broad global geographic view of ice sheet and climate dynamics.

In addition to identifying the direct records of sea level change (carbonate platforms, glacial-interglacial sediment change), the *JOIDES Resolution* can also contribute to separating various influences on sea level change by recovering records from particular regions where each influence is thought to be the most important or evident. More specifically, the *JOIDES Resolution* can investigate ice sheet instabilities in the past and their potential causes. This includes establishing rates and magnitudes of sea level changes during rapid (suborbital) climate changes (e.g., during Heinrich events and Marine Isotope Stage 3), and investigating mechanisms and rates of Cenozoic open-ocean responses to changes in the cryosphere. Drilling in different regions allows for the linking of more proximal and more distal records (e.g., drifts) and to investigations of associated changes in deep-water circulation and chemistry. Scheduled drilling of three Antarctic expeditions and planned drilling of two more, along with one APL, will provide an unparalleled view of the Southern Ocean ice-sea interactions and the history of the Antarctic ice sheet, including time intervals when the continental ice sheets were much smaller and sea-levels commensurately higher (e.g., early Pliocene ca. 3 Ma; early-middle Miocene, ca. 17-15 Ma).

The regional approach allowed for some expeditions (e.g., Expedition 359) to focus on sea level change, but allows for the development of complementary data from allied expeditions in the same geographic region. Thus, although sea level may not be a primary focus of certain expeditions, the patterns of sedimentation provide critical insights to aid in deeper understanding of the targeted sea level objective.

***Sea Change* Priority Question 3: How have ocean biogeochemical and physical processes contributed to today's climate and its variability, and how will this system change over the next century?** Cores obtained by *JOIDES Resolution* are a unique and necessary source for generation of high-resolution paleoceanographic and paleoclimatological analyses. The *JOIDES Resolution* is the only platform to reliably recover high-resolution, high-quality continuous records in a range of environments and water depths to investigate climate over million-year time scales at Milankovitch to centennial-scale resolution. The continuity of the cores allows for the construction of an astronomical chronology, providing the foundation for analysis of organic burial rates and linkages between terrestrial and marine systems (e.g., uplift, weathering, and its impact on ocean chemistry). The *JOIDES Resolution* is the only platform that provides the volume and quality of core needed to obtain insight into deep-time, deep ocean chemistry-disturbances (e.g., nature and cause of oceanic anoxic events; Southern Ocean role in biogeochemical cycles) that have important implications for understanding our modern system and the type, scale, and rates of change possible.

Expeditions 361, 353, and 363 obtained material that will place constraints on the carbon budget, especially CO_2 records. Our understanding of high CO_2 worlds is possible only because of the high-quality coring capabilities of the *JOIDES Resolution*. The *JOIDES Resolution* allows access to deep-sea archives in each of the ocean basins, which is essential to understand the complex interactions between the atmosphere, hydrosphere, and cryosphere under higher CO_2 conditions. Future *JOIDES Resolution* drilling will investigate Miocene and pre-Neogene intervals of global warmth in all the major ocean basins. Recent *JOIDES Resolution* drilling allows us to test the relationship between ancient times of elevated CO_2 and climate by providing continuous, well constrained sedimentary archives from some key regions and time intervals (e.g., late Miocene to Recent, 10-0 Ma). A variety of proxies to reconstruct past sea surface temperature and pCO_2 have been developed and tested using deep-sea sediments, most of which are from ocean drilling. In addition, mapping climatic and ecological consequences of variable CO_2 levels in the Earth's past requires improved geographic coverage, particularly in high latitude regions that are presently under-sampled.

Expeditions 359, 361, 363 and 356 focused on ocean circulation. Scientific ocean drilling provides important insight into modern ocean circulation by constraining past patterns of deep ocean hydrology and intermediate water mass structure and chemistry (e.g., Atlantic meridional overturning circulation). Proposed future drilling will provide material to more firmly constrain latitudinal gradients (tropics-poles), allowing for better interpretation of ocean systems. Proxies allow for interpretation of past changes, but often are impacted by changes that occurred during storage; thus, obtaining fresh core material is critical for continued proxy development.

Expeditions 346, 353, 354, 355, 356, 361 362, and 363 have assessed the regional Asian, Australian, Indian, and African monsoon systems. The wide geographic coverage provided by this overarching mission to understand the monsoon allows deciphering the local, regional, and global causes and effects of changes in the evaporation-precipitation budget. Similarities and differences in the timing and response of monsoonal changes from East Asia through the Arabian sea testify to the efficacy a regional focus on a major scientific issue.

***Sea Change* Priority Question 5: How different will marine food webs be at mid-century? In the next 100 years?** Although the *JOIDES Resolution* is not identified by the *Sea Change* report as a primary element of the research infrastructure for understanding biodiversity and marine ecosystem, cores obtained by ocean drilling are ideally suited to evaluate the biotic response and resilience to environmental perturbations, particularly temperature, CO_2, and sea level. Two of the four IODP Science Plan themes address biological interactions and evolution: 1) Biosphere Frontiers: Deep Life and Environmental Forcing of Evolution; and 2) Climate and Ocean Change: Reading the Past, Informing the Future. The long records that the *JOIDES*

Resolution recovers allow researchers to track evolutionary changes and associated oceanic and climatic changes through time, potentially providing answers to questions regarding biological response and sensitivity to sustained elevated greenhouse gases. The deep time approach provides the foundation for understanding the patterns of evolution, and the ability of species to recover after major environmental and chemical perturbations, such as the oceanic anoxic events and the Paleocene Eocene Thermal Maximum. Scientific ocean drilling on continental margins provides an opportunity to link the marine and terrestrial biospheres (Expeditions 353, 354, 356, 361, 362, and 363). The reorganization of eukarytoic phytoplankton food webs in response to such perturbations may inform our understanding of food webs of the future. The burgeoning field of geomicrobiology is beginning to address these issues at the molecular and cellular level as well (Expeditions 349, 360, and 366), and provides constraints on the limits of life in regions inaccessible by other vessels. Thus, the *JOIDES Resolution* is a critical infrastructure asset for biodiversity, and an asset in support of food web investigations.

***Sea Change* Priority Question 6: What are the processes that control the formation and evolution of ocean basins?** This priority was identified by *Sea Change* as a question that the *JOIDES Resolution* is uniquely suited to address. This question also is a component of the Earth Connections theme of the IODP Science Plan. Since the beginning of IODP, ocean basin evolution has been addressed on ten expeditions in the Western Pacific and Indian Ocean. Scheduled and potential future expeditions along the current ship track include the south Atlantic/Indian Ocean (Agulhas Plateau; Walvis Ridge; Atlantic Bank), western Pacific (Brothers Arc, Hikurangi, IBM), eastern Pacific (Costa Rica; Gulf of California; EPR; northeast Pacific/Aleutians), and North Atlantic (Reykjanes Ridge).

The *JOIDES Resolution* is critical for studying ocean basins because it recovers data and samples from demanding sub-seafloor environments. Drilling and coring methods continue to evolve to sample the transition from sediment to fractured and/or intact igneous oceanic crust. The primary merit of the *JOIDES Resolution* in addressing these priorities is its ability to collect spatially oriented, fresh rock samples and *in situ* data with multi-dimensional drilling that can be used to extend interpretations of regional geophysics to beyond the borehole. Collecting data and material in a rigorous stratigraphic context is difficult for other ocean science facilities (e.g., submersibles, ROVS, dredges). For example, Expeditions 350, 351 and 352 to the IBM collected thousands of stratigraphically controlled tephra and rock samples, including dozens of fresh volcanic glasses tied to the regional geophysical (seismic refraction and reflection) record that will allow a synthetic view of how subduction zones initiate and continental crust is formed within oceanic basins. Deep subseafloor drilling in this type of fractured and hard rock is technically very challenging, yet the *JOIDES Resolution* excels at this because of its operational flexibility and the institutional knowledge and experience of the drillers and shipboard technicians. Expedition 360, on the slow-spreading SW Indian ridge, drilled nearly 800m of gabbroic rocks, a first time accomplishment in scientific ocean drilling. This is the current record for the deepest penetration into basement made during a single drilling leg. Expeditions 349, 367 and 368 in the South China Sea explored evolution of crust and mantle during various stages of continent rifting and basin evolution by recovering basalt and evidence of post-spreading volcanism from multiple >1 km deep holes. Expedition 366 drilled serpentine mud volcanoes in the IBM forearc, investigating the transfer of fluids and solid materials from the subducting plate to the upper plate, serpentinization of upper-plate mantle, the transfer of these materials to the surface in serpentine slurries, and the associated deep biosphere.

***Sea Change* Priority Question 7: How can risk be better characterized and the ability to forecast geohazards like mega-earthquakes, tsunamis, undersea landslides, and volcanic eruptions be improved?** The *JOIDES Resolution* is well suited to address global geohazards, a component of the Earth in Motion theme of the IODP Science Plan. The geohazards theme has been addressed on Expedition 362 where it documented the role of subduction zone inputs (i.e., sedimentary pressure, temperature, lithology and fluid chemistry) in controlling shallow slip and tsunamigenesis. Although Expedition 362 drilled well seaward of the deformation front, the science party documented ongoing diagenetic and dehydration reactions leading to strengthening of material that promotes shallow slip. Upcoming Expeditions 372 and 375 to the Hikurangi subduction margin near New Zealand, will explore the phenomenon of slow slip on a subducting plate boundary, through drilling to sample and monitor both the forearc and the subducting plate. Monitoring will occur through installation of borehole observatories in the frontal thrust and upper plate above the slow slip source area. Tsunamis are most commonly generated from earthquakes that rupture shallowly, as observed at Sumatra.

The proposed ship track over the next five years puts the *JOIDES Resolution* in position to explore geohazards at other convergent margins and at sites of large landslides. Examples include the ability to evaluate the range of slip behavior at locations such as Cascadia, the Caribbean, the Aleutians, the Mediterranean, Mexico, and Japan, and landslide processes at the Aleutians, the Cape Fear slide, the Sahara slide, and the Lesser Antilles.

The *JOIDES Resolution* is the most cost-effective platform in the world for addressing the wide range of geohazards under consideration. It excels at complete recovery of cores at relatively low cost. It routinely takes continuous cores to depth and provides the facilities for core analysis and physical property measurements. It has the capability to measure, in real time, temperature, pressure, and fluid chemistry *in situ*, coupled with ability to recover fault zone cores and other downhole data. Together these data provide the community with the ability to characterize subduction zone input material and the geochemical and diagenetic changes in the evolving strength of the incoming plate, as was done on Expedition 362. Essential drilling capabilities include fault zone drilling and drilling for the installation of observatories, such as those planned for Expedition 375.

***Sea Change* Priority Question 8: What is the geophysical, chemical, and biological character of the subseafloor environment and how does it affect global elemental cycles and understanding of the origin and evolution of life?** The *JOIDES Resolution* is actively exploring the geophysical, chemical, and biological character of the subseafloor environment. These concepts are key challenges in the Biosphere Frontiers theme of the IODP Science Plan and are addressed through multiple IODP drilling platforms. In the past four years, this theme has been explicitly explored using the *JOIDES Resolution* on Expeditions 360 and 366. Expedition 360 drilled into high pH oceanic crust to examine if there is life in the lower crust and hydrated/serpentinized mantle. A primary objective was to determine the microbiology of the lower crust across all three domains of life. The expedition recovered carbonate veins in rocks that are sites of past and present fluid movement along cracks and fissures, and these are sites of particular interest for microbiologists, as they may represent zones where deeply circulating seawater may deliver carbon and energy sources crucial for sustaining a microbial biosphere. Microbiology sampling during Expedition 366 focused on exploring the limits of microbial life in serpentinite mud habitats across multiple depths. Sampling efforts targeted both near surface and deeper whole-round cores, especially if there was evidence of transitions across gradients of microbiologically affecting compounds and gases (e.g., hydrogen, methane, hydrogen sulfide, and sulfate). The study of the sub-seafloor microbial communities within the samples recovered from Expedition 366 cores will provide information on the evolution of life, as many biologists are considering serpentinization of mantle peridotite a likely source of fuel for development of the first cells. The origin, composition, and global significance of the sub-seafloor biosphere have engaged many in the marine biological community in the study of serpentinization and associated communities of microbes and megafauna in a variety of environments. The sensitivity of ecosystems within the conduits of serpentinite mud volcanoes to changes in the rate of flow of deep-derived slab fluids is likely to change during earthquakes that take place near the base of the plumbing system. The four cased seafloor observatory holes on the Mariana forearc permit monitoring of changes in fluid compositions and egress rates as well as changes in microbial communities.

In addition to Expeditions 360 and 366, microbiologists sailed on Expedition 349, where samples were collected to explore the extent and diversity of the deep microbial biosphere in sediments. The samples collected allowed an assessment of how communities changed with depth at three different core locations. Different core materials were selected and were contrasted with the goal of detecting shifts in microbial communities across transitions at turbidite-clay and ash-clay boundaries.

There is great potential for advancement of this theme on expeditions along the proposed *JOIDES Resolution* ship track. Movement into new ocean basins will continue to increase knowledge of biogeography, biosphere formation and survival. Environments of seeps and hydrates need further study, such as Expedition 386 in the Gulf of Mexico. We need to more clearly define limits of life by focusing on metabolite exchange, bioavailability of energy, and carbon sources. Further research into crustal biomes across basement age is needed and may be addressed by a highly-ranked South Atlantic Transect proposal in the IODP system that targets sediment and basement at increasing basement ages.

The *JOIDES Resolution* has greatly expanded its capabilities to examine the subseafloor biosphere through improvements in monitoring for contamination and in core flow and handling by all involved in sampling (core techs, microbiologists and other researchers). The primary positive attribute of the *JOIDES Resolution* is its ability to collect high-quality, uncontaminated cores in a range of lithologies to >1 km subseafloor depths. The *JOIDES Resolution* can sample fluids through active borehole monitoring or porewater extraction to study for crust-sediment exchange and the resulting influence on the resident biosphere. The facility has exceptional flexibility for studying a range of subseafloor environments. For example, Expeditions 360 and 366 sampled high pH conditions in hard and soft rock settings, respectively, whereas the upcoming Expedition 385 will sample a low pH and hot sedimentary environment in the actively rifting Guaymas Basin, Gulf of California.

Section VI: Conclusions

The conclusions of *JOIDES Resolution* Assessment Workshop represent the culmination of a multi-phased, year-long community review of the performance of the *JOIDES Resolution* in implementing the International Ocean Discovery Program. Our conclusions incorporate the input of the 876 scientists who participated in an extensive survey about the vessel and its science accomplishments, and the 81 participants who distilled and analyzed the survey data and expedition results at an in-person meeting in Denver, Colorado in September of 2017.

The survey results underscore the scientific community's deep overall satisfaction with the *JOIDES Resolution* facility and its unique ability to pursue the objectives of the 2013-2023 IODP Science Plan over the next five years. Responses were strongly positive with respect to the ship's drilling systems, analytical systems, and logging systems, with each receiving favorable ratings from over 90% of the respondents. The survey results also show the broad interest of the scientific community in the *JOIDES Resolution*. Overall, the participants represented at least 84 U.S. institutions (only 57% of U.S. respondents provided their institution name), and more than 44% of total respondents identified as either a graduate student or early career scientist (defined as being less than ten years post-PhD), indicating that the U.S. IODP community continues to be successful in recruiting new scientists into its pipeline.

The survey results were used to guide discussions in terms of the broad community's interest in IODP. The in-person workshop participants reviewed IODP expeditions implemented by the *JOIDES Resolution*, discussed the impact of regional operational planning, documented efficiencies, and identified how the *JOIDES Resolution* facility is contributing to addressing science priorities outlined in the National Academy of Sciences *Sea Change* report.

Using the survey results and in-person discussion, the workshop participants determined that IODP's successes rests largely on the operationally diverse capabilities of the *JOIDES Resolution*. The ship expertly recovers both hard rock and sediment cores, effectively operates in many different environments, and addresses a myriad of scientific objectives. Specific example of how the *JOIDES Resolution's* capabilities support IODP include:

- The ship is exceptional at recovering continuous sedimentary core for deep time studies.
- The ship can operate in a broad range of water depths to address thematic science goals, such as marine-terrestrial ecosystem evolution and microbial ecosystems.
- The ship's operational flexibility and new procedures decrease drilling time while increasing core quality.
- The ship is able to address important societal questions by drilling into fault zones and examine carbon flow and storage in the subseafloor.
- The ship's equipment improvements in lab areas have markedly increased the analytical capabilities and decreased the turn-around time for data collection.
- The ship is the most cost-effective vessel in the world for routinely recovering and analyzing continuous cores to specific depths.

- The ship can efficiently and effectively install CORKs and similar observatories in the subseafloor.
- The ship's onboard analytical facilities provide the real-time data required to guide drilling operations and accomplish expedition objectives.

Expeditions implemented by the *JOIDES Resolution* since the inception of IODP have contributed to each of the four themes in the 2013-2023 IODP Science Plan. These expeditions have advanced the forefront of science in all four Climate and Ocean Change challenges, especially in understanding monsoons, their climate controls, and associated weathering and tectonism. Research in the Biosphere Frontiers theme continues to advance rapidly as a result of the advent of analytical methods that generate high-quality data with lower biomass samples, such as those typical of deep biosphere work. The *JOIDES Resolution* has also made substantial advances in the Earth Connections theme through multiple expeditions to the South China Sea and the Izu-Bonin-Mariana arc regions, and the Earth in Motion theme through studies focused on fault zone mechanics and the flow and storage of carbon in the subseafloor.

The *JOIDES Resolution* is also expected to continue making significant contributions to the 2013-2023 IODP Science Plan during the remainder of the current IODP. The *JOIDES Resolution* will begin working in new regions this year, which will increase the geographic coverage of the facility and particularly broaden the scientific focus of expeditions within the Climate and Ocean Change theme. Upcoming Biosphere Frontiers themed-expeditions include Brothers Arc Flux, which will study subseafloor hydrothermal activity, and Guaymas Basin Tectonics and Biosphere, which will investigate hydrothermal circulation related to volcanic sills intruded into thick sedimentary sequences in the Guaymas Basin. The Guaymas Basin expedition also contributes to the Earth Connections theme, and Expeditions 372 and 375 to the Hikurangi margin will contribute to the Earth in Motion theme, among others.

IODP has greatly benefited from the *JOIDES Resolution's* regional operations model. Regional planning has minimized transit time between expeditions, resulting in significant savings in fuel costs while maximizing time available for science. In addition, recent drilling and coring advances—such as the half-length APC, drill-in casing, and drill-in guide base—have greatly improved core quality, while more detailed contingency planning has improved expedition management. Coupling those efficiencies with income from co-sponsored complementary project proposals (CPPs) has resulted in the *JOIDES Resolution* providing an additional two months of operations per a year to IODP for achieving high-priority science goals.

During the first years of the program, IODP expeditions conducted with the *JOIDES Resolut*ion have contributed to five of the eight *Sea Change* research priority questions, and future expeditions will provide insight into two more. These research topics include improving our understanding of sea level change, ocean and climate variability, the formation and evolution of ocean basins, the characterization of geohazards such as earthquakes and tsunamis, and the origin and evolution of life. The types of samples and data collected by the *JOIDES Resolution* are fundamental to the evaluation of this broad range of scientific challenges and cannot be collected by another single vessel.

The community identified several possible areas for improvement to the *JOIDES Resolution* that could advance scientific outcomes over the next five years. The identified community priorities range from additional instrumentation to enhanced coring recovery. While important to consider, many are not necessarily simple or even possible to implement, or they may be too costly at this stage in the program. For example, instrumentation may be limited by space; thus, a seemingly simple request, such as the addition of scanning XRF on board the *JOIDES Resolution*, potentially requires a reorganization of the lab areas and elimination of other instruments. Other suggestions focus on software and training, which also must be managed in light of budgetary constraints. Engineering updates to improve coring and logging are considered high priority as well, particularly for operations in more complex environments, such as thick continental shelf sedimentary sequences, when drilling more than 1.5 km into ocean crust hard rock, or in locations with acidic, hot fluid flow and/or gas hydrates. Finally, the ability to store and ship organic-rich core after splitting requires integration of shipboard systems with post-cruise handling by shipping agents.

Overall, the workshop participants offer the following recommendations:

- As science objectives, approaches, and requirements evolve, periodic reviews of the analytical capabilities of the *JOIDES Resolution* should be undertaken to ensure that it is able to continue to conduct state-of-the-science operations. This includes additional analytical capabilities for shipboard use that could improve high-resolution core characterization (e.g., CT scanner, XRF, SEM with energy dispersive x-ray spectroscopy, high-resolution magnetic susceptibility tool).
- Because many cores are not sampled until several months after an expedition, there should be a systematic review to explore improving core storage options for vulnerable material, to help facilitate discovery in new regions and allow for recovery of non-traditional materials.
- Dedicated biosphere expeditions would benefit from the addition of a -80°C freezer in the Gulf Coast Repository. Such new microbial long-term storage capabilities would significantly enhance the value of an expedition through the ability to generate results for many years post-expedition.
- Climate and ocean science relies heavily on stratigraphic correlation to ensure continuous recovery of critical intervals. Improvements that facilitate real-time shipboard coring, as well as continued improvements in correlation software, sensors, and training, will allow researchers to take greatest advantage of the multiple-hole approach.
- Overall, accomplishment of the 14 challenges in the IODP Science Plan will be enhanced with continued efforts to improve core recovery and quality in traditionally difficult to core sediments using the XCB tool, or further improvements to the depth range of the APC and half-APC tool. Continued advances in drilling techniques that improve recovery in hard and/or fractured rocks, the development of tools to sample liquid in fractured rock and take *in situ* measurements, improvements in heave compensation, and the

ability to orient APC and XCB cores are also important to advancing the science carried out by the *JOIDES Resolution*.

In conclusion, the survey and workshop results affirmed the strong support by the U.S. community for the performance of the *JOIDES Resolution* facility in accomplishing the goals of the 2013-2023 IODP Science Plan. Innovations in operation, technology, and procedures have contributed to an efficient and effective vessel that is critical to the future success of ocean and earth science research as identified in the *Sea Change* report. The U.S. scientific community unwaveringly supports the continued use of the *JOIDES Resolution* and its unique research capabilities to fulfill the remainder of the 2013-2023 IODP Science Plan.

