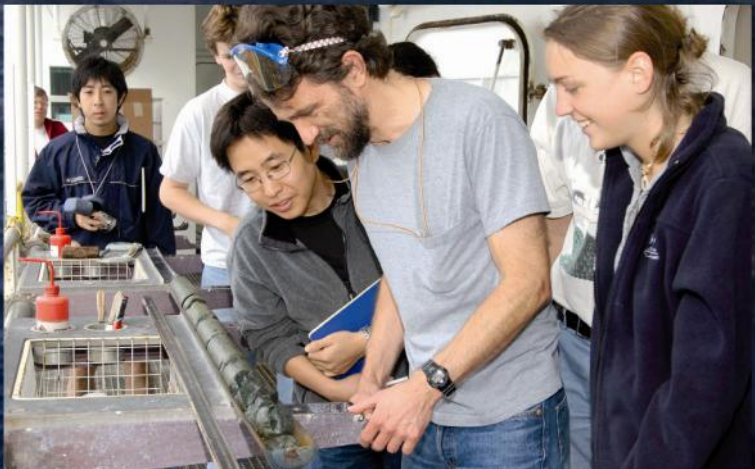
INVEST REPORT

IODP New Ventures in Exploring Scientific Targets - Defining New Goals of an International Drilling Program



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IODP New Ventures in Exploring Scientific Targets (INVEST) – Defining The New Goals of an International Drilling Program

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IODP INTEGRATED OCEAN DRILLING PROGRAM

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Executive Summary

Introduction

The IODP New Ventures in Exploring Scientific Targets (INVEST) conference, an international meeting to define the scientific goals and required technology for a new ocean drilling program, was held at the University of Bremen on 22–25 September 2009. Based on the large attendance and vigorous engagement of scientists in the discussion of new science/technology ideas, INVEST was extremely successful. Initially 400 participants were expected, but the INVEST steering and organization committees were thrilled to see a much larger number of scientists flock to Bremen to demonstrate their support and enthusiasm for the continuation of an international scientific ocean drilling program. In all, 584 participants, including sixty-four students, from twenty-one nations and >200 institutions and agencies attended the INVEST conference. Contributions to INVEST included 103 submitted white papers that were posted on the INVEST webpage (http://www.marum.de/iodp-invest.html), and breakout discussions in fifty working groups that focused on a range of topics during the course of the conference. In addition, students and early career scientists, as well as national funding agency managers and platform providers, presented a total of eighty-six posters. Interspersed with the working group and plenary sessions were twelve keynote lectures, chosen to highlight overarching themes and new directions in research and technology.

The conference was sponsored by the Integrated Ocean Drilling Program Management International (IODP-MI), the Deutsche Forschungsgemeinschaft (DFG) and the MARUM research center. Using input from national workshops that took place in the year prior to the INVEST conference and that provided initial ideas for scientific directions and themes, the INVEST working group sessions were organized within six conference themes: (1) Co-evolution of Life and Planet, (2) Earth's Interior, Crust and Surface Interactions, (3) Climate Change – Records of the Past, Lessons for the Future, (4) Earth System Dynamics, Reservoirs and Fluxes, (5) Earth-Human-Earth Interactions, and (6) Science Implementation.

Each meeting attendee was given the opportunity to participate in three working groups: one within conference themes one through three, one within conference themes four and five, and one within conference theme six. Up to eighteen working groups met in parallel sessions. All working groups within one conference theme met to report to each other the results of the individual working group discussions. The conference theme co-chairs then met with the working group chairs and scribes to prepare a plenary presentation of the conference theme.

The steering committee, with the help of some conference session chairs, used the working group notes and plenary session presentation materials to write the INVEST conference report. The main chapters of the report are "Climate Change Impacts", "The Lithospheric Membrane – The Key Interface and Processing Zone", "Co-evolution of Life and the Planet", and "Earth-Human-Earth Interactions". In addition, several *Cross-disciplinary Research Frontiers* were identified as being important new ocean drilling themes and were highlighted in a separate section of the report. Implementation and outreach aspects are summarized in the chapters "Technology Needs and Developments" and "Outreach, Education, and Branding". "Recommendations for the New Ocean Drilling Program" is the final chapter of the INVEST report and pertains to what the community considers desirable program architecture and science advisory structure. A brief synopsis of each of these chapters is presented below. More details on the INVEST meeting structure, white papers and background material can be found at the INVEST website (http://www.marum.de/iodp-invest.html).