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Appendix B: Selected Quotes from the *JOIDES Resolution* Community Survey

Oceans and Climate

"Greater use of half-length APC coring has enabled recovery of sediments that we wouldn't have been able to recover so cleanly (or at all) before."

"Half APC technique has enabled the recovery of undisturbed, continuous, and deeper stratigraphic record, which is the most essential to reconstruct past changes and events in climate and ocean."

"In the last few years, since the JR's voyage into the Indian Ocean, there will be a myriad of research that comes out which will reveal unparalleled information about the history of the Indian monsoons. There is a CRITICAL need to characterize and advance monsoon theory in light of future greenhouse gases, and this facet of JR research will [undoubtedly] yield important constraints on this climatic phenomena."

"Access to these cores have allowed our community to continue to push the frontiers of knowledge regarding paleoceanography, paleoclimate and paleoenvironment through time and throughout the oceans. Specifically, the multiple cruises sailed as part of the Asian/Australasian monsoon series (Exps 346, 353, 355, 356) represent an enormous opportunity to better understand this enigmatic, but societally very important, climate system and its stability during periods of global climate change ... "

" … the Indian Ocean and Western Pacific legs are filling huge gaps in knowledge of tectonic, oceanographic, and climatic processes, and increasing understanding of a region driving (in particular) climate changes in the near future."

"There is growing realization that the best records of subaerial volcanic and tectonic processes associated with collisional tectonics can be obtained from marine sediments, and IODP is uniquely placed to obtain this type of material."

"The studies we did on the IODP samples recovered from South China Sea (IODP Expedition 349) gave us a clear connection between Earth's internal workings on the dynamics at the surface, as well as the impact on the past ocean conditions. This knowledge will help us understand the interconnection between deep Earth and ocean conditions at present."

"Drilling in the Indian Ocean is now allowing us to really address the question about how monsoon evolution is linked to the development of high topography in South Asia."

“DSDP/ODP/IODP material is integral to so many important papers in climate science and paleoceanography it is hard to pick out just one. A short list: Understanding past concentrations in atmospheric CO_2 Neogene vegetation history in India, Africa, Australia.”

“For the paleoclimate records, the improved drilling technology and the priority to duplicate and triplicate core is fantastic.”

“The goal of getting Pliocene sections to fill gaps of knowledge on the interesting interval of geologic time … has broad applications to understanding our changing world.”

“As far as I can tell the fields of paleoclimatology and paleoceanography, particularly for deep-time paleoenvironments, would barely exist without the JR.“

“The core recovery on the JR is amazing. Long (greater than 400 m) APC records allow detailed investigations of paleoclimate at the sub-orbital scale. This level of detail was not possible previously. The records are providing new insights into climate variability and the response of the biota to climatic change.”

“We need to establish the sensitivity of various aspects of the Earth System to carbon dioxide variations, particularly during times when Earth was warmer than today. For this, we require sites with high sedimentation rates and both organic and inorganic pCO_2 proxies.”

“[It is a priority to [collect] high-resolution climate archives that address changes in climate and ocean on decadal-centennial time scales for past warm periods. Rates of change in ice-sheet and high latitude ocean systems are still poorly established.”

Biosphere Frontiers

“The JR continues to offer a unique capability to sample and measure sediments deeply buried beneath the sea-floor.”

“Samples from the core repositories facilitated research in to the role of continental shelfs on global biogeochemical cycles.”

“Without deep sampling it would be impossible to address any of the Science Plan themes.”

“Microbiology contamination testing techniques have improved vastly and have been implemented … readily and consistently.”

“My specific project focuses on one specific topic, but will also investigate broader topics including microbial presence and relative abundance and their metabolisms. The research I will be conducting is a ground breaking topic within the deep biosphere and the new scientific and technical developments from [the] JR gives me the opportunity to investigate it.”

“ … we’ve put some estimates on the limits of life (challenge 6) just by looking where cells are sparse and inactive, but need to do further work to understand the mechanisms underlying the limits of life.”

“These new developments allow investigation of areas that would not be accessible or very minimally accessible. The four focus points listed in the Science Plan are extensive and encompass many different topics. The advancements made will aid in successfully exploring and analyzing these isolated environments.”

“ … new knowledge about the size of the deep biosphere, the life forms and the limits of life are continuously obtained.”

“The [half-APC] massively improves our ability to recover uncontaminated cores.”

“Probably the most exciting [development] to me has been the identification of fungi in the deep subsurface - I would not have predicted that, and would certainly like to see these investigations continue.”

Earth Connections

“Drill-in casing … significantly decreases the amount of time required for drilling.”

“The three Izu-Bonin-Mariana expeditions in 2014 have been extremely successful. First results have been published and many articles are currently in press/in review or in preparation. These expeditions contributed significantly to our further understanding of subduction zones (e.g. their initiation), elemental recycling through the Earth’s interior and ultimately the formation of the continental crust.”

New data [have been obtained] on the role of mantle flow & of lithosphere contribution to the composition of the volcanic crust (MOR & lavas emplaced during subduction initiation) … This research … improve[s] our understanding of the connections between seafloor spreading, mantle composition and melting and the links to ocean crustal architecture (Challenges 8-9).”

“Recently completed triple leg in the IBM system (350/351/352) is poised for significant leaps in understanding of subduction initiation. A great, ambitious program of linked expeditions.”

“[The JR] recovered a unique sample set (basement and cover) that is recording the evolution of volcanism and sedimentation after the subduction initiation and the evolution of the intra-oceanic arc-basin systems in time. Without the JR this cannot be achieved anywhere on land.”

“Hand-held XRF in the chemistry lab - speeds up obtaining compositional data that can affect drilling decisions.”

Integrated expeditions on the JR has allowed us to conduct more comprehensive and integrated investigations of plate margin processes (geological, chemical, biological).”

“Drilling results have contributed significantly to our understanding tectonism/magmatism of slow spread ridge systems.”

“We have been able to discover a never before see pattern of tectonic subsidence on a passive margin (the NW shelf of Australia). What we have found is a nearly perfect pattern of ‘reversible’ tectonic subsidence and I think … this was facilitated by a much more complete sampling of a tectonic process with the kind of sampling needed for studies of the climate (on the one hand) and a much greater focus on the paleobathymetry.”

“It revealed the evolutionary history of arc evolution, which should result in the formation of continental crust. Also, the evolution of submarine caldera could be revealed only by drilling of submarine tephras.”

“The studies we did on the IODP samples recovered from South China Sea (IODP Expedition 349) gave us a clear connection between Earth’s internal workings on the dynamics at the surface, as well as the impact on the past ocean conditions. This knowledge will help us understand the interconnection between deep Earth and ocean conditions at present.”

“The JR has created new ways of drilling to recover more sediment and reduce time needed to drill. A free-fall funnel was placed on top of a re-entry cone during Exp 367 for the first time in IODP history to ensure the visibility of the hole. The JR is also drilling and recovering sediment that is deeper and harder to drill due to the technological advances and new ideas on the rig floor.”

“Recovery rates in hard rock legs has improved tremendously. Everything on board the JR is supporting the science I am involved and interested in.”

“ … The emplacement of screened casing at the summits of three active mud volcanoes on the Mariana forearc will provide sites for emplacement of CORK-Lites to allow monitoring of episodes of eruption at the mud volcanoes and determine the response to seismicity and whether variations in fluid composition, rate of flow, and temperature/pressure changes affect subsurface microbial populations.”

“Most importantly the IODP has provided an environment for collaborative discovery that has led to transformative and societally relevant research and education/outreach opportunities regarding ocean science.”

Earth in Motion

"… the JR has sampled several margins around the world whose samples help us understand the crustal–scale processes involved at plate boundaries from sediment provenance to volcanism to frictional properties and seismic potential to biological productivity."

"[The JR has] increased ability to constrain strength of materials and *in situ* stresses (young field for IODP but advances are being made)."

"The JR allowed for the deep geophysical exploration of the forearc environment, a tectonic region that still has not been sufficiently investigated."

"The JR [has] unique ability in installing seafloor observatories in revolutionizing the types and quality of science that can be done."

"The JR has continued to improve its capabilities and successes in many different environments. Convergent margins are particularly difficult but the JR is up to the challenge more than any time in its past."

"… The JR, and the pressure coring technologies they have developed and plan to implement ….. represent staggeringly large leaps forward in our ability to measure the physical properties of hydrate-bearing sediment."

"Sumatra drilling results are just coming out, but appear to make significant headway in understanding how the incoming sediments may control the extent of megathrust earthquake ruptures, and hence also the generation of large tsunami. Upcoming Hikurangi drilling has huge momentum and should produce further critical results."

"Improvements in long term monitoring instrumentation provide time series showing processes and connections between processes that illuminate tectonic processes."

"Understanding subduction initiation is necessary if we want to make progress in evaluating the risk at this type of margin."

"The technical development has contributed to several expeditions including those that address the themes of …. Earth in Motion: what mechanisms control the occurrence of destructive earthquakes, landslides and tsunami."

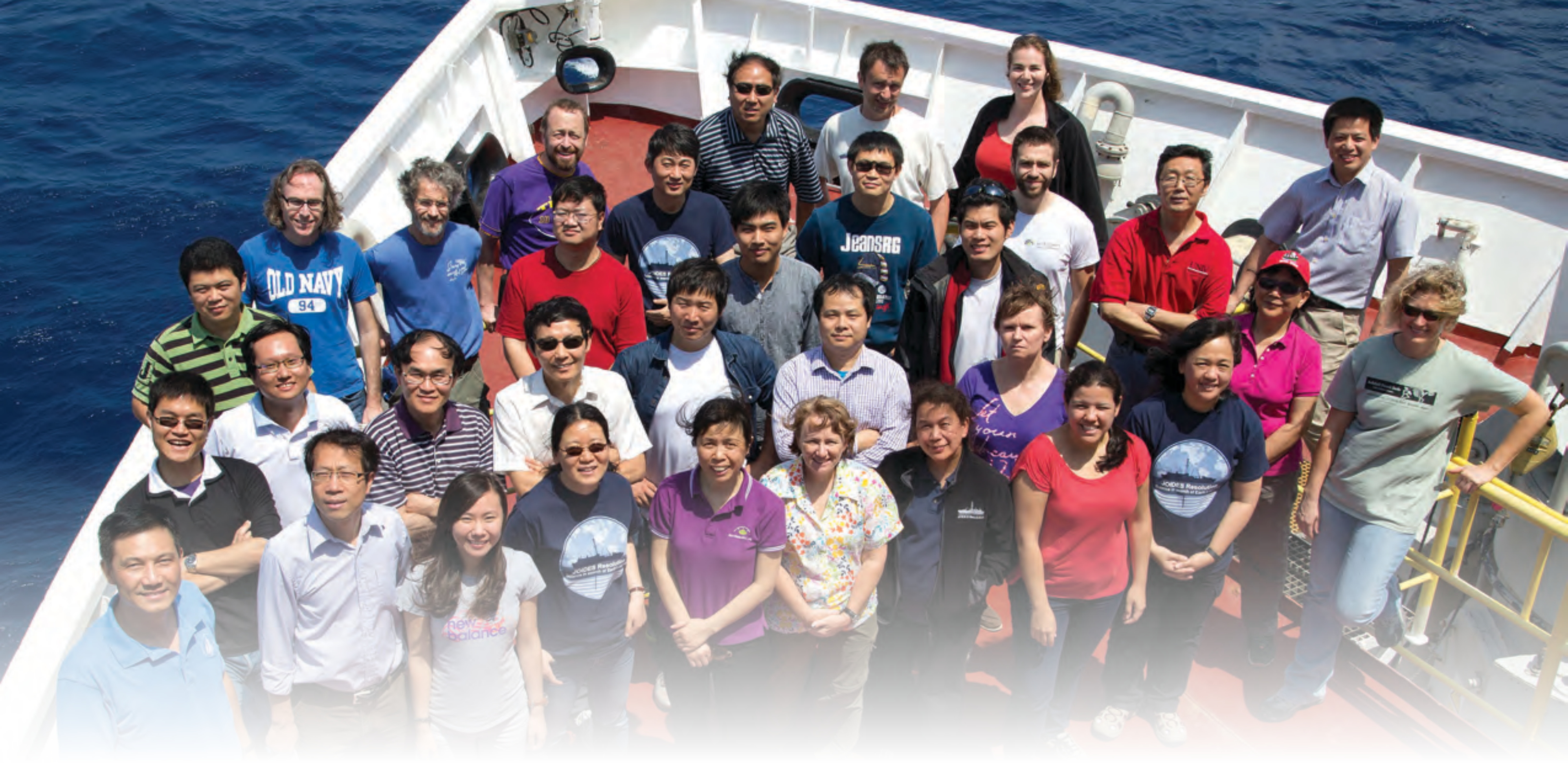
"Better coring and monitoring facilities certainly help with … Earth in Motion, allowing for more accurate and longer duration sampling."

"Only ocean drilling can directly sample materials deforming in active subduction zones, and allow installation of seafloor and sub-seafloor monitoring equipment – critical to the challenge of understanding earthquakes and tsunami risk in coastal areas."

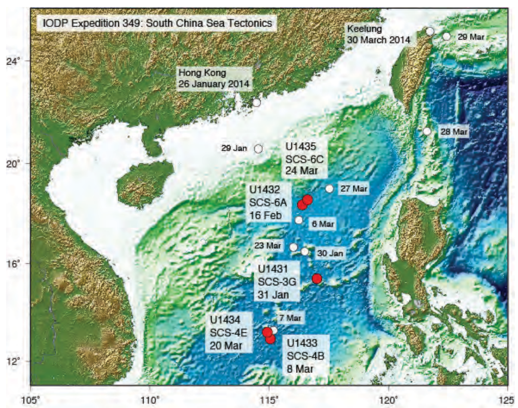
"… the expedition that has just been completed in the South China Sea and which will continue with Expedition 368 may be a keystone in documenting a new type of magma-poor rifted margin … "

Appendix C: Index of Acronyms

ADP – amphibious drilling proposal
AGU – American Geophysical Union
AMOC - Atlantic meridional overturning circulation
ANDRILL – Antarctic Geological Drilling
APC – advanced piston core
APL – Ancillary Project Letter
C-DEBI – Center for Dark Energy Biosphere Investigations
CoDL – Census of Deep Life
CPP – Complementary Project Proposal
CT – computed tomography
DSDP – Deep Sea Drilling Project
EDS – energy dispersive spectroscopy
EPSP – Environmental Protection and Safety Panel
HLAPC – half-length advanced piston core
IBM – Izu-Bonin-Mariana
ICDP – International Continental Drilling Program
ICP-AES – inductively coupled plasma atomic emission spectrometer
IODP – International Ocean Discovery Program
JRFB – *JOIDES Resolution* Facility Board
JRSO – *JOIDES Resolution* Science Operator
LIP – large igneous province
LGM – last glacial maximum
LWD – logging-while-drilling
MDHDS – motion decoupled hydraulic delivery system
MORB – mid-ocean-ridge basalt
MSP – mission-specific platform
NSF – National Science Foundation
ODP – Ocean Drilling Program
OOI – Ocean Observatory Initiative
ROV – remotely operated vehicle
SEM – scanning electronic microscope
SEP – Science Evaluation Panel
USSSP – U.S. Science Support Program
XCB – extended core barrel
XRF – X-ray fluorescence



Expedition 349: South China Sea Tectonics



General Information

Sites: U1431–U1435
Dates: 26 January to 30 March 2014
Ports: Hong Kong to Keelung
Co-chief Scientists: Chun-Feng Li & Jian Lin
Staff Scientist: Denise Kulhanek
Logging Staff Scientist: Trevor Williams

Reports and Publications

Ship reports:
http://iodp.tamu.edu/scienceops/sitesumm/349/index.html

Scientific Prospectus:
http://publications.iodp.org/scientific_prospectus/349/

Preliminary Report:
http://publications.iodp.org/preliminary_report/349/

IODP Proceedings:
http://publications.iodp.org/proceedings/349/349title.html

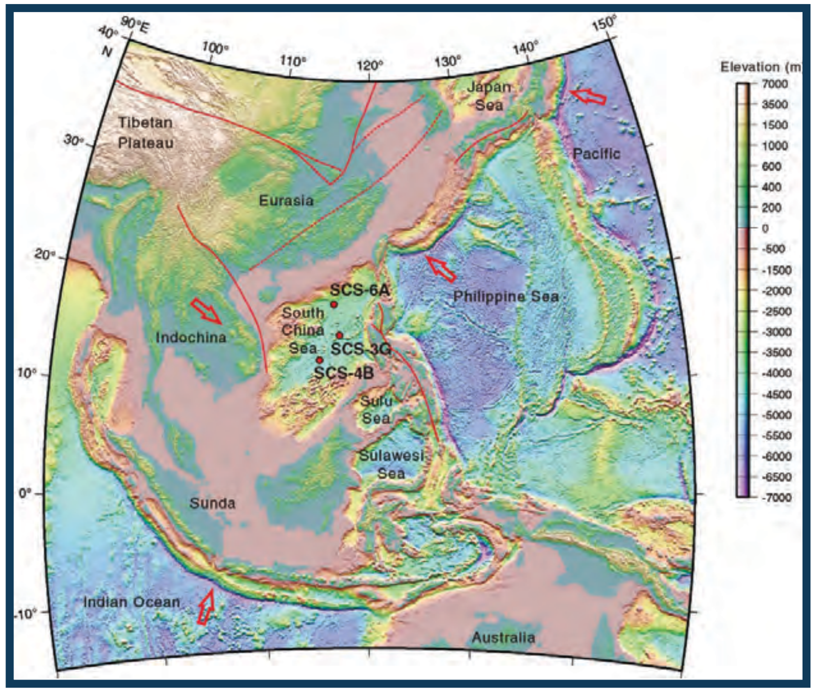
Expedition-related citations:
http://publications.iodp.org/proceedings/349/349title.html#bib

Abstract from *Scientific Prospectus*

The South China Sea (SCS) is situated at the junction of the Eurasian, Pacific, and Indo-Australian plates. It has undergone nearly a complete Wilson cycle despite its relatively small size and short evolutionary history, and it is a critical site linking some of the major western Pacific tectonic units. The opening of the SCS reveals complex patterns of continental margin breakup and basin formation. Despite extensive studies, sampling of basement rocks and overlying sediments in the deep basin is currently lacking. This leaves a large margin of error in estimated opening ages and renders various hypotheses regarding its opening mechanism and history untested. This also hampers our understanding of East Asian tectonic and paleoenvironmental evolution. International Ocean Discovery Program Expedition 349 (28 January–30 March 2014) will drill three sites to ~100 m into basement (Sites SCS-3G, SCS-6A, and SCS-4B) in two different sub-basins of the SCS to address questions regarding the opening and evolution of the SCS and how it affected the paleoceanography of the region. These sites are located to determine the timing of onset and cessation of seafloor spreading in the East and Southwest Sub-basins. Geochemical sampling of basement rocks of different ages within the different magnetic zones of the SCS will provide critical information on how the crust and mantle evolved during various stages of basin evolution. Coring of the sedimentary section above basement will provide direct constraints on the age of the underlying basement through biostratigraphy and will allow examination of changes in sedimentation and paleoceanography through time as the basin opened and then began subducting beneath the Manila Trench. All sites will be single cored using the advanced piston corer and extended core barrel to refusal, followed by rotary core barrel drilling through the remaining sediment section and basement. If permitted by the Environmental Protection and Safety Panel, we will drill through the top 900 m of the highest priority site (SCS-6A), which would recover a similar sequence to that cored at the first site (SCS-3G). This option gives the best opportunity of reaching and coring basement at all three primary sites. If full coring is required, two additional sites that reach basement with shallower penetration will be substituted. Downhole logging is planned for all sites using the triple combination and Formation MicroScanner–sonic tool strings. Additional tool strings may be run if time and hole conditions permit, including a check shot survey, the Ultrasonic Borehole Imager, the magnetometer tool, and the magnetic susceptibility sonde.

Abstract from *IODP Proceedings*

The South China Sea (SCS) provides an outstanding opportunity to better understand complex patterns of continental margin breakup and basin formation. The SCS is situated at the junction of the Eurasian, Pacific, and Indo-Australian plates and is a critical site linking some of the major western Pacific tectonic units. Despite extensive studies, sampling of basement rock and directly overlying basal sediment in the deep basin is lacking. This leaves a large margin of error in estimated ages of the SCS opening and closing, rendering various hypotheses regarding its opening mechanism and history untested. This also hampers understanding of East Asian tectonic and paleoenvironmental evolution.



Regional topography and geodynamic framework of Southeast Asia. Data based on Smith and Sandwell (1997). Solid red lines = regional faults. Red arrows show direction of plate movement and solid red circles mark sites drilled during Expedition 349.

We drilled five sites in the deep basin of the SCS. Three of these sites (U1431, U1433, and U1434) cored into oceanic basement near the fossil spreading center. The two remaining sites (U1432 and U1435) are located proximal to the northern continent/ocean boundary. We recovered a total of 1524 m of sediment/sedimentary rock and 78 m of oceanic basalt and also carried out downhole geophysical logging (triple combination and Formation MicroScanner- sonic tool strings) at the two deepest sites (U1431 and U1433). These materials and data were extensively examined and discussed during the expedition and allowed us to draw the following principal conclusions on the opening of the SCS:

1. Based on shipboard dating of microfossils in the sediment immediately above the basaltic basement and between the lava flow units, the preliminary cessation age of spreading in both the East and Southwest Subbasins is around early Miocene (16–20 Ma). Further postcruise radiometric dating of basement basalt from these sites plus additional calibration of magnetic anomaly models and paleomagnetic measurements will further refine the age range. Overall, a large difference is not apparent in the terminal ages of seafloor spreading between the two subbasins.
2. At Site U1435, we were able to drill into a structural high standing along the continent/ocean boundary. Coring at this site recovered a sharp unconformity at ~33 Ma, above which is marine sediment and below which are poorly sorted sandstone and black mudstone, interpreted as littoral deposits. Environmental interpretation will require further shore-based studies because the sequence is almost entirely barren of marine microfossils. Nevertheless, we interpret this unconformity to be likely directly related to the continental breakup during the initial opening of the SCS. The onset of seafloor spreading is therefore estimated to be at~33Ma.
3. All sites contain deep marine deposits but show significant areal variations in postspreading sedimentary environment and provenance. Site U1431 records evidence for deep-marine turbidite deposition from terrestrial sources. The observed coarser silt turbidites may have a source in Taiwan or other surrounding blocks, whereas interbedded calcareous turbidites at this site could be transported from local sources, such as nearby seamounts topped by carbonate platforms. In contrast, the source for upper Miocene clay and silt turbidites at Site U1433 could be Borneo or mainland Southeast Asia, with the source of the inter- bedded carbonate turbidites likely the Dangerous Grounds or Reed Bank area located south of the site.
4. Sites U1431 and U1434 are close to seamounts developed along the relict spreading center. Occurrences of basaltic clasts and mineral fragments in the volcaniclastic sandstone and breccia may reveal the magmatic history and mantle source of the seamounts and potentially their relationship with the terminal pro- cesses of spreading. The volcaniclastic breccia and sandstone at Site U1431 are dated as late middle Miocene to early late Miocene (~8–13 Ma), suggesting a 5 million year duration of seamount volcanism starting a few million years after the cessation of seafloor spreading. At Site U1434, volcaniclastic breccia and sandstone are most likely sourced from the adjacent seamount ~15 km to the north. The age of this recovered unit is late Miocene (younger than 9 Ma). Further postcruise sedimentological and geochemical studies, as well as radiometric dating of potassium-bearing mineral fragments, will refine the ages and timing of these seamount activities and reveal how magma sources at the dying spreading center evolved through time.
5. We successfully cored into ocean basement in the SCS for the first time and recovered basalt at three sites (U1431, U1433, and U1434). The cored basalt has variable phase assemblages of plagioclase, olivine, and clinopyroxene and is concluded to be typical mid-ocean-ridge basalt based on petrological and geochemical evidence. Postcruise radiometric dating will determine the absolute ages of the basaltic basement units. Postcruise petrological and geochemical analyses on the basalts will provide information on the mantle sources, melting, and crystallization history of the youngest ocean crust.

JOIDES Resolution Science Operator

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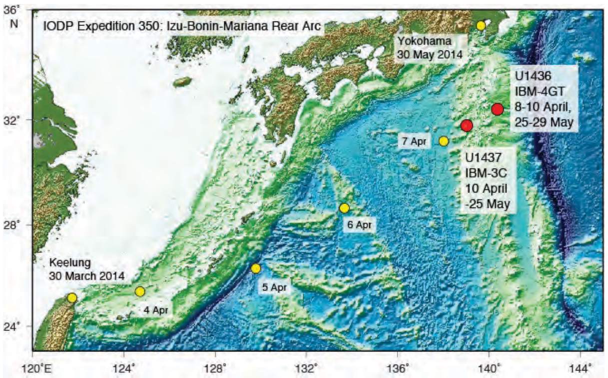
Expedition 350: Izu-Bonin-Mariana Rear Arc



General Information

Sites: U1436–U1437
Dates: 30 March to 30 May 2014
Ports: Keelung, Taiwan to Yokohama, Japan
Co-chief Scientists: Yoshihiko Tamura & Cathy Busby
Staff Scientist: Peter Blum
Logging Staff Scientist: Gilles Guèrin

Reports and Publications

Ship reports:
http://iodp.tamu.edu/scienceops/sitesumm/350/

Scientific Prospectus:
http://publications.iodp.org/scientific_prospectus/350/

Preliminary Report:
http://publications.iodp.org/preliminary_report/350/

IODP Proceedings:
http://publications.iodp.org/proceedings/350/350title.html

Expedition-related citations:
http://publications.iodp.org/proceedings/350/350title.html#bib

Abstract from *Scientific Prospectus*

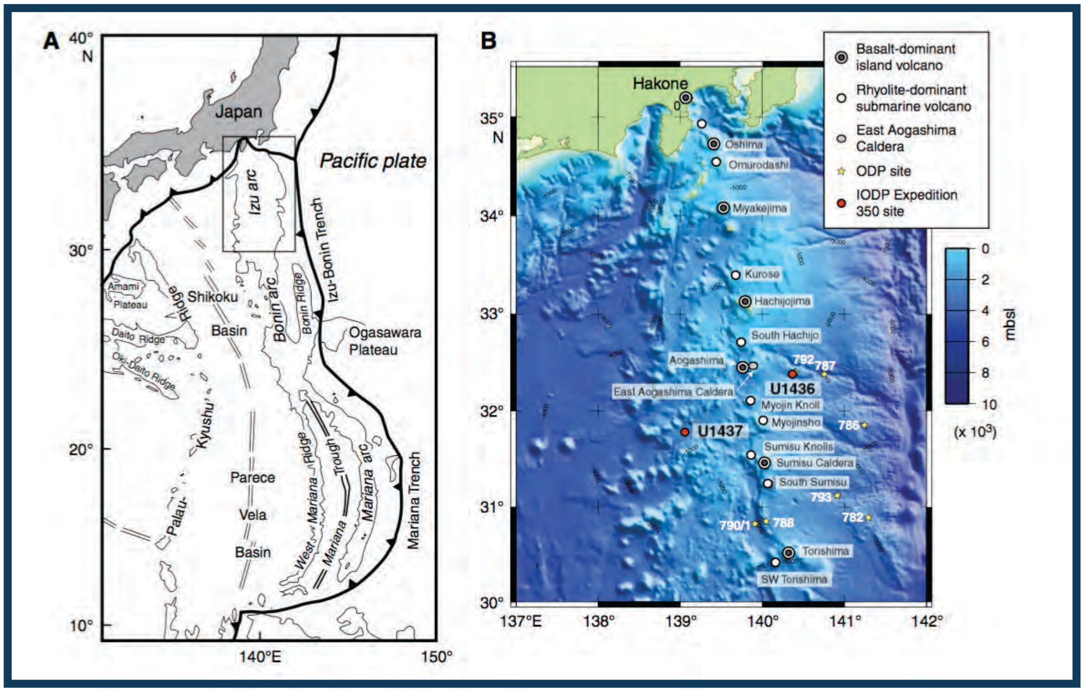
The spatial and temporal evolution of arc magmas within a single oceanic arc is fundamental to understanding the initiation and evolution of oceanic arcs and the genesis of continental crust, which is one key objective of the International Ocean Discovery Program Initial Science Plan. The Izu-Bonin-Mariana (IBM) arc has been a target for this task for many years, but previous drilling efforts have focused mainly on the IBM fore arc and the magmatic evolution of the volcanic front through 50 Ma. Rear-arc IBM magmatic history has not been similarly well studied in spite of its importance in mass balance and flux calculations for crustal evolution, in establishing whether and why arc-related crust has inherent chemical asymmetry, in testing models of mantle flow and the history of mantle depletions and enrichments during arc evolution, and in testing models of intracrustal differentiation.

Expedition 350 will contribute to the understanding of intraoceanic arc evolution and continental crust formation by drilling in the IBM rear arc to examine three phenomena:

1. Crust develops that is "continental" in velocity structure and seismically similar beneath both the volcanic front and rear arc but is heterogeneous in chemical composition.
2. Magmas at the volcanic front are rich in fluid-mobile recycled slab components that swamp the mantle, yet these magmas are so depleted in mantle-derived fluid-immobile elements that they are dissimilar to "average continental crust" in detail. This is less true in the rear arc where the diminished slab signature and lower degrees of mantle melting create crust that is more typical of the continents and allows the temporal history of the mantle source to be tracked more easily.
3. The crust beneath the rear arc is volumetrically more abundant than beneath the volcanic front.

To understand the evolution of the whole IBM crust, we will drill the Izu rear-arc region west of the modern volcanic front to recover a complete record of rear-arc volcanism from the present back to its likely inception in early Oligocene or Eocene times. The rear arc contains the record of the "other half" of the subduction factory output, and recovering that record is essential to the IBM drilling strategy.

Abstract from *IODP Proceedings*



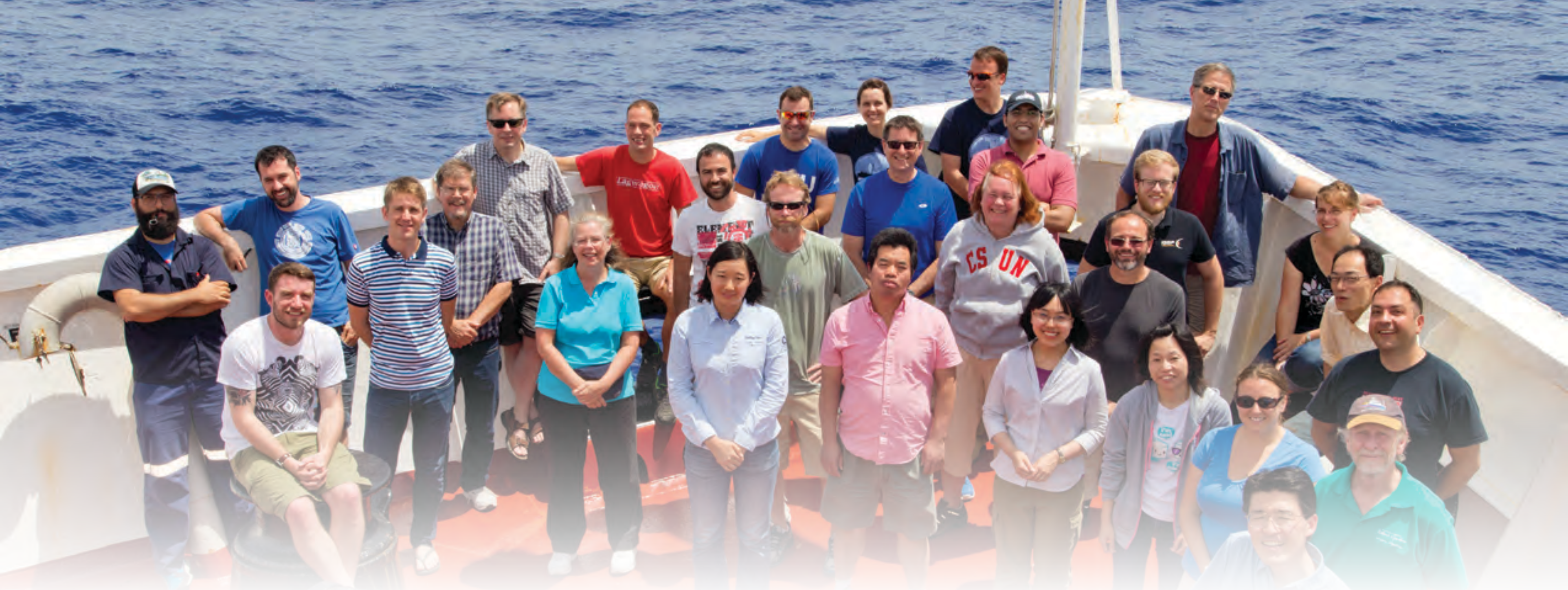
Tectonic setting of IBM arc (from Taylor, 1992; Tamura and Tatsumi, 2002). The IBM arc-trench system forms the convergent margin between the Pacific and Philippine Sea plates. Double lines indicate spreading centers active in the Mariana Trough and relict in the Shikoku and Parece Vela Basins. Izu- Bonin, West Mariana, and Mariana arcs are outlined by the 3 km bathymetric contour, and other basins and ridges are outlined by the 4 km contour. Box shows area of B. B. Map of the 16 Quaternary volcanoes on the arc front (from Tamura et al., 2009), showing Expedition 350 site positions (Site U1436 in fore arc and Site U1437 in rear arc) and previous ODP site locations. Dotted line along arc front indicates locations of 103 ocean-bottom seismometers, deployed at ~5 km intervals (Kodaira et al., 2007a, 2007b); for profile see Figure F5.

International Ocean Discovery Program (IODP) Hole U1436A (proposed Site IBM-4GT) lies in the western part of the Izu fore-arc basin, ~60 km east of the arc-front volcano Aogashima, ~170 km west of the axis of the Izu-Bonin Trench, and 1.5 km west of Ocean Drilling Program (ODP) Site 792, at 1776 meters below sea level (mbsl). It was drilled as a 150 m deep geotechnical test hole for potential future deep drilling (5500 meters below seafloor [mbsf]) at proposed Site IBM-4 using the *D/V Chikyu*. Core from Site U1436 yielded a rich record of Late Pleistocene explosive volcanism, including a distinctive black glassy mafic ash layer that may record a large-volume subaqueous eruption on the Izu arc front. Because of the importance of this discovery, Site U1436 was drilled in three additional holes (U1436B, U1436C, and U1436D), as part of a contingency operation, in an attempt to get better recovery on the black glassy mafic ash layer and its enclosing sediments and to better constrain its thickness.

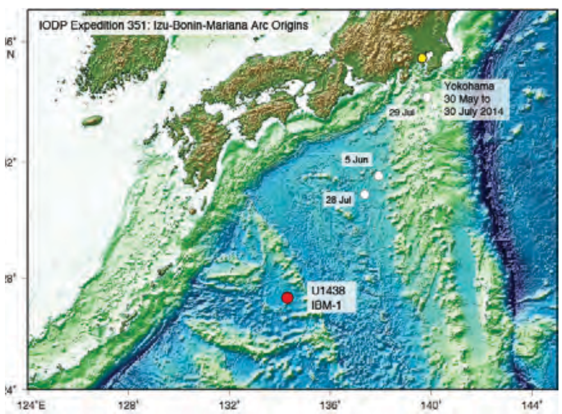
IODP Site U1437 is located in the Izu rear arc, ~330 km west of the axis of the Izu-Bonin Trench and ~90 km west of the arc-front volcanoes Myojinsho and Myojin Knoll, at 2117 mbsl. The primary scientific objective for Site U1437 was to characterize "the missing half of the subduction factory" because numerous ODP/Integrated Ocean Drilling Program sites had been drilled in the arc-front to fore-arc region (i.e., ODP Site 782A Leg 126), but this was the first site to be drilled in the rear-arc region of the Izu arc. A complete view of the arc system is needed to understand the formation of oceanic arc crust and its evolution into continental crust. Site U1437 on the rear arc had excellent core recovery in Holes U1437B and U1437D, and we succeeded in hanging the longest casing ever in the history of R/V JOIDES Resolution scientific drilling (1085.6 m) in Hole U1437E and cored to 1806.5 mbsf.

The stratigraphy at Site U1437 was divided into seven lithostratigraphic units (I–VII) that were distinguished from each other based on the proportions and characteristics of tuffaceous mud/mudstone and interbedded tuff, lapilli-tuff, and tuff-breccia. The section is much more mud rich than expected, with ~60% tuffaceous mud for the section as a whole (89% in the uppermost 433 m) and high sedimentation rates of 100–260 m/My for the upper 1320 m (Units I–V). The proportion (40%) and grain size of volcaniclastics are much smaller than expected for an intra-arc basin, composed half of ash/tuff and half of lapilli-tuff of fine grain size (clasts <3 cm). These volcaniclastics were deposited by suspension settling through water and from density currents, in relatively distal settings. Volcanic blocks are only sparsely scattered through the lowermost 25% of the section (Units VI and VII, 1320–1806.5 mbsf), which includes hyaloclastite, in situ quench-fragmented blocks, and a rhyolite peperite intrusion (i.e., proximal deposits). The transition from unconsolidated to lithified rocks occurred progressively; however, sediments were considered lithified from 427 mbsf (top of Hole U1437D) downward. Alteration resulted in destruction of fresh glass from ~750 mbsf downward, but minerals are less altered. Because of the alteration, the deepest biostratigraphic datum was at ~850 mbsf and the deepest paleomagnetic datum was at ~1300 mbsf. Additional age control deeper than ~1300 mbsf is provided by an age range of 10.97–11.85 Ma inferred from a nannofossil assemblage at ~1403 mbsf and a preliminary U-Pb zircon concordia intercept age of 13.6 +1.6/−1.7 Ma, measured postcruise on a rhyolite peperite in Unit VI at ~1390 mbsf.

Based on the seismic profiles, the Miocene–Oligocene hiatus (~17–23 Ma) was predicted to lie at ~1250 mbsf, but strata at that depth (Unit V, 1120–1312 mbsf) are much younger (~9 Ma), indicating that we recovered a thicker Neogene section of volcaniclastics and associated igneous rocks than anticipated. Our preliminary interpretation of shipboard geochemistry of solids is that arc-front versus rear-arc sources can be distinguished for individual intervals in the upper, relatively distal 1320 m of the section (Units I–V), whereas data for the lower, proximal 25% of the section (Units VI– VII) overlap and exceed the compositional fields for Neogene rear-arc seamounts and Quaternary arc-front volcanoes. This suggests that the compositional divergence between arc-front and rear-arc magmas only fully developed after ~13 Ma.



Expedition 351: Izu-Bonin-Mariana Arc Origins



General Information

Sites: U1438
Dates: 30 May to 30 July 2014
Ports: Yokohama, Japan to Yokohama, Japan
Co-chief Scientists: Richard Arculus & Osamu Ishizuka
Staff Scientist: Kara Bogus
Logging Staff Scientist: Laureen Drab

Reports and Publications

Ship reports:
http://iodp.tamu.edu/scienceops/sitesumm/351/

Scientific Prospectus:
http://publications.iodp.org/scientific_prospectus/351/

Preliminary Report:
http://publications.iodp.org/preliminary_report/351/

IODP Proceedings:
http://publications.iodp.org/proceedings/351/351title.html

Expedition-related citations:
http://publications.iodp.org/proceedings/351/351title.html#bib

Abstract from *Scientific Prospectus*

Oceanic lithosphere created at oceanic ridges is returned to Earth's interior at sutures marked by deep-sea trenches in a process called subduction. The formation and destruction of lithospheric plates is a fundamentally important process leading to the creation of most important surface features and a major driver of the physical and chemical evolution of Earth. Although we have a relatively good understanding of the processes accompanying the formation of lithosphere in the so-called "rift-to-drift" cycle, we have minimal direct evidence of how subduction is initiated. This essential component of the global plate tectonic cycle is targeted as one of the major challenges of the new science plan for the International Ocean Discovery Program (IODP).

As an initial step in addressing this challenge, during IODP Expedition 351 we will core and log a prime site in the Amami Sankaku Basin, located <100 km west of the northern portion of the Kyushu-Palau Ridge (KPR), a remnant arc of the intraoceanic Izu-Bonin-Mariana (IBM) arc in the western Pacific on the northern part of the Philippine Sea plate. Over the past several decades, multidisciplinary efforts, including deep-sea drilling, have been made to understand the crustal characteristics and structure, tectonic and temporal evolution, and magma origins of the IBM system since its inception 52 m.y. ago. Subsequently, Site IBM-1 has been identified in the Amami Sankaku Basin where samples of the pre-arc basement can be recovered. We infer a Cretaceous to Paleogene age for the basement, overlain by a pre-arc-inception sediment section and an upper sedimentary sequence recording regional tectonic events accompanying formation of the KPR as a proto-arc at 52 Ma. Additional sedimentary cover recorded the Paleogene volcaniclastic and pyroclastic evolution of the Izu-Bonin arc with diminishing completeness, as the KPR was abandoned as a remnant arc at ~25 Ma, accompanying formation of the Shikoku back-arc basin.

The objectives of Expedition 351 involve the study of both the sediment (oceanic crust Layer 1) and igneous basement (Layer 2) and were established to address a number of fundamental aims. The primary objectives include

1. Determining the nature of the preexisting crust and mantle prior to subduction onset in the middle Eocene,
2. Identifying and modeling the subduction initiation process and initial arc crust formation,
3. Determining the Paleogene compositional evolution of the IBM arc, and
4. Establishing the geophysical properties of the Amami Sankaku Basin.

We also have a number of secondary objectives based on recovering sedimentary records of (1) early Tertiary and possibly Late Cretaceous paleooceanographic conditions in the eastern Tethys–western Pacific, (2) onset and persistence of the East Asia Monsoon and other climate-modulated terrestrial inputs, and (3) an ash record of the evolution of the Ryukyu-Kyushu arc, located west of the Amami Sankaku Basin.

Expedition 351 is conceptually straightforward, targeting a single site involving penetration of a thick sedimentary section overlying oceanic crust of normal thickness. Nevertheless, the water depth (4720 m), sediment thickness (1300 m), and consequent depth into basement (~150 m) impose technical challenges. Relatively short transit times to and from the Amami Sankaku Basin will maximize the time available for scientific drilling and logging operations.

Abstract from *IODP Proceedings*

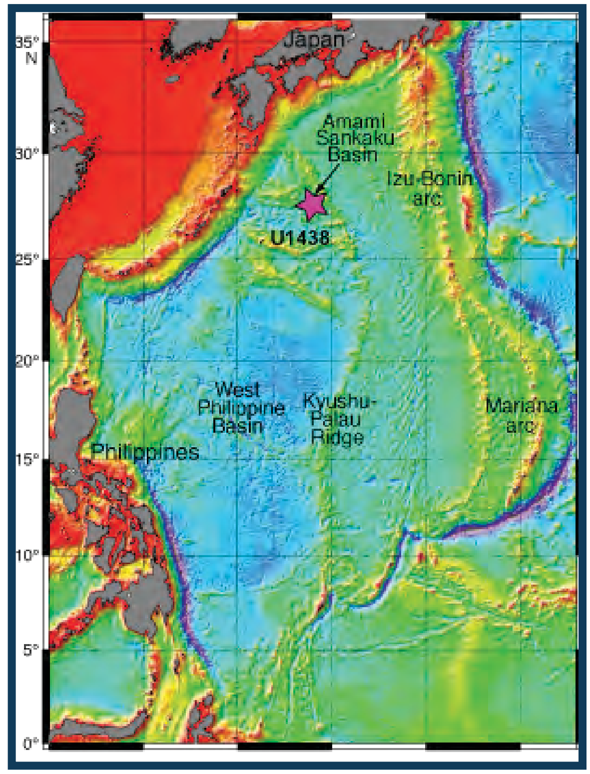


Figure caption

The intraoceanic Izu-Bonin-Mariana (IBM) arc in the western Pacific has been intensively examined over the past few decades, and the outlines of its overall tectonic and magmatic history have been revealed. Arc inception occurred at ~52 Ma, concurrent with a major change in the motion of the Pacific plate. Rifting of the active volcanic axis took place at ~25 Ma, with accompanying seafloor spreading and eastward migration of the active volcanic front forming a volcanically inactive remnant arc (Kyushu-Palau Ridge; KPR). The Amami Sankaku Basin (ASB) flanks the northern KPR; the ASB seafloor has a simple structure comprising ~1.5 km of sediment overlying igneous oceanic crust. International Ocean Discovery Program Expedition 351 targeted the ASB, anticipating recovery of the sedimentary record of the earliest stages of arc inception and evolution of the northern IBM arc. Igneous basement samples would permit determination of the petrological, geochemical, and age characteristics of the pre-KPR crust in the region, from which the geochemical composition of the mantle prior to IBM arc inception and growth could be inferred.