Climate Change Impacts

Earth's climate results from complex interactions among Earth system components, including the atmosphere, hydrosphere, cryosphere, lithosphere, and biosphere. Variations in these systems over short and long timescales, including the way material cycles among them (*e.g.*, carbon cycle, hydrological cycle), result in changes to Earth's climate. Understanding how climate has changed in the past and how it will change in the future requires understanding of how the Earth system behaves over a range of conditions. Instrumental records, collected over the last century or so, are insufficient by themselves to study long-term climate change. On the other hand, ocean drilling of sediments and corals provides a unique opportunity to acquire the high-resolution records of past change needed to examine and understand the baseline of natural climate variability against which current climate change can be compared. These records will also allow study of the behavior of the Earth system during different climate states and major climate transitions throughout the Cenozoic, as well as the origin of and mechanisms that lead to abrupt, seasonal- to millennial-scale climate changes.

Fundamental climate change questions that can be addressed by ocean drilling are outlined throughout the INVEST report. This section on "Climate Change Impacts" focuses on scientific questions that, when answered, will underpin our understanding of climate change. It explores the behavior of the climate during abrupt and extreme events, the stability of ice sheets and their relationship to sea level and coastal/shoreline processes, and the impact of regional and global climate on the hydrological cycle. In the "Earth-Human-Earth Interactions" section, climate change questions are framed in anticipation of future conditions associated with increasing levels of atmospheric carbon dioxide. Climate change questions related to tectonics and hominin evolution are explored in the "Cross-disciplinary Research Frontiers" section.

Ocean drilling can provide unprecedented insight into climatic and oceanic processes through investigation of past rapid and extreme climate events (see Fig. 2.6 in section 2.4.4). These globally significant events represent major deviations from the natural variability of Earth's climate. Extreme events originate from perturbations in a specific component of the Earth system and typically propagate through complicated feedbacks across some or all components, allowing interconnected processes to be examined and understood. Extreme and rapid events stand out in noisy sediment-derived proxy records and are thus easy to quantify. This allows investigation of dynamic system behavior, such as tipping points and thresholds. Ocean drilling remains the only means to reconstruct, at medium to high temporal resolution, the global climate evolution of the Earth system throughout the Cenozoic. Large amplitude perturbations often mark epoch boundaries and provide one of the main avenues to investigate large-scale events, including those that involve extreme climates, ecosystem turnover, and biodiversity evolution. Drilling is also the only means to study how rapid climate phenomena that occur on seasonal to millennial timescales, such as the El Niño Southern

Oscillation (ENSO) or Dansgaard-Oeschger (D-O) cycles, behave under different boundary conditions.

Only ocean drilling can provide the geologic perspective necessary to understand ice-sheet dynamics and the resulting impacts to sea level and shorelines. Over the past 100 m.y., sea-level change reflects global climate evolution from a time characterized by ephemeral Antarctic ice sheets (100 Ma to 33 Ma), to a time when large ice sheets occurred primarily in Antarctica (33 Ma to 2.5 Ma), and finally to a world with large Antarctic and Northern Hemisphere ice sheets (2.5 Ma to present). Over the last ~800 kyr, the cyclic growth and decay of continental ice sheets induced rapid sea-level change with maximum amplitudes of 120–140 m at intervals of ~100 kyr. Ice volume fluctuations can be inferred from eustatic sea-level curves deciphered through comparison of regional sea-level records from various latitudes and tectonic settings. For example, observations from sites distal to glaciated regions (*i.e.*, the 'far field') are less affected by isostatic deformation and therefore better suited to constrain glacial eustasy, whereas sea-level data from sites proximal to former ice sheets (*i.e.*, the 'near field') provide information on local ice-sheet dynamics.