The expedition successfully accomplished its primary and most of its secondary objectives at Site U1438 in 4700 m water depth. Drilling penetrated 1461 m of sediment and 150 m of variably altered and veined aphyric to sparsely phyric tholeiitic basalt lava flows, which form the uppermost igneous oceanic basement (lithostratigraphic Unit 1). Four sedimentary units have been established in the sedimentary column above basement, described here from oldest to youngest. Lithostratigraphic Unit IV (99.7 m) consists of early Eocene mudstone, tuffaceous siltstone, breccia-conglomerate, sandstone, and radiolarian-bearing mudstone. The oldest radiolarian age is 50–53 Ma (Section 351-U1438E-63R-1; 40 m above basement), and the oldest foraminifer age is less than 57.8 Ma (Section 351-U1438E-66R-CC; 12 m above basement). Lithostratigraphic Unit III (1046 m) consists of Eocene–Oligocene tuffaceous mud-stone, tuffaceous sandstone, sandstone with gravel, and brecciaconglomerate with pebble/cobble-sized volcanic and sedimentary rock clasts. Lithostratigraphic Unit II (139.4 m) is Oligocene tuffaceous mudstone, siltstone, and fine sandstone with localized slumping. Lithostratigraphic Unit I (160.3 m) is latest Oligocene to recent, mud and ooze of terrigenous and biogenic origin, with interspersed discrete tephra layers.

In addition to fossil age constraints, in situ downhole temperature measurements and thermal conductivity measurements on core material from Unit I give a calculated heat flow of 73.7 mW/m2, implying a thermal age for the underlying lithosphere of 40–60 Ma. The recovery at Site U1438 of an extensive sediment sequence of early Eocene age in Unit IV, coeval with the putative initiation of the IBM arc at ~52 Ma determined by radiometric dating of fore-arc igneous samples, will allow comprehensive analysis of the provenance, geochemical and petrological characteristics, and style of earliest arc magmatic activity in the KPR. The geochemical and petrological equivalence of the Unit 1 lava flows with the "fore-arc basalts" of the IBM fore arc has critical implications regarding the style of magmatism accompanying arc initiation and the lateral (across-strike) extent of this type of igneous activity. The apparent absence of boninite at Site U1438, however, may indicate petrologic provinciality was established within the first few million years of IBM magmatism.

The voluminous volcaniclastic rocks recovered from the Eocene through Oligocene sequence of Units II, III, and IV contain sufficiently fresh glass (at least in the shallower section) and igneous minerals and clasts to allow comprehensive petrological and geochemical description of the compositional evolution during the Paleogene IBM arc. A noteworthy feature of the mineral assemblage is the persistent but minor occurrence of amphibole. This phase is rare in the tephra recovered from previously drilled sites in the IBM fore arc and may indicate that significant across-strike variability of magma compositions was established in the Paleogene. Formation MicroScanner images show bedding and other features that may help characterize the large-scale tectonic development of the ASB; structural orientation may characterize the geographic provenance of the coarse-grained sediments. Sonic and density data from logs and cores will give a seismic traveltime-depth relationship for the site, providing characterization of seismic boundaries and accurate tie-points between core-log data and seismic data. The seismic velocity structure of the ASB specifically and the adjacent KPR more generally will become better constrained.

The quality of the cores obtained in the uppermost Unit I provide an excellent paleoceanographic sedimentary record, including the Oligocene–Miocene transition, the mid-Miocene climatic optimum, and the Pliocene–Pleistocene onset of Northern Hemisphere glaciation and mid-Pliocene transition. Numerous layers of volcanic ash were recovered in the recent to Miocene sediments of Unit I, comprising vitric pumice and shards, as well as phenocrysts and isolated volcanogenic crystals of pyroxene, plagioclase, biotite, quartz, and opaque minerals. Comparison of glass and mineral compositions with Ryukyu-Kyushu, Honshu, and Neogene IBM tephras will permit identification of the sources of volcanic ash; pending further age constraints, new data from Site U1438 will permit refined modeling of volumes, explosivity, and geochemical properties of the explosive output of the respective arcs surrounding the ASB.

The fundamentally important discoveries of the age (>50 Ma based on biostratigraphy; <60 Ma thermal age) and composition of the oceanic basement at Site U1438 provide critical constraints on the inception of the intraoceanic IBM arc. It appears a major change in Pacific plate motion following subduction of the Izanagi-Pacific Ridge beneath East Asia led to reorganization of equatorially located networks of island arc systems in the region between the Australian and Asian plates. The Philippine Sea plate developed in this region and experienced trench roll-back at one or more of its bounding plate margins. Rotation of the Philippine Sea plate led to propagation of transpressional forces on its northeastern margin, accompanied by rifting and seafloor spreading invading the former arc edifices forming much of the oldest part of the plate. Localization of a defined volcanic front in the IBM arc developed as the Philippine Sea plate migrated northward, and the transpressional boundary rotated clockwise to orthogonality with the westward-subducting Pacific plate. The oldest magmatic basement of the IBM arc developed in a latitudinally and longitudinally extensive seafloor spreading regime and is dominated by tholeiitic magmas sourced from highly depleted upper mantle.

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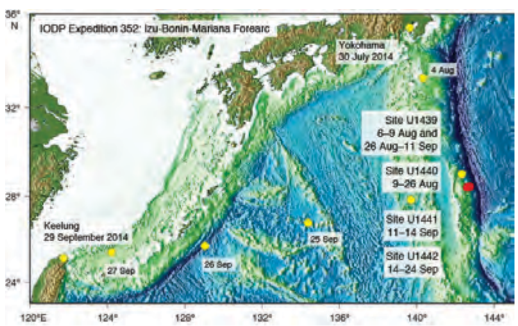
EXPEDITION 352: IZU-BONIN-MARIANA FOREARC



Abstract from *Preliminary Report*

During International Ocean Discovery Program Expedition 352, we intend to drill a section through the volcanic stratigraphy of the outer fore arc of the Izu-Bonin-Mariana system in order to trace the processes of magmatism, tectonics, and crustal accretion associated with subduction initiation. This study in turn has implications for understanding the origin of the many ophiolites that are now believed to form in this setting, and the expedition provides a good opportunity to test this supra-subduction zone ophiolite model. We intend two primary sites in the Bonin fore arc (Sites BON-1A and BON-2A), which form an offset-drilling pair that together should penetrate the full ~1.25 ± 0.25 km lava section. The sites have been surveyed and surface-sampled by several diving and dredging cruises. Studies of the recovered samples have established a stratigraphy in which peridotites, gabbros, and sheeted dikes are overlain by "fore-arc basalt" (FAB) and then in turn by boninites. Drilling Sites BON-1A and BON-2A will contribute to our understanding of intra-oceanic convergent plate margins by providing (1) a high-fidelity record of magmatic evolution during subduction initiation; (2) a test of the hypothesis that FAB tholeiites lie beneath boninites; (3) a record of the chemical gradients within these units and across their transitions; (4) information on how mantle melting processes evolve during subduction initiation from early decompression melting of fertile asthenosphere to late flux melting of depleted mantle, providing key empirical constraints for realistic subduction initiation geodynamic models; and (5) a test of the hypothesis that fore-arc lithosphere created during subduction initiation is the birthplace of supra-subduction zone ophiolites. Deep Sea Drilling Project Site 459 in the Mariana fore arc provides a well-surveyed alternate site of similar age, stratigraphy, and setting that should allow coring of a similar lava sequence to Site BON-1A.

General Information

Sites: U1439–U1442
Dates: 30 July to 29 September 2014
Ports: Yokohama, Japan to Keelung, Taiwan
Co-chief Scientists: Julian Pearce & Mark Reagan
Staff Scientist: Katerina Petronotis
Logging Staff Scientist: Sally Morgan

Reports and Publications

Ship reports:
http://iodp.tamu.edu/scienceops/sitesumm/352/

Scientific Prospectus:
http://publications.iodp.org/scientific_prospectus/352/

Preliminary Report:
http://publications.iodp.org/preliminary_report/352/

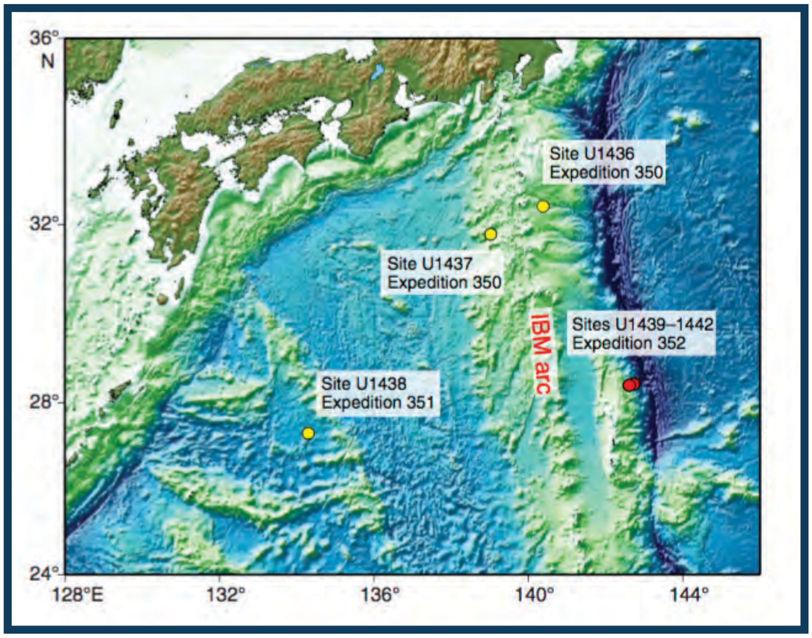
IODP Proceedings:
http://publications.iodp.org/proceedings/352/352title.html

Expedition-related citations:
http://publications.iodp.org/proceedings/352/352title.html#bib

Abstract from *IODP Proceedings*

The objectives for International Ocean Discovery Program Expedition 352 were to drill through the entire volcanic sequence of the Bonin fore arc to:

1. Obtain a high-fidelity record of magmatic evolution during subduction initiation and early arc development,
2. Test the hypothesis that fore-arc basalt lies beneath boninite and understand chemical gradients within these units and across the transition,
3. Use drilling results to understand how mantle melting processes evolve during and after subduction initiation, and
4. Test the hypothesis that the fore-arc lithosphere created during subduction initiation is the birthplace of suprasubduction zone ophiolites.

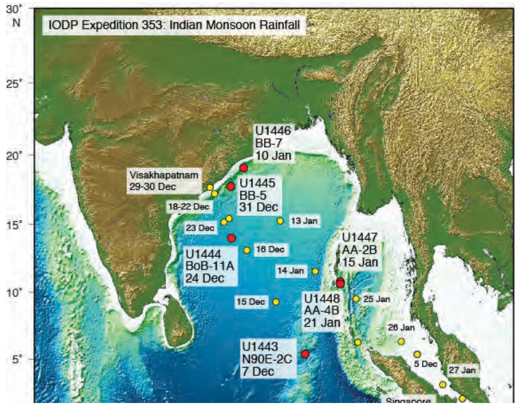


Regional map of the Izu-Bonin-Mariana (IBM) system showing the location of sites from Expeditions 350, 351, and 352.

Expedition 352 successfully cored 1.22 km of igneous basement and 0.46 km of overlying sediment, providing diverse, stratigraphically controlled suites of fore-arc basalt (FAB) and boninites related to seafloor spreading and earliest arc development. FAB and related rocks were recovered at the two deeper water sites (U1440 and U1441) and boninites and related rocks were recovered at the two sites (U1439 and U1442) drilled upslope to the west. FAB lavas and dikes are depleted in high–field strength trace elements such as Ti and Zr relative to mid-ocean-ridge basalt but have relatively diverse concentrations of trace elements because of variation in degrees of melting, and potentially, the amount of subducted fluids involved in their genesis. FAB are relatively differentiated, and average degree of differentiation increases with depth, which is consistent with crystal fractionation in a persistent magma chamber system beneath a spreading center. Holes U1439C and U1442A yielded entirely boninite differentiation series lavas that generally become more primitive and have lower TiO_2 concentrations upward. The presence of dikes at the base of the sections at Sites U1439 and U1440 provides evidence that boninitic and FAB lavas are both underlain by their own conduit systems and, therefore, that FAB and boninite group lavas are likely offset more horizontally than vertically. We thus propose that seafloor spreading related to subduction initiation migrated from east to west after subduction initiation and during early arc development. Initial spreading was likely rapid, and an axial magma chamber was present. Melting was largely decompressional during this period, but subducted fluids affected some melting. As subduction continued and spreading migrated to the west, the embryonic mantle wedge became more depleted and the influence of subducted constituents dramatically increased, causing the oceanic crust to be boninitic rather than tholeiitic. The general decrease in fractionation upward in the boninite holes reflects the eventual disappearance of persistent magma chambers, either because spreading rate was decreasing with distance from the trench or because spreading was succeeded by off-axis magmatism trenchward of the ridge. The extreme depletion of the sources for all boninitic lavas was likely related to the incorporation of mantle residues from FAB generation. This mantle depletion continued during generation of lower silica boninitic magmas, exhausting clinopyroxene from the mantle such that the capping high-silica, low-titanium boninites were generated from harzburgite.

Additional results of the cruise include recovery of Eocene to recent deep-sea sediment that records variation in sedimentation rates with time resulting from variations in climate, the position of the carbonate compensation depth, and local structural control. Three phases of highly explosive volcanism (latest Pliocene to Pleistocene, late Miocene to earliest Pliocene, and Oligocene) were identified, represented by 132 graded air fall tephra layers. Structures found in the cores and reflected in seismic profiles show that this area had periods of normal, reverse, and strike-slip faulting. Finally, basement rock P-wave velocities were shown to be slower than those observed during logging of normal ocean crust sites.

EXPEDITION 353: INDIAN MONSOON RAINFALL



Abstract from *Scientific Prospectus*

Scientific ocean drilling (Deep Sea Drilling Project [DSDP], Ocean Drilling Program [ODP], and Integrated Ocean Drilling Program) has never taken place in the Bay of Bengal north of 9°N. Thus, the core region of summer monsoon precipitation has never been investigated. DSDP Leg 22 (1974) and ODP Leg 121 (1989) drilled the southernmost region (5°–9°N), capturing the distal end of the summer monsoon influence. India's partnership in the International Ocean Discovery Program (IODP) provides an opportunity to investigate this key northern region. IODP Expedition 353 seeks to recover Upper Cretaceous–Holocene sediment sections that record erosion and runoff signals from river input to the Bay of Bengal as well as the resulting north–south surface water salinity gradient. Analysis of sediment sections from the Mahanadi Basin (northeast Indian margin), the Nicobar-Andaman Basin (Andaman Sea), and the northern Ninetyeast Ridge (southern Bay of Bengal) will be used to understand the physical mechanisms underlying changes in monsoonal precipitation, erosion, and run-off across timescales from millennial through tectonic. These sites will provide crucial new information within which to interpret differences among existing results from previous monsoon-themed drilling expeditions in the Arabian Sea (ODP Leg 117), the South China Sea (ODP Leg 184), and the Sea of Japan (Integrated Ocean Drilling Program Expedition 346). These goals directly address challenges in the "Climate and Ocean Change" theme of the IODP Science Plan.

General Information

Sites: U1443–U1448
Dates: 29 November 2014–29 January 2015
Ports: Singapore to Singapore
Co-chief Scientists: Steven Clemens & Wolfgang Kuhnt
Staff Scientist: Leah LeVay

Reports and Publications

Ship reports:
http://iodp.tamu.edu/scienceops/sitesumm/353/index.html

Scientific Prospectus:
http://publications.iodp.org/scientific_prospectus/353/

Preliminary Report:
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Expedition-related citations:
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Abstract from *IODP Proceedings*

International Ocean Discovery Program (IODP) Expedition 353 (29 November 2014–29 January 2015) drilled six sites in the Bay of Bengal, recovering 4280 m of sediments during 32.9 days of on-site drilling. Recovery averaged 97%, including coring with the advanced piston corer, half-length advanced piston corer, and extended core barrel systems. The primary objective of Expedition 353 is to reconstruct changes in Indian monsoon circulation since the Miocene at tectonic to centennial timescales. Analysis of the sediment sections recovered will improve our understanding of how monsoonal climates respond to changes in forcing external to the Earth's climate system (i.e., insolation) and changes in forcing internal to the Earth's climate system, including changes in continental ice volume, greenhouse gas concentrations, sea level, and the ocean-atmosphere exchange of energy and moisture. All of these mechanisms play critical roles in current and future climate change in monsoonal regions.

The primary signal targeted is the exceptionally low salinity surface waters that result, in roughly equal measure, from both direct summer monsoon precipitation above the Bay of Bengal and runoff from the numerous large river basins that drain into the Bay of Bengal. Changes in rainfall and surface ocean salinity are captured and preserved in a number of chemical, physical, isotopic, and biological components of sediments deposited in the Bay of Bengal. Expedition 353 sites are strategically located in key regions where these signals are the strongest and best preserved. Salinity changes at IODP Sites U1445 and U1446 (northeast Indian margin) result from direct precipitation as well as runoff from the Ganges-Brahmaputra river complex and the many river basins of peninsular India. Salinity changes at IODP Sites U1447 and U1448 (Andaman Sea) result from direct precipitation and runoff from the Irrawaddy and Salween river basins. IODP Site U1443 (Ninetyeast Ridge) is an open-ocean site with modern surface water salinity very near to the global mean but is documented to have recorded changes in monsoonal circulation over orbital to tectonic timescales. This site serves as an anchor for establishing the extent to which the north to south (19°N to 5°N) salinity gradient changes over time.

Introduction from *IODP Proceedings*

The *R/V JOIDES Resolution* has conducted scientific ocean drilling in many of the marginal basins surrounding monsoon-influenced regions of India and Asia including the Arabian Sea (Ocean Drilling Program [ODP] Leg 117), the South China Sea (ODP Leg 184), the East China Sea (Integrated Ocean Drilling Program Expedition 346), and the marginal sea bordered by the Eurasian continent, the Korean Peninsula, and the Japanese Islands (Expedition 346). Sediments recovered have been used to reconstruct changes in summer monsoon upwelling and eolian transport (Leg 117), summer and winter monsoon surface and intermediate water dynamics in the northern and southern regions of the South China Sea (Leg 184), the influence of the westerlies on monsoonal circulation in the marginal sea bordered by the Eurasian continent, the Korean Peninsula, and the Japanese Islands (Expedition 346), and the influence of Yangtze River runoff on the surface waters of the East China Sea (Expedition 346). These records will be complemented by future drilling during scheduled International Ocean Discovery Program (IODP) expeditions in the Eastern Arabian Sea (Expedition 355), the Maldives (Expedition 359), and the Timor Sea (Expedition 363) (Figure F1). Prior to Expedition 353, however, no scientific drilling has occurred in the core convective region of the Indo- Asian monsoon system, the northern Bay of Bengal. Scientific drilling last occurred in the Bay of Bengal in 1972 (Deep Sea Drilling Project Leg 22) when the *D/V Glomar Challenger* drilled Sites 217 and 218 in the southernmost Bay of Bengal (8°N to 9°N). However, scientific studies performed on India's National Gas Hydrate Program Expedition 1 cores collected aboard the *JOIDES Resolution* in 2006 (Collett et al., 2008; Ramana et al., 2014), which provided the foundation for selecting most of the sites for Expedition 353, indicate the excellent potential for paleoclimatic and paleoceanographic reconstructions in the region (i.e., Ponton et al., 2012; Cawthern et al., 2014; Flores et al., 2014; Johnson et al., 2014; Phillips et al., 2014a, 2014b; Ali et al., in press). Expedition 353 fills this scientific/geographic gap by drilling targets in the Bay of Bengal that span 5°N to 20°N (Figure F2). Analysis of these sediments will help to address the scientific objectives outlined below.

Pliocene-Pleistocene Objectives

- Establish the sensitivity and timing of changes in monsoon circulation relative to insolation forcing, latent heat export from the Southern Hemisphere, global ice volume extent, and green- house gas concentrations;
- Determine the extent to which Indian and East Asian monsoon winds and precipitation are coupled and at what temporal and geographic scales;
- Better separate the effects of climate change and tectonics on erosion and runoff; and
- Provide verification targets for climate models, including the rapidly evolving water isotope–enabled, time-dependent models.

Campanian-Miocene Objectives

- Understand the timing and conditions under which monsoonal circulation initiated and reconstruct the variability of the Indian monsoon at orbital timescales;
- Understand the relationship between Indian monsoon variability and major past global climatic events such as the Oligocene/Miocene cooling (Zachos et al., 1997), the onset of the mid-Miocene climatic optimum (Holbourn et al., 2007, 2014; Zachos et al., 2001), mid-Miocene cooling and Antarctic cryosphere expansion (Holbourn et al., 2013), and the Pliocene-Pleistocene enhancement of Northern Hemisphere glaciation (Lisiecki and Raymo, 2005, 2007);
- Establish a complete Oligocene–present astronomically tuned timescale based on high-resolution benthic and planktonic isotope reference curves for the Indian Ocean; and
- Integrate high-resolution distribution studies of well-preserved Oligocene–recent calcareous and siliceous microfossils from the Indian Ocean into global compilation studies of paleoclimatic and biotic evolution.

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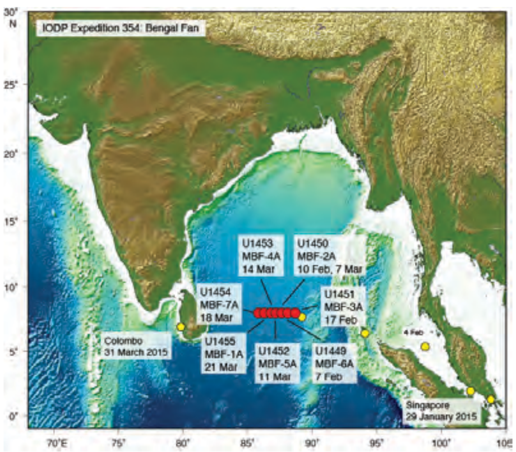
EXPEDITION 354: BENGAL FAN



Abstract from *Scientific Prospectus*

Expedition 354 will drill a transect of holes in the Bay of Bengal to address interactions among the growth of the Himalaya and Tibet, the development of the Asian monsoon, and processes affecting the carbon cycle and global climate. Because sedimentation in the Bengal Fan responds to both climate and tectonic processes, its terrigenous sediment records the past evolution of both the Himalaya and regional climate. The histories of the Himalayan/Tibetan system and the Asian monsoon require sampling different periods of time with different levels of precision. Accordingly, we propose a transect of six holes in the fan at 8°N with two complementary objectives. (1) We will study the early stages of Himalayan erosion, which will bear on the India-Eurasia collision and the development of the Himalaya and Tibet as topographic features. We will drill a deep site (MBF-3A to ~1500 m) in the west flank of the Ninetyeast Ridge where a reflector interpreted as a Paleocene-Eocene unconformity could be reached at a reasonable depth. (2) We will study the Neogene development of the Asian monsoon and its impact on sediment supply and flux. Our east–west transect of drill sites at 8°N will include Site MBF-3A and two other 900 m penetration sites (MBF-1A and MBF-2A) to reach sediment at least as old as 10–12 m.y. Records from the Arabian Sea and the Indian subcontinent suggest that at ~7–8 Ma the intensity of the monsoon increased and C4 plants expanded. Moreover, these changes appear to be linked to changes in the erosional regime as recorded by Ocean Drilling Program Leg 116 and possibly to the tectonic evolution of southeast Asia. This transect will allow study of the extent to which a strengthening of the monsoon encompassed the Bay of Bengal, where increased rainfall, not strengthened wind, characterizes the monsoon, and will allow quantitative studies of the interrelations of climate change and sediment accumulation. In addition, three sites (MBF-4A, MBF-5A, and MBF-6A) will document how the depocenter migrated across this transect during the Pleistocene and will provide the most complete record of channel-derived terrigenous material through this time interval.

General Information

Sites: U1449–U1455
Dates: 29 January–31 March 2015
Ports: Singapore to Colombo, Sri Lanka
Co-chief Scientists: Christian France-Lanord & Volkhard Spiess
Staff Scientist: Adam Klaus

Reports and Publications

Ship reports:
http://iodp.tamu.edu/scienceops/sitesumm/354/index.html

Scientific Prospectus:
http://publications.iodp.org/scientific_prospectus/354/

Preliminary Report:
http://publications.iodp.org/preliminary_report/354/

IODP Proceedings:
http://publications.iodp.org/proceedings/354/354title.html

Expedition-related citations:
http://publications.iodp.org/proceedings/354/354title.html#bib

Abstract from *IODP Proceedings*

International Ocean Discovery Program Expedition 354 to 8°N in the Bay of Bengal drilled a seven-site, 320 km long transect across the Bengal Fan. Three deep-penetration and an additional four shallow holes give a spatial overview of the primarily turbiditic depositional system that comprises the Bengal deep-sea fan. Sediments originate from Himalayan rivers, documenting terrestrial changes of Himalayan erosion and weathering, and are transported through a delta and shelf canyon, supplying turbidity currents loaded with a full spectrum of grain sizes. Mostly following transport channels, sediments deposit on and between levees while depocenters laterally shift over hundreds of kilometers on millennial timescales. During Expedition 354, these deposits were documented in space and time, and the recovered sediments have Himalayan mineralogical and geochemical signatures relevant for reconstructing time series of erosion, weathering, and changes in source regions, as well as impacts on the global carbon cycle. Miocene shifts in terrestrial vegetation, sediment budget, and style of sediment transport were tracked. Expedition 354 has extended the record of early fan deposition by 10 My into the late Oligocene.

Introduction from *IODP Proceedings*

Of regions where tectonics and climate interact, southern Asia seems to illustrate their possible influences on each other more dramatically than any other region. The high elevation of the Tibetan Plateau and the rapid rise from the lowlands of northern India across the Himalaya profoundly affect both the average temperature structure of the atmosphere responsible for the seasonal winds and the distribution of precipitation that characterize the south Asian monsoon (Molnar et al., 2010; Boos and Kuang, 2011). Concurrently, monsoonal precipitation along the Himalaya generates one of the most important erosion fluxes of the planet. This surface mass transfer acts on the thermal structure and stress field of the mountain range and partly controls its morphology (Avouac and Burov, 1996). Finally, the erosion processes contribute to the global atmospheric CO_2 drawdown responsible for Cenozoic global cooling through organic carbon burial and silicate weathering. However, if the Tibetan Plateau and the Himalaya have influenced climate during Cenozoic time, the evidence suggesting such an influence is wholly inadequate to understand quantitatively how these geographical features have developed through time. This inadequacy is mostly due to the fact that direct records of the erosion of the mountain range are rare or limited in duration, so there is no consensus on the mass accumulation rate generated by the Ti- bet-Himalayan erosion to date (Métivier et al., 1999; Clift, 2006). Because of the lack of adequate sedimentary archives, the early stages of Himalayan evolution since the continental collision ~55 My ago to the Miocene are essentially unknown.

Expedition 354 was proposed to obtain data that can not only test hypothetical links between climate and tectonics but also provide new data not easily acquired but relevant for understanding a number of Earth processes. This expedition focuses on the erosional record of the Himalaya and on the development of the Asian monsoon over Cenozoic time. Because geology lacks the tools for determining paleoelevations except in unusual and ideal circumstances, the sedimentary record of material eroded from a mountain belt holds the least ambiguous record of its paleotopography. Approximately 80% of the material eroded from the Himalaya was deposited in the Bay of Bengal, which therefore hosts the most complete record.

Reconstructing accumulation rates from fan deposits is challenging because (1) the 2500 km length of the fan leads to variable thickness and onlap time from north to south and (2) the nature of fan deposition means that accumulation at a given location is highly discontinuous and hence cannot capture a regional trend of accumulation. For these reasons, this expedition is based on an east– west transect approach with a large number of holes. As the transect crosses the fan at 8°N latitude (middle fan), Paleogene deposits, if they exist, are in reach of reasonable drilling depths. The transect is anchored on the western flank of the Ninetyeast Ridge with a deep hole located to recover the oldest fan deposits. From there, the transect extends west across the central axis of the fan and ends at Deep Sea Drilling Project (DSDP) Site 218 above the 85°E Ridge. To resolve characteristics of fan construction during the Quaternary, a spacing of ≈50 km between sites was chosen based on the typical width of channel-levee systems.

During Expedition 354, seven sites were drilled on an east–west transect at 8°N, including

- One deep site to ~1200 meters below seafloor (mbsf) (Site U1451) to recover a complete sequence of fan deposits and in particular to reach prefan deposits;
- Two sites to ~900 mbsf (Sites U1450 and U1455) complementing Site U1451 to provide a transect of three sites across ~300 km to recover Pliocene and upper Miocene sediment to study Neogene fan evolution and the impact of the monsoonal system on sediment supply and flux; and
- Four dedicated shallow sites to 200–300 mbsf (Sites U1449, U1452, U1453, and U1454) to recover a complete terrigenous record of the Himalayan flux over the last 1–2 My, complemented by the shallow portion of the three deep-penetration sites.

During Expedition 354, the original transect of six sites was complemented by a seventh, alternate site (U1454) west of Site 218 that extended the transect to ~300 km. Expedition 354 builds on knowledge acquired during earlier drilling and seismic exploration of the Bengal Fan (DSDP Leg 22; Ocean Drilling Program [ODP] Leg 116; and *R/V Sonne* Cruises SO93 [Legs 1–3] and SO125, SO126, and SO188 [Legs 1 and 2]) and on current studies of the tectonic, geologic, geomorphological, and sedimentological processes acting on the Himalaya, the floodplain and delta of the Ganga-Brahmaputra, and the Bengal Fan. This expedition is one part of an integrated effort for International Ocean Discovery Program (IODP) drilling syntectonic basins around the Himalaya to improve our knowledge of monsoon evolution and its interaction with Himalayan growth and erosion. This includes in particular IODP Expeditions 353 (Indian Monsoon) and 355 (Arabian Sea Monsoon) on the Indus Fan.

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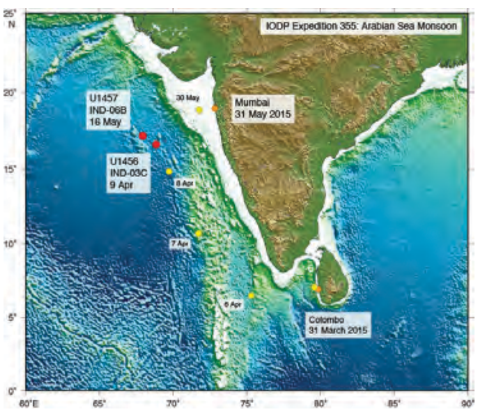
Expedition 355: Arabian Sea Monsoon



General Information

Sites: U1456–U1457
Dates: 31 March–31 May 2015
Ports: Colombo, Sri Lanka to Mumbai, India
Co-chief Scientists: Dhananjai Pandey & Peter Clift
Staff Scientist: Denise Kulhanek

Reports and Publications

Ship reports:
http://iodp.tamu.edu/scienceops/sitesumm/355/index.html

Scientific Prospectus:
http://publications.iodp.org/scientific_prospectus/355/355sp_3.htm

Preliminary Report:
http://publications.iodp.org/preliminary_report/355/

IODP Proceedings:
http://publications.iodp.org/proceedings/355/355title.html

Expedition-related citations:
http://publications.iodp.org/proceedings/355/355title.html#bib

Abstract from *Scientific Prospectus*

Interactions between the solid Earth and climate system represent a frontier area for geoscientific research that is strongly emphasized in the International Ocean Discovery Program (IODP) Science Plan. The continental margin of India adjoining the Arabian Sea offers a unique opportunity to understand tectonic-climatic interactions and the net impact of these on weathering and erosion of the Himalaya. Scientific drilling in the Arabian Sea is designed to understand the coevolution of mountain building, weathering, erosion, and climate over a range of timescales. The southwest monsoon is one of the most intense climatic phenomena on Earth. Its long-term development has been linked to the growth of high topography in South and Central Asia. Conversely, the tectonic evolution of the Himalaya, especially the exhumation of the Greater Himalaya, has been linked to intensification of the summer monsoon rains, as well as to plate tectonic forces. Weathering of the Himalaya has also been linked to long-term drawdown of atmospheric CO_2 during the Cenozoic, culminating in the onset of Northern Hemisphere glaciation. No other part of the world has such intense links between tectonic and climatic processes. Unfortunately, these hypotheses remain largely untested because of limited information on the history of erosion and weathering recorded in the resultant sedimentary prisms. This type of data cannot be found on shore because the proximal foreland basin records are disrupted by major unconformities, and depositional ages are difficult to determine with high precision. We therefore propose to recover longer records of erosion and weathering from the Indus Fan that will allow us to understand links between paleoceanographic processes and the climatic history of the region. The latter was partially addressed by Ocean Drilling Program (ODP) Leg 117 on the Oman margin, and further studies are proposed during IODP Expedition 353 (Indian Monsoon Rainfall) that will core several sites in the Bay of Bengal. Such records can be correlated to structural geological and thermochronology data in the Himalaya and Tibetan Plateau to estimate how sediment fluxes and exhumation rates change through time. The drilling will be accomplished within a regional seismic stratigraphic framework and will for the first time permit an estimation of sediment budgets together with quantitative estimates of weathering fluxes and their variation through time. Specific goals of this expedition include

1. Testing whether the timing of the exhumation of Greater Himalaya correlates with an enhanced erosional flux and stronger chemical weathering after ~23 Ma,
2. Determining the amplitude and direction of the environmental change at 8 Ma, and
3. Dating the age of the base of the fan and the underlying basement to constrain the timing of India-Asia collision.

Drilling through the fan base and into the underlying basement in the proposed area will permit additional constraints to be placed on the nature of the crust in the Laxmi Basin (Eastern Arabian Sea), which has a significant bearing on paleogeographic reconstructions along conjugate margins in the Arabian Sea and models of continental breakup on rifted volcanic margins.

Abstract from *IODP Proceedings*

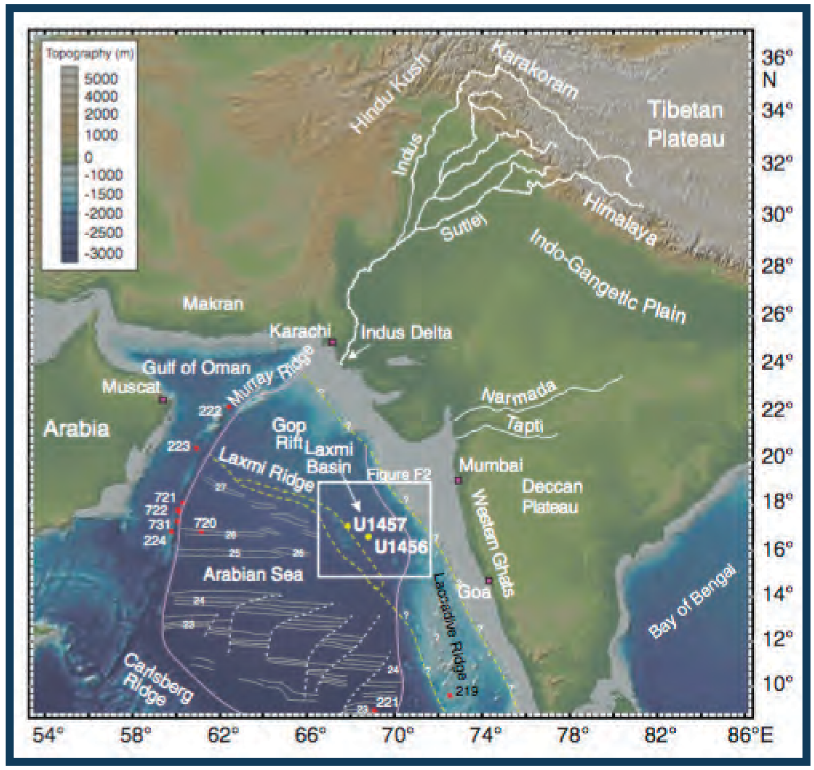
The Indian (southwest) summer monsoon is one of the most intense climatic phenomena on Earth, with its long-term development possibly linked to the growth of high topography in South and Central Asia. The Indian continental margin, adjoining the Arabian Sea, offers a unique opportunity to investigate tectonic–climatic interactions and the net impact of these processes on weathering and erosion of the western Himalaya. During International Ocean Discovery Program Expedition 355, two sites (U1456 and U1457) were drilled in Laxmi Basin in the eastern Arabian Sea to document the coevolution of mountain building, weathering, erosion, and climate over a range of timescales. In addition, recovering basement from the eastern Arabian Sea provides constraints on the early rifting history of the western continental margin of India with special emphasis on continental breakup between India and the Seychelles and its relationship to the plume-related volcanism of the Deccan Plateau.

Drilling and coring operations during Expedition 355 recovered sediment from Sites U1456 and U1457 in Laxmi Basin, penetrating 1109.4 and 1108.6 m below seafloor (mbsf), respectively. Drilling reached sediment dated to 13.5–17.7 Ma (late early to early middle Miocene) at Site U1456, although with a large hiatus between the lowermost sediment and overlying deposits dated at <10.9 Ma. At Site U1457, a much longer hiatus occurs near the base of the cored section, spanning from ~10.9 to ~62 Ma. At both sites, hiatuses span ~8.2–9.2 and ~3.6–5.6 Ma with a possible condensed section spanning ~2.0–2.6 Ma, although the total duration for each hiatus is slightly different between the two sites.

A major submarine fan probably draining the western Himalaya and Karakoram must have been supplying sediment to the eastern Arabian Sea since at least ~17 Ma. Sand mineral assemblages indicate that the Greater Himalayan Crystalline Sequence was fully exposed to the surface by this time. Most of the recovered sediment appears to be derived from the Indus River and includes minerals that are unique to the Indus Suture Zone, in particular glaucophane and hypersthene, most likely originating from the structural base of the Kohistan arc (i.e., within the Indus Suture Zone). Pliocene sandy intervals at Site U1456 were deposited in lower fan "sheet lobe" settings, with intervals of basin–plain turbidites separated by hemipelagic muddy sections deposited during the Miocene. Site U1457 is more distal in facies, reflecting its more marginal setting. No major active lobe appears to have affected Laxmi Basin since the late early Pleistocene (~1.2–1.5 Ma).

We succeeded in recovering sections spanning the 8 Ma climatic transition, when monsoon intensity is believed to have changed strongly, although the nature of this change awaits postcruise analysis. We also recovered sediment from large mass transport deposits measuring ~330 and ~190 m thick at Sites U1456 and U1457, respectively. These sections include an upper sequence of slump-folded muddy and silty rocks, as well as underlying calcarenites and limestone breccias, together with smaller amounts of volcanic clasts, all of which are likely derived from the western Indian continental shelf. Identification of similar facies on the regional seismic lines in Laxmi Basin suggests that these deposits form parts of one of the world's largest mass transport deposits.

Coring of igneous basement was achieved at Site U1457. Recovery of massive basalt and associated volcaniclastic sediment at this site should address the key questions related to rifting and volcanism associated with formation of Laxmi Basin. Geochemical analysis indicates that these are low-K, high-Mg subalkaline tholeiitic basalts and do not represent a typical mid-ocean-ridge basalt. Other observations made at the two sites during Expedition 355 provide vital constraints on the rift history of this margin. Heat flow measurements at the two drill sites were calculated to be ~57 and ~60 mW/m2. Such heat flow values are compatible with those observed in average oceanic crust of 63–84 Ma age, as well as with the presence of highly extended continental crust. Postcruise analyses of the more than ~1722 m of core will provide further information about the nature of tectonic–climatic interactions in this global type area for such studies.



Bathymetric map of the Arabian Sea and surrounding landmasses from GeoMapApp (Ryan et al., 2009). Yellow circles = Expedition 355 sites, white lines = major rivers and tributaries, red stars = earlier scientific drilling sites that have sampled the Indus Fan, pink line = approximate extent of the fan after Kolla and Coumes (1987), yellow dashed lines = speculated location of the continent/ocean boundary, depending on whether Laxmi Basin is oceanic or continental, gray lines with numbers = magnetic anomalies from Royer et al. (2002)

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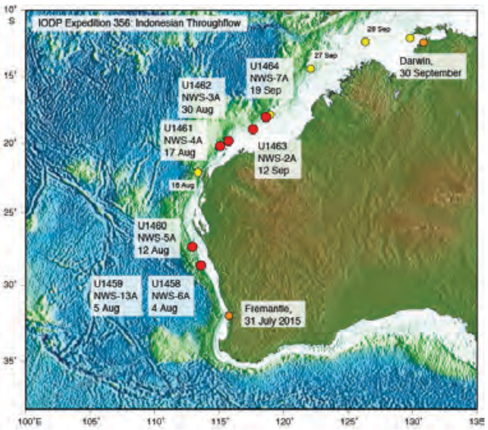
EXPEDITION 356: INDONESIAN THROUGHFLOW



Abstract from *Scientific Prospectus*

The Indonesian Throughflow (ITF) is a critical part of the global thermohaline conveyor. It plays a key role in transporting heat from the equatorial Pacific (the Indo-Pacific Warm Pool) to the Indian Ocean and exerts a major control on global climate. The complex tectonic history of the Indonesian Archipelago, a result of continued northward motion and impingement of the Australasian Plate into the Southeast Asian part of the Eurasian Plate, makes it difficult to reconstruct long-term (i.e., million year) ITF history from sites within the archipelago. The best areas to investigate ITF history are downstream in the Indian Ocean, either in the deep ocean away from strong tectonic deformation or along proximal passive margins that are directly under the influence of the ITF. Although previous Ocean Drilling Program and Deep Sea Drilling Project deepwater cores recovered in the Indian Ocean have been used to chart Indo-Pacific Warm Pool influence and, by proxy, ITF variability, these sections lack direct biogeographic and sedimentological evidence of the ITF. International Ocean Discovery Program Expedition 356 will drill a transect of cores over 10° latitude on the northwest shelf (NWS) of Australia to obtain a 5 m.y. record of ITF, Indo-Pacific Warm Pool, and climate evolution that has the potential to match orbital-scale deep-sea records in its resolution. Coring the NWS will reveal a detailed shallow-water history of ITF variability and its relationship to climate. It will allow us to understand the history of the Australian monsoon and its variability, a system whose genesis is thought to be related to the initiation of the East Asian monsoon and is hypothesized to have been in place since the Pliocene or earlier. It also will lead to a better understanding of the nature and timing of the development of aridity on the Australian continent.

Detailed paleobathymetric and stratigraphic data from the transect will also allow subsidence curves to be constructed to constrain the spatial and temporal patterns of vertical motions caused by the interaction between plate motion and convection within the Earth's mantle, known as dynamic topography. The NWS is an ideal location to study this phenomenon because it is positioned on the fastest moving continent since the Eocene, on the edge of the degree two geoid anomaly. Accurate subsidence analyses over 10° of latitude can resolve whether northern Australia is moving with/over a time-transient or long-term stationary downwelling within the mantle, thereby vastly improving our understanding of deep-Earth dynamics and their impact on surficial processes.