Understanding the processes that control changes in the hydrologic cycle is one of the most pressing issues in climate-change research because changes in precipitation and evaporation impact the salinity/density distribution in the surface ocean, ecosystems on land, floods, aridification, water resources, and climate-vegetation feedbacks. A comprehensive examination of climatic controls on the hydrologic cycle requires the study of long-term trends and variability over a range of climatic states. In fact, even small global temperature changes impact the energy balance in tropical regions, resulting in changes in evaporation and storm and hurricane activity. In the mid-latitudes, changes in atmospheric thermal gradients can impact atmospheric circulation, the location of storm tracks, and the intensity of storms. There is an urgent need to understand controls on the Intertropical Convergence Zone (ITCZ), climate oscillation modes and their behavior during different mean climate states, wind-driven upper ocean circulation and its coupling to atmospheric forcing, monsoon dynamics, and the relationship between precipitation patterns, density stratification, and biogeochemical processes, to name a few. Future ocean drilling is absolutely necessary to obtain the records needed to constrain past changes in surface ocean conditions associated with major changes in large-scale atmospheric circulation. This must be complemented by continental climate reconstructions obtained from drilling sediments on continental margins and on land. Finally, ocean drilling studies focused on the hydrologic cycle should be used to validate regional climate models used to predict climate change and its associated impact on water resources.

The Lithospheric Membrane – The Key Interface and Processing Zone

Our tectonically active planet evolves by chemical and physical changes from the core and mantle, through the lithosphere, to the ocean and atmosphere. Flow of material and energy among these reservoirs drives both gradual changes in the Earth's structure and composition, as well as extremely rapid volcanic events that impact Earth's environment. The lithosphere is the major interface between the solid interior of the Earth and the exterior hydrosphere/atmosphere/biosphere (see Fig. 3.3 in section 3.2.2). Quantifying the fluxes mediated by the lithospheric processing zone is crucial for understanding the state and evolution of our planet, and ocean drilling provides a key tool in this endeavor.

From direct sampling we can examine the fundamental steady-state processes of ocean crust accretion, plate aging, and recycling, as well as intermittent events such as eruptions of large igneous provinces (LIPs) and rifting of continents. These processes affect the presence and state of resources that society depends upon—including sources of energy, fresh water, and nutrients—but they also create deleterious effects on society through earthquakes, tsunamis, and volcanic eruptions.

It is timely to stress that many of the things to be learned about the ‘lithospheric membrane’ of the Earth are of great societal relevance. Understanding initiation of plate boundaries and evolution of plates is fundamental to learning how the Earth works and how the continents we live upon were formed and evolve. Plate boundary formation and related volcanism have impacted past climate and may yield information about agents of climate change. Rifted continental margins host major hydrocarbon reservoirs that are an essential energy resource. Subduction zone hydration-dehydration cycling affects earthquakes and volcanic hazards. Hydrothermal systems form polymetallic sulfide deposits of potential economic interest and also host microorganisms that may be useful for bioengineering. Finally, the ocean crust provides vast opportunities for CO_2 capture and storage.

Understanding hydrothermal transfers of heat and mass between the lithosphere and hydrosphere/atmosphere on a global scale has been identified as a high-priority overarching research question. Seawater circulation facilitates microbial growth within the ocean floor and is critical to the transport and distribution of microorganisms; however, the size, activity, and connectivity of the intracrustal oceanic biosphere and its influence on global geochemical and biogeochemical cycles are unknown. Investigation of the coupling between hydrogeological, geochemical, thermal, mechanical, and biological processes and their relationship to the architecture and physical nature of oceanic lithosphere is essential. Of primary importance is addressing the nature of the Mohorovičić discontinuity (Moho), a first-order geophysical interface within our planet, which is uncertain in slow-spreading mid-ocean ridge environments. It could be an igneous boundary or a serpentinization front—a difference with profound consequences for the chemical and rheological properties of the lithosphere. As much as one-quarter of the seafloor exposed at slow-spreading mid-ocean ridges is a heterogeneous assemblage of peridotite and gabbroic lithologies, which is hydrothermally more reactive and undergoes greater changes in physical properties than layered basaltic crust. To understand ocean-crust composition, structure, and evolution, it is essential to drill a complete crustal section across the Moho and into the shallow mantle at a fast-spreading ridge. Complete sampling is also necessary to provide *in situ* confirmation of geophysical imaging of the ocean crust.