General Information

Sites: U1458–U1464
Dates: 31 July–30 September 2015
Ports: Fremantle to Darwin, Australia
Co-chief Scientists: Stephen Gallagher & Craig Fulthorpe
Staff Scientist: Kara Bogus

Reports and Publications

Ship reports:
http://iodp.tamu.edu/scienceops/sitesumm/356/index.html

Scientific Prospectus:
http://publications.iodp.org/scientific_prospectus/356/

Preliminary Report:
http://publications.iodp.org/preliminary_report/356/

IODP Proceedings:

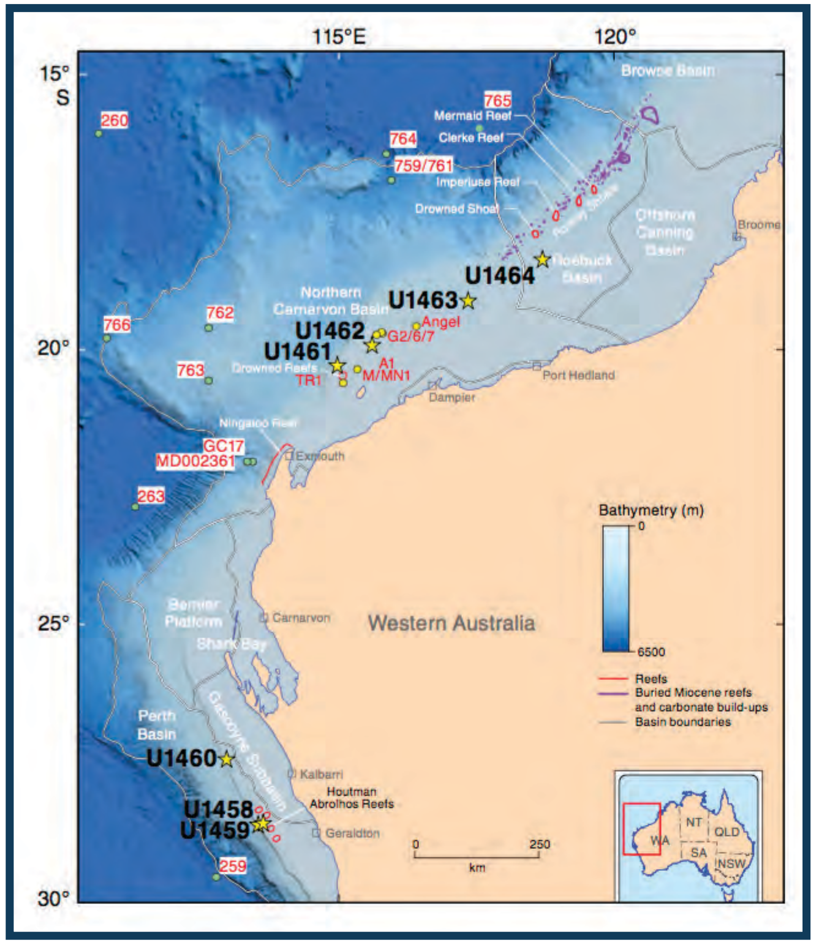
http://publications.iodp.org/proceedings/356/356title.html

Expedition-related citations:
http://publications.iodp.org/proceedings/356/356title.html#bib

Abstract from *IODP Proceedings*

The Indonesian Throughflow (ITF) is a critical part of the global thermohaline conveyor. It plays a key role in transporting heat from the equatorial Pacific (the Indo-Pacific Warm Pool) to the Indian Ocean and exerts a major control on global climate. The complex tectonic history of the Indonesian archipelago, a result of continued northward motion and impingement of the Australasian plate into the southeast Asian part of the Eurasian plate, makes it difficult to reconstruct long-term (i.e., million year) ITF history from sites within the archipelago. The best areas to investigate ITF history are downstream in the Indian Ocean, either in the deep ocean away from strong tectonic deformation or along proximal passive margins that are directly under the influence of the ITF. Although previous Ocean Drilling Program and Deep Sea Drilling Project deep- water cores recovered in the Indian Ocean have been used to chart Indo-Pacific Warm Pool influence and, by proxy, ITF variability, these sections lack direct biogeographic and sedimentological evi- dence of the ITF. International Ocean Discovery Program Expedition 356 cored seven sites covering a latitudinal range of 29°S–18°S off the northwest coast of Australia to obtain a 5 My record of the ITF, Indo-Pacific Warm Pool, and climate evolution that has the potential to match orbital-scale deep-sea records in its resolution. The material recovered will allow us to describe the history of the Australian monsoon and its variability, a system whose genesis is thought to be related to the initiation of the East Asian monsoon and is hypothesized to have been in place since the Pliocene or earlier. It also will lead to a better understanding of the nature and timing of the development of aridity on the Australian continent.

Detailed paleobathymetric and stratigraphic data from the transect will also allow subsidence curves to be constructed to constrain the spatial and temporal patterns of vertical motions caused by the interaction between plate motion and convection within the Earth's mantle, known as dynamic topography. The northwest shelf is an ideal location to study this phenomenon because it is positioned on the fastest moving continent since the Eocene, on the edge of the degree 2 geoid anomaly. Accurate subsidence analyses over 10° of latitude can resolve whether northern Australia is moving with or over either a time-transient or long-term stationary downwelling within the mantle, thereby vastly improving our understanding of deep-Earth dynamics and their impact on surficial processes.



Map of the NWS showing major basins and location of modern and "fossil" reefs. Seismic data near Site U1461 is shown in Figure F8. Stars = drill sites, green circles = Deep Sea Drilling Project (DSDP)/Ocean Drilling Program (ODP) sites and other core locations referred to in text, yellow cir- cles = industry well locations (Angel = Angel-1; G2/6/7 = Goodwyn-2, Good- wyn-6, Goodwyn-7; A1 = Austin-1; M/MN1 = Maitland/Maitland North-1; TR1 = West Tryal Rocks-1). WA = Western Australia, NT = Northern Territory, SA = South Australia, QLD = Queensland, NSW = New South Wales.

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IODP INTERNATIONAL OCEAN DISCOVERY PROGRAM

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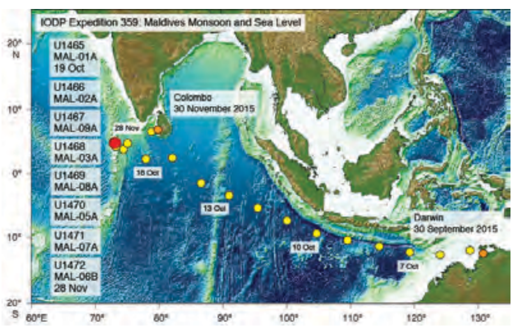
Expedition 359: Maldives Monsoon and Sea Level



General Information

Sites: U1465–U1472

Dates: 30 September to 30 November 2015

Ports: Darwin, Australia to Colombo, Sri Lanka

Co-chief Scientists: Christian Betzler & Gregor Eberli

Staff Scientist: Carlos Alvarez Zarikian

Reports and Publications

Ship reports:
http://iodp.tamu.edu/scienceops/sitesumm/359/index.html

Scientific Prospectus:
http://publications.iodp.org/scientific_prospectus/359/

Preliminary Report:
http://publications.iodp.org/preliminary_report/359/

IODP Proceedings:
http://publications.iodp.org/proceedings/359/359title.html

Expedition-related citations:
http://publications.iodp.org/proceedings/359/359title.html#bib

Abstract from *Scientific Prospectus*

International Ocean Discovery Program (IODP) Expedition 359 is designed to address sea level, currents, and monsoon evolution in the Indian Ocean. Seven proposed drill sites are located in the Maldives and one site is located in the Kerala-Konkan Basin on the western Indian continental margin. The Maldives carbonate edifice bears a unique and mostly unread Indian Ocean archive of the evolving Cenozoic icehouse world. It has great potential to serve as a key area for better understanding the effects of this global evolution in the Indo-Pacific realm. Based mainly on seismic stratigraphic data, a model for the evolution of this carbonate bank has been developed, showing how changing sea level and ocean current patterns shaped the bank geometries. A dramatic shift in development of the carbonate edifice from a sea level–controlled to a predominantly current-controlled system is thought to be directly linked to the evolving Indian monsoon. Fluctuations in relative sea level control the stacking pattern of depositional sequences during the lower to middle Miocene. This phase was followed by a two-fold configuration of bank development: bank growth continued in some parts of the edifice, whereas in other places, banks drowned. Drowning steps seem to coincide with onset and intensification of the monsoon-related current system and the deposition of giant sediment drifts. The shapes of drowned banks attest to the occurrence of these strong currents. The drift sediments, characterized by off-lapping geometries, formed large-scale prograding complexes, filling the Maldives Inner Sea basin. Because the strong current swept most of the sediment around the atolls away, relict banks did not prograde, and steady subsidence was balanced by aggradation of the atolls, which are still active today.

One important outcome of Expedition 359 is ground-truthing the hypothesis that the dramatic, pronounced change in the style of the sedimentary carbonate sequence stacking was caused by a combination of relative sea level fluctuations and ocean current system changes. Answering this question will directly improve our knowledge on processes shaping carbonate platforms and their stratigraphic records. Our findings would be clearly applicable to other Tertiary carbonate platforms in the Indo-Pacific region and to numerous others throughout the geological record. In addition, the targeted successions will allow calibration of the Neogene oceanic $\delta^{13}C$ record with data from a carbonate platform to platform-margin series. This is becoming important, as such records are the only type that exist in deep time. Drilling will provide the cores required for reconstructing changing current systems through time that are directly related to the evolution of the Indian monsoon. As such, the drift deposits will provide a continuous record of Indian monsoon development in the region of the Maldives. These data will be valuable for a comparison with proposed Site KK-03B in the Kerala-Konkan Basin (see Geological setting of the Kerala-Konkan Basin, below) and other monsoon-dedicated IODP expeditions.

The proposed site in the Kerala-Konkan Basin provides the opportunity to recover colocated oceanic and terrestrial records for monsoon and premonsoon Cenozoic climate in the eastern Arabian Sea and India, respectively. The site is located on a bathymetric high immediately north of the Chagos-Laccadive Ridge and is therefore not affected by strong tectonic, glacial, and nonmonsoon climatic processes that affect fan sites fed by Himalayan rivers. The cores are expected to consist of a continuous sequence of foraminifer-rich pelagic sediments with subordinate cyclical siliciclastic inputs of fluvial origin from the Indian Peninsula for the Neogene and a continuous paleoclimate record at orbital timescales into the Eocene and possibly the Paleocene.

Abstract from *IODP Proceedings*

International Ocean Discovery Program Expedition 359 was designed to address changes in sea level and currents, along with monsoon evolution in the Indian Ocean. The Maldives archipelago holds a unique and mostly unread Indian Ocean archive of the evolving Cenozoic icehouse world. Cores from eight drill sites in the Inner Sea of the Maldives provide the tropical marine record that is key for better understanding the effects of this global evolution in the Indo-Pacific realm. In addition, the bank geometries of the carbonate archipelago provide a physical record of changing sea level and ocean currents. The bank growth occurs in pulses of aggradation and progradation that are controlled by sea level fluctuations during the early and middle Miocene, including the mid-Miocene Climate Optimum. A dramatic shift in development of the carbonate edifice from a sea level–controlled to a predominantly current controlled system appears to be directly linked to the evolving Indian monsoon. This phase led to a twofold configuration of bank development: bank growth continued in some parts of the edifice, whereas in other places, banks drowned. Drowning steps seem to coincide with onset and intensification of the monsoon-related current system and subsequent deposition of contourite fans and large-scale sediment drifts. As such, the drift deposits will provide a continuous record of Indian monsoon development in the region of the Maldives.

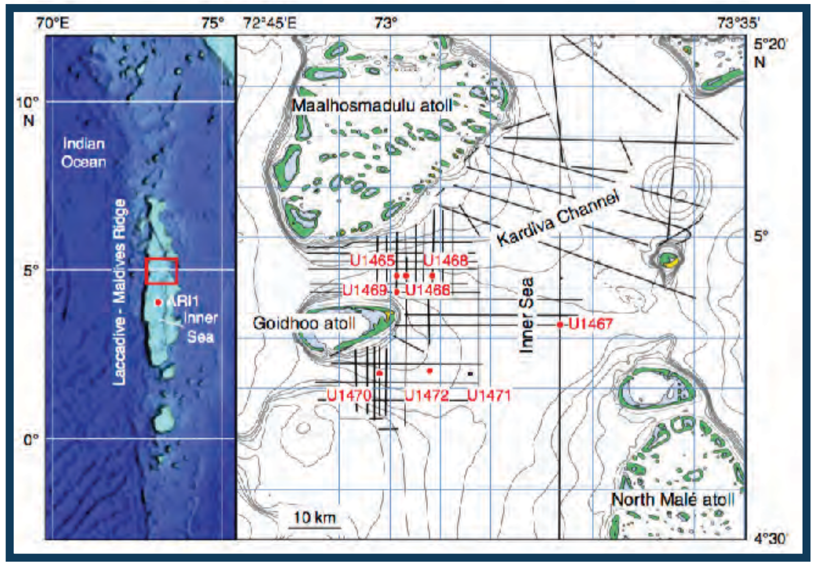


Figure F5. Location map of Expedition 359 sites in the Inner Sea of the Maldives with line plan of site survey seismic lines for ARI 1, an existing industrial well that served for preexpedition seismic stratigraphic interpretation.

A major focus of Expedition 359 was to date precisely the onset of the current system. This goal was successfully completed during the expedition. The second important outcome of Expedition 359 was groundtruthing the hypothesis that the dramatic, pronounced change in style of the carbonate platform sequence stacking was caused by a combination of relative sea level fluctuations and ocean current system changes. These questions are directly addressed by the shipboard scientific data.

In addition, Expedition 359 cores will provide a complete Neogene $\delta^{13}C$ record of the platform and platform margin sediments and a comparison with pelagic records over the same time period. This comparison will allow assessment of the extent to which platform carbonates record changes in the global carbon cycle and whether changes in the carbon isotopic composition of organic and inorganic components covary and the implications this has on the deep-time record. This determination is important because such records are the only type that exists in deep time.

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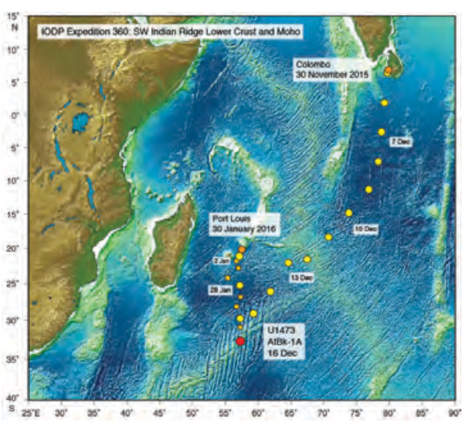
EXPEDITION 360: SW INDIAN RIDGE LOWER CRUST AND MOHO



General Information

Sites: U1473
Dates: 30 November 2015 to 30 January 2016
Ports: Colombo, Sri Lanka to Port Louis, Mauritius
Co-chief Scientists: Henry Dick & Chris MacLeod
Staff Scientist: Peter Blum

Reports and Publications

Ship reports:
http://iodp.tamu.edu/scienceops/sitesumm/360/index.html

Scientific Prospectus:
http://publications.iodp.org/scientific_prospectus/360/index.html

Preliminary Report:
http://publications.iodp.org/preliminary_report/360/

IODP Proceedings:
http://publications.iodp.org/proceedings/360/360title.html

Expedition-related citations:
http://publications.iodp.org/proceedings/360/360title.html#bib

Abstract from *Scientific Prospectus*

International Ocean Discovery Program (IODP) Expedition 360 will form the first leg of a multiphase drilling project that aims to drill through the crust/mantle boundary at the ultraslow-spreading Southwest Indian Ridge and investigate the nature of the Mohorovičić seismic discontinuity (Moho). Expedition 360 is expected to drill ~1300 m into lower crustal gabbro and is unlikely to penetrate the crust–mantle transition or recover a significant amount of peridotite. Drilling will be sited at Atlantis Bank, on an elevated wave-cut platform on the east flank of the Atlantis II Transform. Previous drilling and mapping shows that Atlantis Bank is a large oceanic core complex, exposing a tectonic window of deep crustal and lithospheric mantle exhumed on the footwall of an oceanic detachment fault. The shallowest part of Atlantis Bank, at 700 m water depth, consists of a ~25 km^2 wave-cut platform rimmed by a thin bioclastic limestone cap. The platform is part of a continuous gabbro massif ~40 km long by 30 km wide, overlying granular mantle peridotite that forms the lower slopes of the eastern wall of the Atlantis II Transform. Mapping shows that basement on the wave-cut platform consists largely of shallow-dipping amphibolitized gabbro mylonite generated by detachment faulting. This fault rooted near-continuously into partially crystalline gabbro for >4 million years. The mylonite exposed on the platform, and by cross-faulting and landslips on the sides of Atlantis Bank, both cut and are cut by steeply north dipping greenschist-facies diabase dikes. Thus, the gabbro crystallized at depth was uplifted into the zone of diking at the ridge axis, creating, in effect, the equivalent to the base of a dike–gabbro transition seen in many ophiolites.

Previous Ocean Drilling Program (ODP) operations at Atlantis Bank drilled the 1508 m deep Hole 735B and 150 m deep Hole 1105A, both recovering long sections of gabbro. During Expedition 360, we propose to drill to a nominal depth of 1.3 km at a site on the northern edge of the Atlantis Bank platform, ~1 km north-northeast of Hole 1105A and ~2 km northeast of Hole 735B. A future drilling expedition, SloMo-Leg 2, aims to deepen the hole to ~3 km, with the overall goal of penetrating the crust–mantle transition, which is believed to be ~2.5 km above the seismically determined Moho. Specific objectives of Expedition 360 include establishing the lateral continuity of the igneous, metamorphic, and structural stratigraphies previously drilled to the southwest, testing the nature of a magnetic polarity transition, and investigating the biogeochemistry of the lower crust.

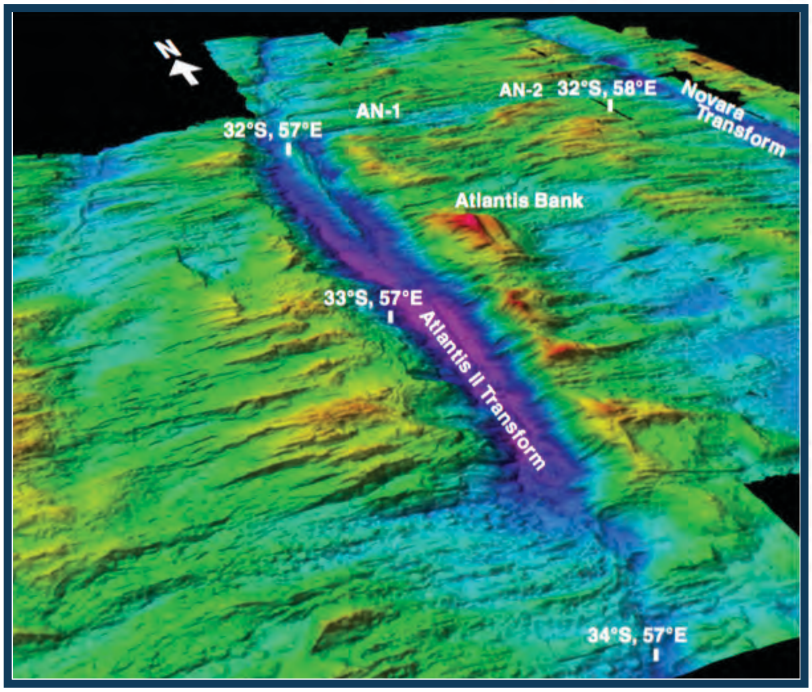
Abstract from *IODP Proceedings*

International Ocean Discovery Program (IODP) Expedition 360 was the first leg of Phase I of the SloMo (shorthand for "The nature of the lower crust and Moho at slower spreading ridges") Project, a multiphase drilling program that proposes to drill through the outermost of the global seismic velocity discontinuities, the Mohorovičić seismic discontinuity (Moho). The Moho corresponds to a compressional wave velocity increase, typically at ~7 km beneath the oceans, and has generally been regarded as the boundary between crust and mantle. An alternative model, that the Moho is a hydration front in the mantle, has recently gained credence upon the discovery of abundant partially serpentinized peridotite on the seafloor and on the walls of fracture zones, such as at Atlantis Bank, an 11–13 My old elevated oceanic core complex massif adjacent to the Atlantis II Transform on the Southwest Indian Ridge.

Hole U1473A was drilled on the summit of Atlantis Bank during Expedition 360, 1–2 km away from two previous Ocean Drilling Program (ODP) holes: Hole 735B (drilled during ODP Leg 118 in 1987 and ODP Leg 176 in 1997) and Hole 1105A (drilled during ODP Leg 179 in 1998). A mantle peridotite/gabbro contact has been traced by dredging and diving along the transform wall for 40 km. The contact is located at ~4200 m depth on the transform wall below the drill sites but shoals considerably 20 km to the south, where it was observed in outcrop at 2563 m depth. Moho reflections, however, have been found at ~5–6 km beneath Atlantis Bank and <4 km beneath the transform wall, leading to the suggestion that the seismic discontinuity may not represent the crust/mantle boundary but rather an alteration (serpentinization) front. This in turn raises the interesting possibility that methanogenesis associated with serpentinization could support a whole new planetary biosphere deep in the oceanic basement. The SloMo Project seeks to test these hypotheses at Atlantis Bank and evaluate the processes of natural carbon sequestration in the lower crust and uppermost mantle.

A primary objective of SloMo Leg 1 was to explore the lateral variability of the stratigraphy established in Hole 735B. Comparison of Hole U1473A with Holes 735B and 1105A allows us to demonstrate a continuity of process and complex interplay of magmatic accretion and steady-state detachment faulting over a time period of ~128 ky. Preliminary assessment indicates that these sections of lower crust are constructed by repeated cycles of intrusion, represented in Hole U1473A by approximately three upwardly differentiated hundreds of meter–scale bodies of olivine gabbro broadly similar to those encountered in the deeper parts of Hole 735B.

Specific aims of Expedition 360 focused on gaining an understanding of how magmatism and tectonism interact in accommodating seafloor spreading, how magnetic reversal boundaries are expressed in the lower crust, assessing the role of the lower crust and shallow mantle in the global carbon cycle, and constraining the extent and nature of life at deep levels within the ocean lithosphere.



3-D perspective view of the Atlantis II Transform, looking north- northeast. Data compiled from multibeam data collected during Conrad Cruise C2709, James Clark Ross Cruise JR31, Yokosuka and Kairei site survey cruises, and several French multibeam expeditions, combined with satellite gravity seafloor data and the Global Multi-Resolution Topography database (http://www.marine-geo.org/portals/gmrt) (see also Mendel et al., 1997, 2003; Dick et al., 1999; Kinoshita et al., 2001; Matsumoto et al., 2002; Sauter et al., 2004; Baines et al., 2007).

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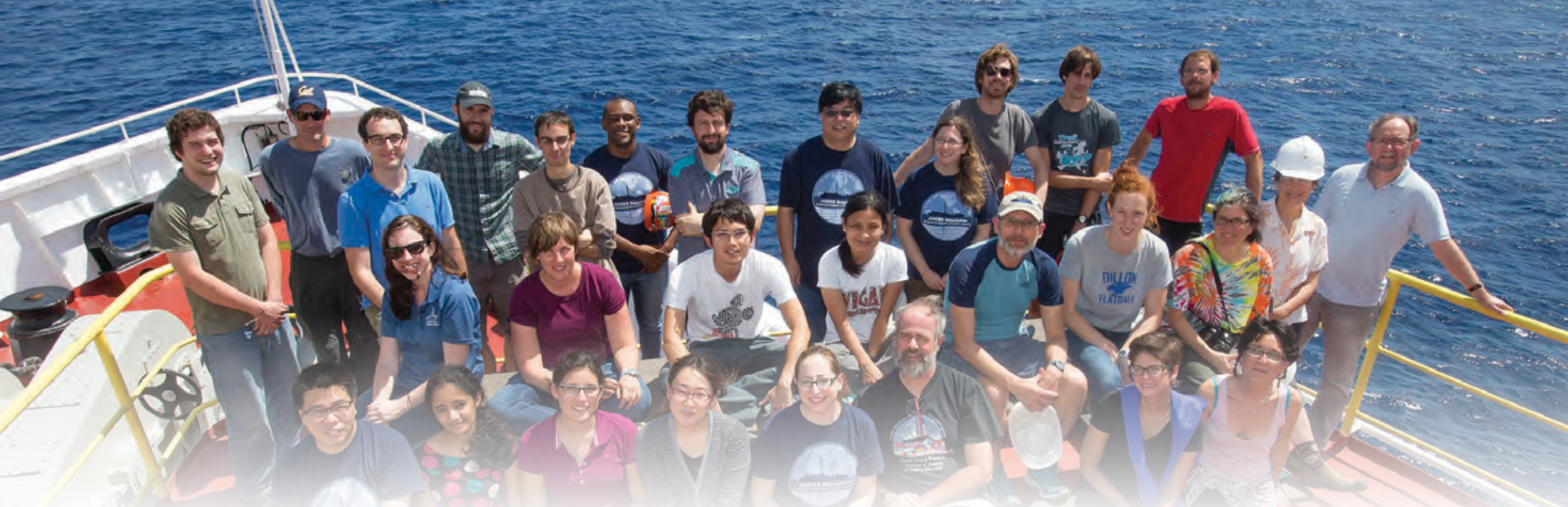
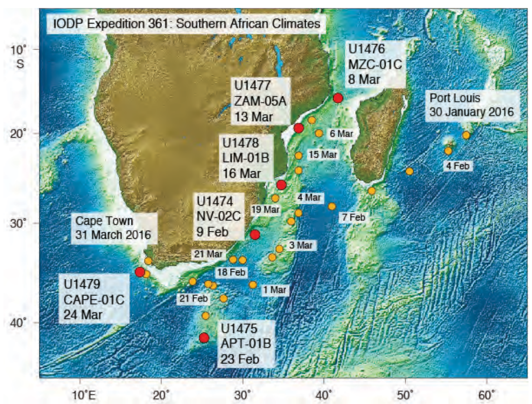


EXPEDITION 361: SOUTH AFRICAN CLIMATES



General Information

Sites: U1474–U1479
Dates: 30 January to 31 March 2016
Ports: Port Louis to Cape Town, South Africa
Co-chief Scientists: Ian Hall & Sidney Hemming
Staff Scientist: Leah LeVay

Reports and Publications

Ship reports:
http://iodp.tamu.edu/scienceops/sitesumm/361/index.html

Scientific Prospectus:
http://publications.iodp.org/scientific_prospectus/361/

Preliminary Report:
http://publications.iodp.org/preliminary_report/361/

IODP Proceedings:
Pending

Expedition-related citations:
http://iodp.tamu.edu/publications/bibliographic_information/361cit.html

Abstract from *Scientific Prospectus*

The Agulhas Current is the strongest western boundary current in the Southern Hemisphere, transporting some 70 Sv of warm and saline surface waters from the tropical Indian Ocean along the East African margin to the tip of Africa. Exchanges of heat and moisture with the atmosphere influence southern African climates, including individual weather systems such as extratropical cyclone formation in the region and rainfall patterns. Recent ocean models and paleoceanographic data further point at a potential role of the Agulhas Current in controlling the strength and mode of the Atlantic Meridional Overturning Circulation (AMOC) during the Late Pleistocene. Spillage of saline Agulhas water into the South Atlantic stimulates buoyancy anomalies that act as a control mechanism on the basin-wide AMOC, with implications for convective activity in the North Atlantic and Northern Hemisphere climate.

International Ocean Discovery Program (IODP) Expedition 361 aims to extend this work to periods of major ocean and climate restructuring during the Pliocene/Pleistocene to assess the role that the Agulhas Current and ensuing (interocean) marine heat and salt transports have played in shaping the regional- and global-scale ocean and climate development. This expedition will core six sites on the southeast African margin and Indian–Atlantic ocean gateway. The primary sites are located between 416 and 3040 m water depths.

The specific scientific objectives are

- To assess the sensitivity of the Agulhas Current to changing climates of the Pliocene/Pleistocene, in association with transient to long-term changes of high-latitude climates, tropical heat budgets, and the monsoon system;
- To reconstruct the dynamics of the Indian–Atlantic gateway circulation during such climate changes, in association with changing wind fields and migrating ocean fronts;
- To examine the connection between Agulhas leakage and ensuing buoyancy transfer and shifts of the AMOC during major ocean and climate reorganizations during at least the last 5 My; and
- To address the impact of Agulhas variability on southern Africa terrestrial climates and, notably, rainfall patterns and river runoff.

Additionally, Expedition 361 will complete an intensive interstitial fluids program at four of the sites aimed at constraining the temperature, salinity, and density structure of the Last Glacial Maximum (LGM) deep ocean, from the bottom of the ocean to the base of the main thermocline, to address the processes that could fill the LGM ocean and control its circulation.

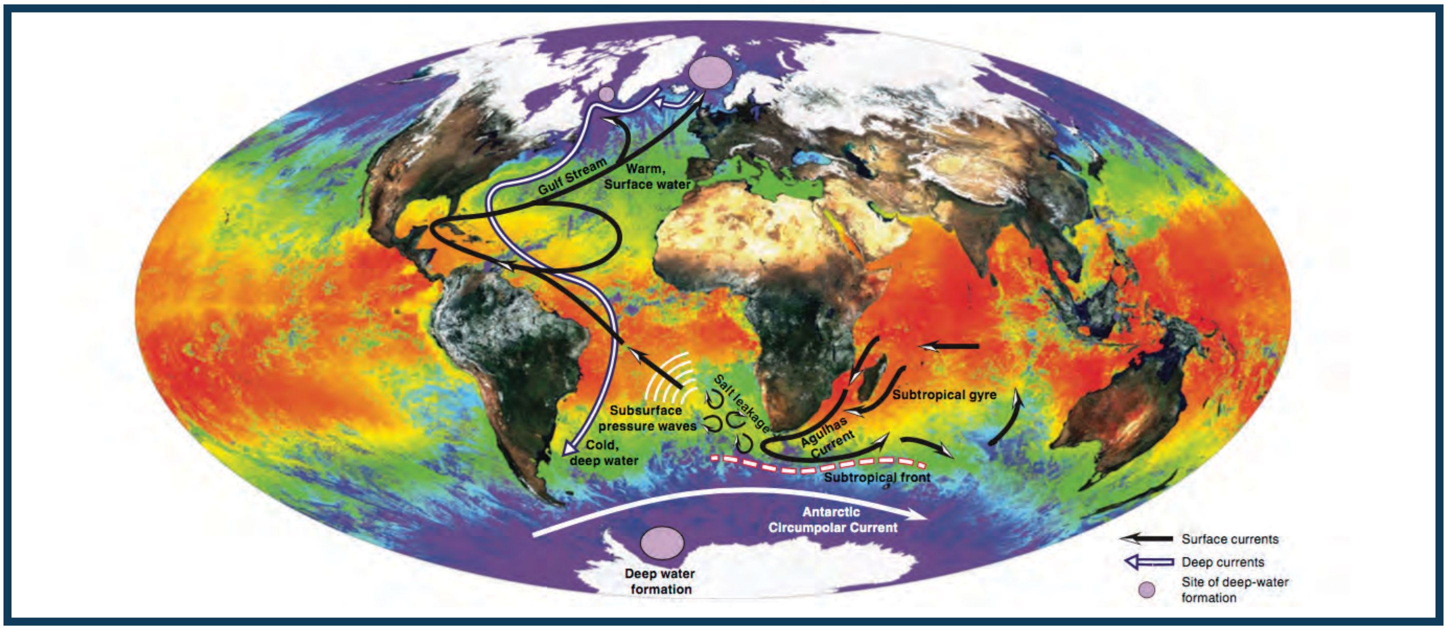
Expedition 361 will seek to recover ~5200 m of sediment in total. The coring strategy will include the triple advanced piston corer system along with the extended core barrel coring system where required to reach target depths. Given the significant transit time required during the expedition (15.5 days), the coring schedule is tight and will require detailed operational planning and flexibility from the scientific party. The final operations plan, including the number of sites to be cored and/or logged, is contingent upon the R/V JOIDES Resolution operations schedule, operational risks, and the outcome of requests for territorial permission to occupy particular sites.

All relevant IODP sampling and data policies will be adhered to during the expedition. Beyond the interstitial fluids program, shipboard sampling will be restricted to acquiring ephemeral data and to limited low-resolution sampling of parameters that may be critically affected by short-term core storage. Most sampling will be deferred to a postcruise sampling party that will take place at the Gulf Coast Repository in College Station, Texas (USA). A substantial onshore X-ray fluorescence scanning plan is anticipated and will be further developed in consultation with scientific participants.

Abstract from *Preliminary Report*

International Ocean Discovery Program (IODP) Expedition 361 drilled six sites on the southeast African margin and in the Indian-Atlantic ocean gateway, southwest Indian Ocean, from 30 January to 31 March 2016. In total, 5175 m of core was recovered, with an average recovery of 102%, during 29.7 days of on-site operations. The sites, situated in the Mozambique Channel at locations directly influenced by discharge from the Zambezi and Limpopo River catchments, the Natal Valley, the Agulhas Plateau, and Cape Basin, were targeted to reconstruct the history of the greater Agulhas Current system over the past ~5 my. The Agulhas Current is the strongest western boundary current in the Southern Hemisphere, transporting some 70 Sv of warm, saline surface water from the tropical Indian Ocean along the East African margin to the tip of Africa. Exchanges of heat and moisture with the atmosphere influence southern African climates, including individual weather systems such as extratropical cyclone formation in the region and rainfall patterns. Recent ocean model and paleoceanographic data further point at a potential role of the Agulhas Current in controlling the strength and mode of the Atlantic Meridional Overturning Circulation (AMOC) during the Late Pleistocene. Spillage of saline Agulhas water into the South Atlantic stimulates buoyancy anomalies that act as control mechanisms on the basin-wide AMOC, with implications for convective activity in the North Atlantic and global climate change. The main objectives of the expedition were to establish the sensitivity of the Agulhas Current to climatic changes during the Pliocene–Pleistocene, to determine the dynamics of the Indian-Atlantic gateway circulation during this time, to examine the connection of the Agulhas leakage and AMOC, and to address the influence of the Agulhas Current on African terrestrial climates and coincidences with human evolution. Additionally, the expedition set out to fulfill the needs of the Ancillary Project Letter, consisting of high-resolution interstitial water samples that will constrain the temperature and salinity profiles of the ocean during the Last Glacial Maximum.

The expedition made major strides toward fulfilling each of these objectives. The recovered sequences allowed generation of complete spliced stratigraphic sections that span from 0 to between ~0.13 and 7 Ma. This sediment will provide decadal- to millennial-scale climatic records that will allow answering the paleoceanographic and paleoclimatic questions set out in the drilling proposal.



Global composite of land surface reflectance and sea-surface temperature (credit: Jacques Descloitres, MODIS Land Science Team, NASA) with sche- matic representation of the greater Agulhas Current system and its links to the Atlantic Meridional Overturning Circulation. The greater Agulhas Current sys- tem around South Africa consists of the Agulhas Current flowing south along the African shelf. Off the southern tip of Africa, the Agulhas Current abruptly retroflects and feeds back into the Indian Ocean. During this process, huge rings of water (Agulhas rings) are separated, drifting into the Atlantic. Upstream of the Agulhas Current, eddies around Madagascar insert short-term variability into the Agulhas Current, leading to short-term offshore meanders of the main current by several 100 km.

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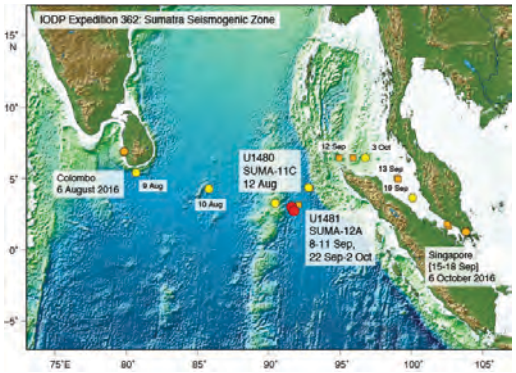
EXPEDITION 362: SUMATRA SEISMOGENIC ZONE



General Information

Sites: U1480–U1481
Dates: 6 August to 6 October 2016
Ports: Colombo, Sri Lanka to Singapore
Co-chief Scientists: Lisa McNeill & Brandon Dugan
Staff Scientist: Katerina Petronotis

Reports and Publications

Ship reports:
http://iodp.tamu.edu/scienceops/sitesumm/362/index.html

Scientific Prospectus:
http://publications.iodp.org/scientific_prospectus/362/

Preliminary Report:
http://publications.iodp.org/preliminary_report/362/

IODP Proceedings:
Pending

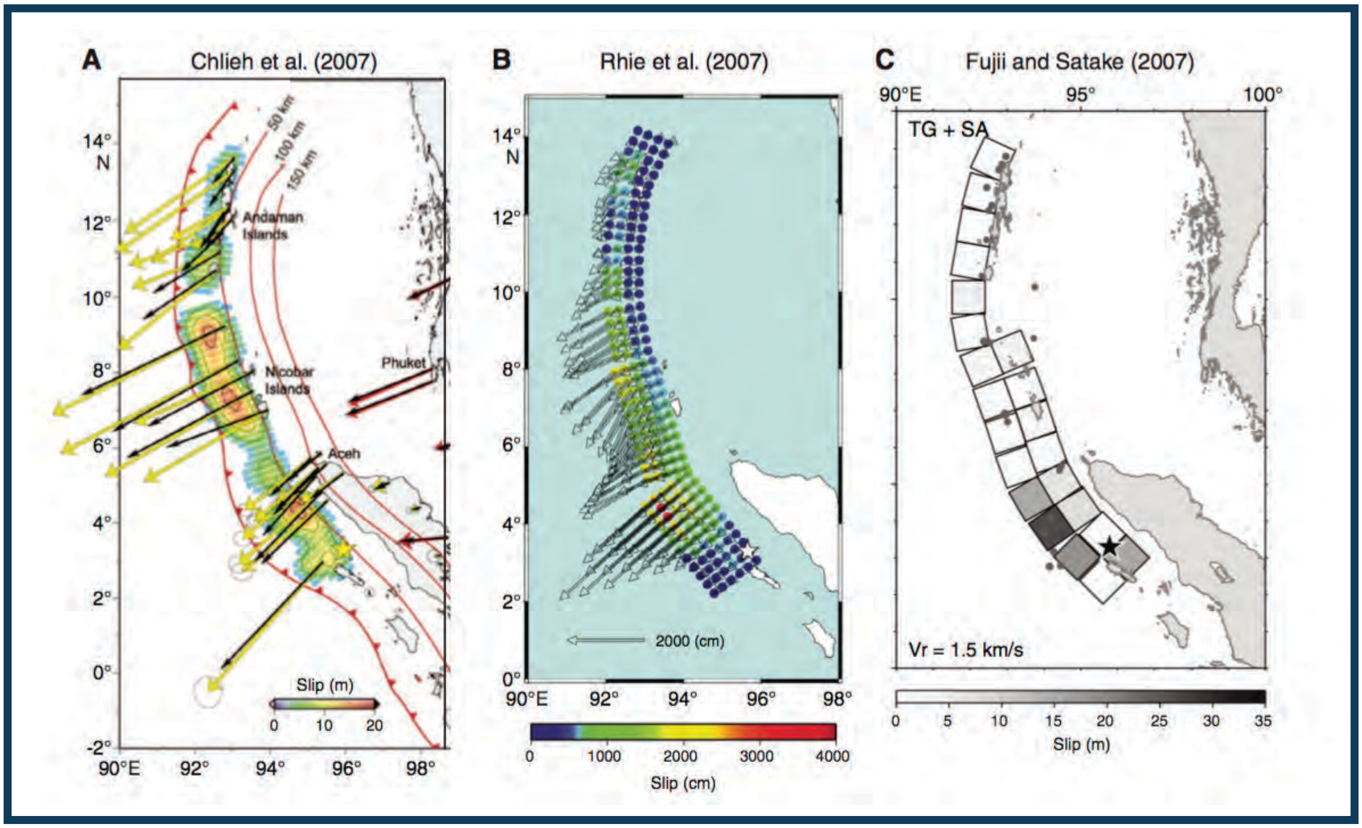
Expedition-related citations:
http://iodp.tamu.edu/publications/bibliographic_information/362cit.html

Abstract from *Scientific Prospectus*

The 2004 Mw 9.2 earthquake and tsunami that struck North Sumatra and the Andaman-Nicobar Islands devastated coastal communities around the Indian Ocean and was the first earthquake to be analyzed by modern techniques. This earthquake and the Tohoku-Oki Mw 9.0 earthquake and tsunami in 2011 showed unexpectedly shallow megathrust slip. In the case of North Sumatra, this shallow slip was focused beneath a distinctive plateau of the accretionary prism. This intriguing seismogenic behavior and forearc structure are not well explained by existing models or by relationships observed at margins where seismogenic slip typically occurs farther landward. The input materials of the North Sumatran subduction zone are a distinctive, thick (up to 4–5 km) sequence of primarily Bengal-Nicobar Fan–related sediments. This sequence shows strong evidence for induration and dewatering and has probably reached the temperatures required for sediment-strengthening diagenetic reactions prior to accretion. The correspondence between the 2004 rupture location and the overlying prism plateau, as well as evidence for a strengthened input section, suggests the input materials are key to driving the distinctive slip behavior and long-term forearc structure. The aim of Expedition 362 is to begin to understand the nature of seismogenesis in North Sumatra through sampling these input materials and assessing their evolution, en route to understanding such processes on related convergent margins. Properties of the incoming section affect the strength of the wedge interior and base, likely promoting the observed plateau development. In turn, properties of deeper input sediment control décollement position and properties, and hence hold the key to shallow coseismic slip. During Expedition 362, two primary, riserless sites (proposed Sites SUMA-11C and SUMA-12A) will be drilled on the oceanic plate to analyze the properties of the input materials. Coring, downhole pressure and temperature measurements, and wireline logging at these sites will constrain sediment deposition rates, diagenesis, thermal and physical properties, and fluid composition. Postexpedition experimental analyses and numerical models will be employed to investigate the mechanical and frictional behavior of the input section sediments/sedimentary rocks as they thicken, accrete, and become involved in plate boundary slip system and prism development. These samples and downhole measurements will augment the internationally collected site survey bathymetric, seismic, and shallow core data that provide the regional geological framework of the margin.

Abstract from *Preliminary Report*

Drilling the input materials of the north Sumatran subduction zone, part of the 5000 km long Sunda subduction zone system and the origin of the Mw ~9.2 earthquake and tsunami that devastated coastal communities around the Indian Ocean in 2004, was designed to groundtruth the material properties causing unexpectedly shallow seismogenic slip and a distinctive forearc prism structure. The intriguing seismogenic behavior and forearc structure are not well explained by existing models or by relationships observed at margins where seismogenic slip typically occurs farther landward. The input materials of the north Sumatran subduction zone are a distinctively thick (as thick as 4–5 km) succession of primarily Bengal-Nicobar Fan–related sediments. The correspondence between the 2004 rupture location and the overlying prism plateau, as well as evidence for a strengthened input section, suggest the input materials are key to driving the distinctive slip behavior and long-term forearc structure. During Expedition 362, two sites on the Indian oceanic plate ~250 km southwest of the subduction zone, Sites U1480 and U1481, were drilled, cored, and logged to a maximum depth of 1500 meters below seafloor. The succession of sediment/rocks that will develop into the plate boundary detachment and will drive growth of the forearc were sampled, and their progressive mechanical, frictional, and hydrogeological property evolution will be analyzed through postcruise experimental and modeling studies. Large penetration depths with good core recovery and successful wireline logging in the challenging submarine fan materials will enable evaluation of the role of thick sedimentary subduction zone input sections in driving shallow slip and amplifying earthquake and tsunami magnitudes, at the Sunda subduction zone and globally at other subduction zones where submarine fan-influenced sections are being subducted.



Example coseismic rupture models of the 2004 Sumatra-Andaman earthquake using combinations of seismic, geodetic, and tsunami data. A. Coseis- mic and ~30 day postseismic slip, with slip offshore North Sumatra concentrated beneath the forearc high. Contours = depth of subducting plate. B. Waveform and GPS inversion suggesting substantial shallow slip (although postseismic transients may be included). C. Model based on tsunami observations that shows significant slip on shallow plate boundary.

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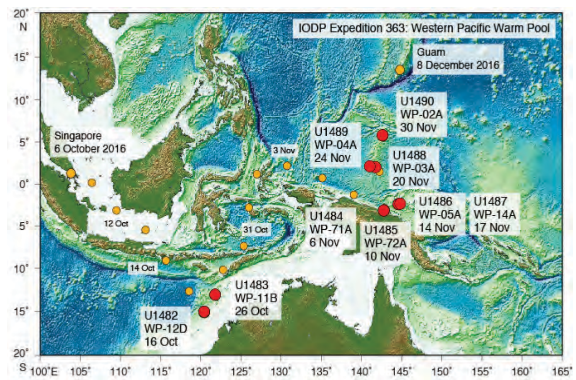
EXPEDITION 363: WESTERN PACIFIC WARM POOL



General Information

Sites: U1482–U1490
Dates: 6 October to 8 December 2016
Ports: Singapore to Guam
Co-chief Scientists: Yair Rosenthal & Ann Holbourn
Staff Scientist: Denise Kulhanek

Reports and Publications

Ship reports:
http://iodp.tamu.edu/scienceops/sitesumm/363/index.html

Scientific Prospectus:
http://publications.iodp.org/scientific_prospectus/363/

Preliminary Report:
http://publications.iodp.org/preliminary_report/363/

IODP Proceedings:
Pending

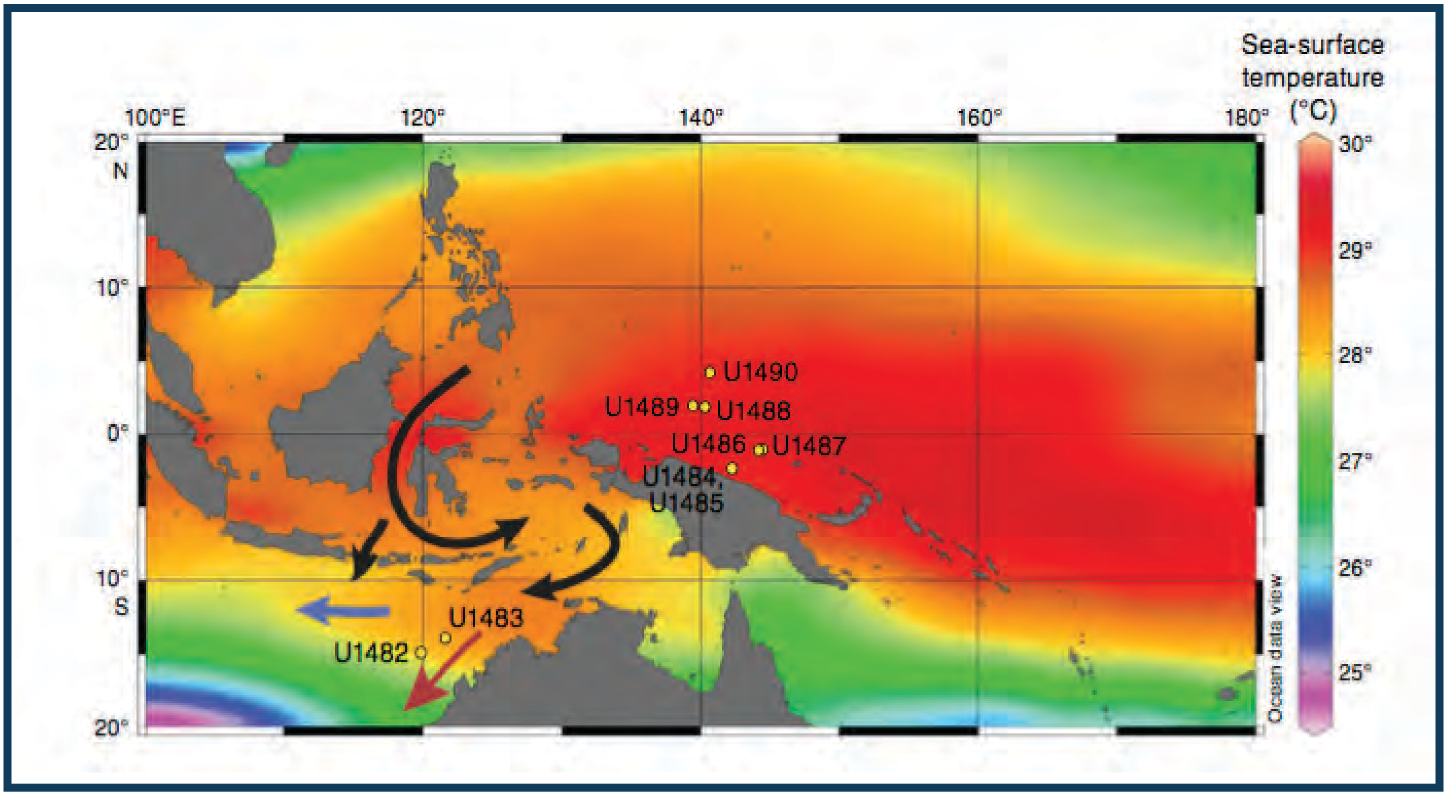
Expedition-related citations:
http://iodp.tamu.edu/publications/bibliographic_information/363cit.html

Abstract from *Scientific Prospectus*

Expedition 363 seeks to document the regional expression of climate variability (e.g., temperature, precipitation, and productivity) in the Western Pacific Warm Pool (WPWP) as it relates to global and regional climate change from the middle Miocene to Late Pleistocene on millennial, orbital, and secular timescales. The WPWP is the largest reservoir of warm surface water on Earth and thus is a major source of heat and moisture to the atmosphere. Variations in sea-surface temperature and the extent of the WPWP influence the location and strength of convection and thus impact oceanic and atmospheric circulation, heat transport, and tropical hydrology. Given its documented importance for modern climatology, changes in the WPWP are assumed to have also played a key role in the past. The proposed drill sites are strategically located at the heart of the WPWP (northern Papua New Guinea and south of Guam) and around its western edge (western margin of Australia to the south and southern Philippine Islands to the north) to capture the most salient features of the WPWP. Combining marginal and open ocean sites will allow us to study these time intervals at different temporal resolutions. The coring program prioritizes seven primary sites and nine alternate sites in 880–3427 m water depth. This depth range will allow the reconstruction of intermediate and deepwater properties through time.

Abstract from *Preliminary Report*

International Ocean Discovery Program Expedition 363 sought to document the regional expression and driving mechanisms of climate variability (e.g., temperature, precipitation, and productivity) in the Western Pacific Warm Pool (WPWP) as it relates to the evolution of Neogene climate on millennial, orbital, and geological timescales. To achieve our objectives, we selected sites with wide geographical distribution and variable oceanographic and depositional settings. Nine sites were cored during Expedition 363, recovering a total of 6956 m of sediment in 875–3421 m water depth with an average recovery of 101.3% during 39.6 days of on-site operations. Two sites are located off northwestern Australia at the southern extent of the WPWP and span the late Miocene to present. Seven sites are situated at the heart of the WPWP, including two sites on the northern margin of Papua New Guinea (PNG) with very high sedimentation rates spanning the past ~450 ky, two sites in the Manus Basin north of PNG with moderate sedimentation rates recovering upper Pliocene to present sequences, and three low sedimentation rate sites on the southern and northern parts of the Eauripik Rise spanning the early Miocene to present. The wide spatial distribution of the cores, variable accumulation rates, exceptional biostratigraphic and paleomagnetic age constraints, and mostly excellent foraminifer preservation will allow us to trace the evolution of the WPWP through the Neogene at different temporal resolutions, meeting the primary objectives of Expedition 363. Specifically, the high sedimentation–rate cores off PNG will allow us to better constrain mechanisms influencing millennial-scale variability in the WPWP, their links to high-latitude climate variability, and implications for temperature and precipitation variations in this region under variable climate conditions. Furthermore, these high accumulation rates offer the opportunity to study climate variability during previous warm periods at a resolution similar to existing studies of the Holocene. With excellent recovery, Expedition 363 sites are suitable for detailed paleoceanographic reconstructions at orbital and suborbital resolution from the middle Miocene to Pleistocene, and thus will be used to refine the astronomical tuning, magneto-, isotope, and biostratigraphy of hitherto poorly constrained intervals within the Neogene timescale (e.g., the late Miocene) and to reconstruct the history of the East Asian and Australian monsoon and the Indonesian Throughflow on orbital and tectonic timescales. Results from high-resolution interstitial water sampling at selected sites will be used to reconstruct density profiles of the western equatorial Pacific deep water during the Last Glacial Maximum. Additional geochemical analyses of interstitial water samples in this tectonically active region will be used to investigate volcanogenic mineral and carbonate weathering and their possible implications for the evolution of Neogene climate.



Mean annual sea-surface temperature within the IPWP with locations of sites cored during Expedition 363 (yellow circles). Black arrows mark the path of the Indonesian Throughflow. Data source: ODV World Ocean Atlas, 2013 (https://odv.awi.de/de/data/ocean/world_ocean_atlas_2013/).

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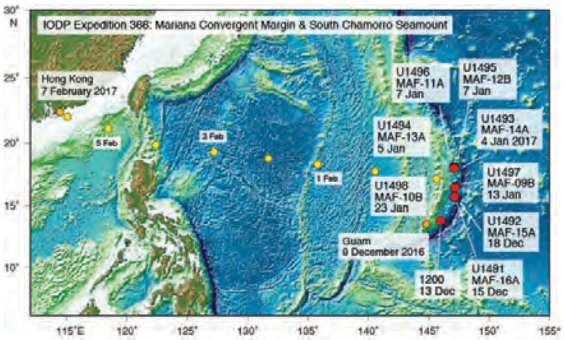
EXPEDITION 366: MARIANA CONVERGENT MARGIN & SOUTH CHAMORRO SEAMOUNT



General Information

Sites: U1491–U1498
Dates: 8 December 2016 to 7 February 2017
Ports: Guam to Hong Kong
Co-chief Scientists: Patricia Fryer & Geoffrey Wheat
Staff Scientist: Trevor Williams

Reports and Publications

Ship reports:
http://iodp.tamu.edu/scienceops/sitesumm/366/index.html

Scientific Prospectus:
http://publications.iodp.org/scientific_prospectus/366/

Preliminary Report:
Pending

IODP Proceedings:
Pending

Expedition-related citations:
http://iodp.tamu.edu/publications/bibliographic_information/366cit.html

Abstract from *Scientific Prospectus*

International Ocean Discovery Program (IODP) Expedition 366 has two primary science objectives. The first objective is devoted to coring a series of sites at the summit and flanks of three large (up to 50 km diameter and 2 km high) serpentinite mud volcanoes in the Mariana forearc (within 100 km west of the Mariana Trench). This objective addresses the broad scientific aim of examining processes of mass transport within the subduction zone of a nonaccretionary convergent margin. In detail, the plan is to recover mudflow materials to (1) examine processes of mass transport and geochemical cycling within the forearc of a nonaccretionary convergent margin; (2) ascertain the spatial variability of slab-related fluids within the forearc environment as a means of tracing dehydration, decarbonation, and water-rock reactions in subduction and suprasubduction zone environments; (3) study the metamorphic and tectonic history of this nonaccretionary forearc region; (4) investigate the physical properties of the subduction zone in relation to dehydration reactions and seismicity; (5) document microbial activity associated with subduction zone material from great depth; and (6) explore linkages among these subduction-related processes, including seismicity, while placing the effects of these processes within a historical context.

The second objective establishes long-term seafloor observatory sites by emplacing cased boreholes at summit (conduit) holes in three mud volcanoes (at Expedition 366 proposed Sites MAF-11A, MAF-9B, and MAF-15A) and removing the circulation obviation retrofit kit (CORK) body from Ocean Drilling Program Hole 1200C. These activities set the foundation for future deployments of sensors and samplers with the possibility of deploying a CORK-Lite structure within the boreholes. CORK-Lites provide a framework for conducting temporal observations that will allow one to "take the pulse of subduction" in an active nonaccretionary convergent plate margin and establish a platform for in situ experimentation.

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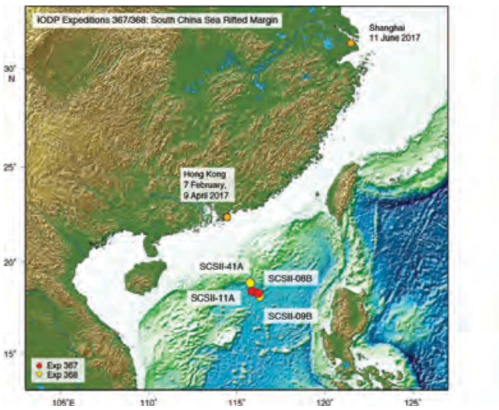
Expeditions 367: South China Sea Rifted Margin A



General Information

Sites: U1499–U1500
Dates: 7 February–9 April 2017
Ports: Hong Kong to Hong Kong
Co-chief Scientists: Zhen Sun & Joann Stock
Staff Scientist: Adam Klaus

Reports and Publications

Ship reports:
http://iodp.tamu.edu/scienceops/sitesumm.html#X367

Scientific Prospectus:
http://publications.iodp.org/scientific_prospectus/367_368/index.html

Preliminary Report:
Pending

IODP Proceedings:
Pending

Expedition-related citations:
http://iodp.tamu.edu/publications/bibliographic_information/367368cit.html

Abstract from *Scientific Prospectus*

International Ocean Discovery Program (IODP) Expeditions 367 and 368 will address the mechanisms of lithosphere extension during continental breakup. State of the art deep reflection seismic data show that the northern South China Sea (SCS) margin offers excellent drilling opportunities that can address the process of plate rupture at a magma-poor rifted margin. The SCS margin shows similarities to the hyperextended Iberia-Newfoundland margins, possibly including exhumed and serpentinized mantle within the continent-ocean transition (COT). However, recent modeling studies suggest that mechanisms of plate weakening other than serpentinization of the subcontinental lithospheric mantle exist. Two competing models for plate rupture (in the absence of excessively hot asthenospheric mantle) have widely different predictions for (1) the crustal structure across the COT, (2) the time lag between breakup and formation of igneous ocean crust, (3) the rates of extension, and (4) the subsidence and thermal history. Proposed drilling will core through thick sedimentary sections and into the underlying basement to firmly discriminate between these models. We plan to occupy four sites across a 150-200 km wide zone of highly extended seaward-thinning crust with a well-imaged COT zone. Three sites will determine the nature of critical crustal entities within the COT and constrain postbreakup crustal subsidence. These three sites will also help constrain how soon after breakup igneous crust started to form. A fourth site on the continental margin landward of the COT will constrain the timing of rifting, rate of extension, and crustal subsidence. If serpentinized mantle is found within the COT, this will lend support to the notion that the Iberia-type margin is not unique, and hence that weakening of the lithosphere by introducing water into the mantle may be a common process during continental breakup. If serpentinite is not found, and alternatively, scientific drilling results for the first time are gained in support of an alternative model, this would be an equally important accomplishment. Constraints on SCS formation and stratigraphy, including industry drilling, Ocean Drilling Program Leg 184 and IODP Expedition 349 drilling, the young (Paleogene) rifting of the margin, and absence of excessively thick postrift sediment allow us to effectively address these key topics by drilling within a well-constrained setting. An initial spreading rate of ~2 cm/y half-rate reduces the potential complexity of magma-starved, slow-spreading crust forming after breakup. Drilling, coring, and logging to address these SCS rifted margin science objectives will be undertaken during Expeditions 367 and 368, which will be implemented as a single science program.

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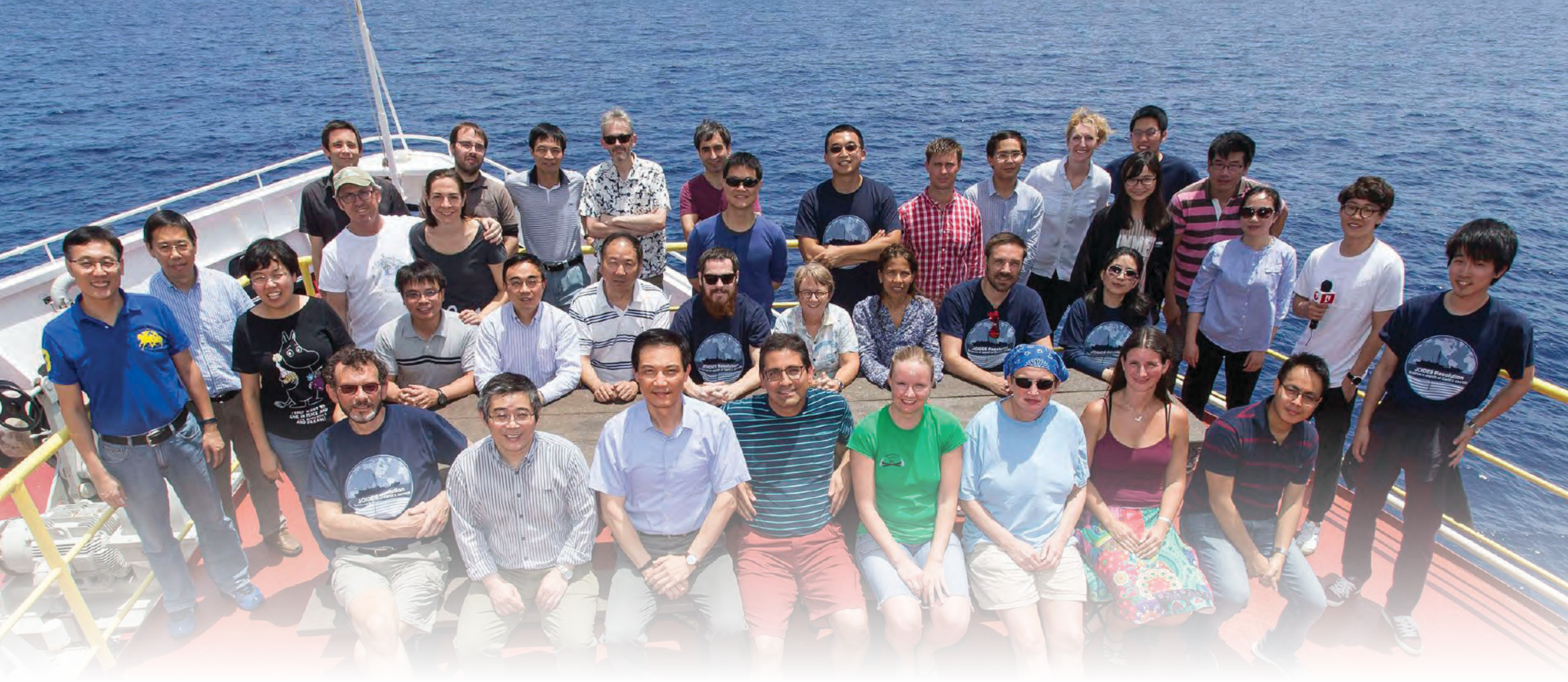
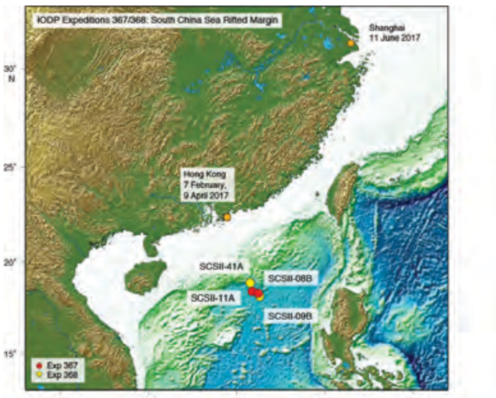


EXPEDITION 368: SOUTH CHINA SEA RIFTED MARGIN B



General Information

Sites:
Dates: 9 April–11 June 2017
Ports: Hong Kong to Shanghai
Co-chief Scientists: Zhimin Jian & Hans Christian Larsen
Staff Scientist: Carlos Alvarez Zarikian

Reports and Publications

Ship reports:
http://iodp.tamu.edu/scienceops/sitesumm.html

Scientific Prospectus:
http://publications.iodp.org/scientific_prospectus/367_368/index.html

Preliminary Report:
Pending

IODP Proceedings:
Pending

Expedition-related citations:
http://iodp.tamu.edu/publications/bibliographic_information/367368cit.html

Abstract from *Scientific Prospectus*

International Ocean Discovery Program (IODP) Expeditions 367 and 368 will address the mechanisms of lithosphere extension during continental breakup. State of the art deep reflection seismic data show that the northern South China Sea (SCS) margin offers excellent drilling opportunities that can address the process of plate rupture at a magma-poor rifted margin. The SCS margin shows similarities to the hyperextended Iberia-Newfoundland margins, possibly including exhumed and serpentinized mantle within the continent-ocean transition (COT). However, recent modeling studies suggest that mechanisms of plate weakening other than serpentinization of the subcontinental lithospheric mantle exist. Two competing models for plate rupture (in the absence of excessively hot asthenospheric mantle) have widely different predictions for (1) the crustal structure across the COT, (2) the time lag between breakup and formation of igneous ocean crust, (3) the rates of extension, and (4) the subsidence and thermal history. Proposed drilling will core through thick sedimentary sections and into the underlying basement to firmly discriminate between these models. We plan to occupy four sites across a 150-200 km wide zone of highly extended seaward-thinning crust with a well-imaged COT zone. Three sites will determine the nature of critical crustal entities within the COT and constrain postbreakup crustal subsidence. These three sites will also help constrain how soon after breakup igneous crust started to form. A fourth site on the continental margin landward of the COT will constrain the timing of rifting, rate of extension, and crustal subsidence. If serpentinized mantle is found within the COT, this will lend support to the notion that the Iberia-type margin is not unique, and hence that weakening of the lithosphere by introducing water into the mantle may be a common process during continental breakup. If serpentinite is not found, and alternatively, scientific drilling results for the first time are gained in support of an alternative model, this would be an equally important accomplishment. Constraints on SCS formation and stratigraphy, including industry drilling, Ocean Drilling Program Leg 184 and IODP Expedition 349 drilling, the young (Paleogene) rifting of the margin, and absence of excessively thick postrift sediment allow us to effectively address these key topics by drilling within a well-constrained setting. An initial spreading rate of ~2 cm/y half-rate reduces the potential complexity of magma-starved, slow-spreading crust forming after breakup. Drilling, coring, and logging to address these SCS rifted margin science objectives will be undertaken during Expeditions 367 and 368, which will be implemented as a single science program.

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