When oceanic lithosphere is recycled during subduction and plate collision, sediments may be scraped off and ocean crust can be accreted to a continent or island arc. Deep in subduction zones, dehydration reactions and melting of subducting sediments and occasionally the upper crust produce continental or oceanic volcanic arcs. Both of these processes can effectively transfer crustal material, fluids, and volatiles from the geologically transient oceanic lithosphere to more permanent continental crust. Ocean drilling is a critical tool necessary to investigate the relative roles of these processes and the magnitudes of element fluxes. Of crucial importance in determination of input fluxes are reliable estimates of the chemical and mineralogical state of the subducting ocean crust. Additionally, subduction zones produce some of the most significant geologic hazards to society including the highest magnitude earthquakes, the greatest tsunamis, and the most explosive eruptions.

Formation, hydrothermal alteration, and subduction of ocean crust generate secular chemical and physical changes throughout the crust and mantle, as well as in the ocean-atmosphere system. Large igneous provinces and hot spot trails are profound examples of massive mantle-crust exchanges and how these vary in time and space. At intermittent intervals, the emplacement of oceanic plateaus and formation of volcanic rifted margins produce significant chemical effects in the ocean and atmosphere. Particularly intense periods of volcanic activity appear to correlate with long-term changes in geodynamic behavior, which could involve interactions between the core and the deep mantle.

Many questions still need to be answered for us to better understand the Earth system. To address these we need to quantify fluxes and interplay within the mantle-crust-ocean system (physical, chemical, and biological) and monitor fault-driven processes. We also need to obtain a better understanding of the components of a subduction zone system that control seismic behavior, which in turn affects the level of hazard posed by the plate boundary. Ocean drilling will continue to significantly contribute to our understanding of these processes.

Co-Evolution of Life and the Planet

Scientific ocean drilling is poised to offer transformative advances to disciplines within the life sciences and provide insight into how life operates and interacts with Earth processes at and below the seafloor, both today and in the past. In particular, the study of paleoenvironmental controls on marine paleoecosystems through the Cenozoic and of extant life in rock and sediments can best be studied through ocean drilling.

Exploration of deeply seated microbial populations has revealed active, extant populations of microbes down to 1.6 km depth. These sedimentary and crustal habitats are vast in scale, physically and chemically diverse, and together represent the largest biome on Earth. A major challenge in the study of subseafloor life is the need to develop a more comprehensive understanding of the microbes that live there. Future research should reveal the biodiversity of the deep biosphere (see Fig. 4.1 in section 4.1), as well as the degree to which it is connected to surface biomes. Metagenomics, observatories, and other emerging technologies will play a significant role in the advancement of our understanding of the function and form of extant life in the subsurface. Advances in our knowledge of subsurface life from past ocean drilling have principally arisen as opportunistic ventures, where a microbiologist would sail on an expedition focused on other scientific objectives. This has resulted in a significantly skewed data set. This view can be changed in the future by utilizing both opportunistic and targeted drilling expeditions for deep biosphere research. A legacy sampling program would also fill critical gaps and lead to a more comprehensive understanding of the largest biome on Earth.

New approaches and dedicated expeditions will also reveal the physiological function and activity of the deep biosphere and provide a quantitative first order understanding of the rates and magnitude of the biogeochemical processes that occur there. How these processes impact elemental cycles of carbon, nitrogen, iron, sulfur, *etc.*, are generally not known. This presents an enormous challenge to understanding, at a very basic level, the global implications of the presence of deep ecosystems. Does this biosphere impact Earth processes such as energy and carbon cycling, and can a better understanding of its function help solve global redox and carbon budgets? To meet these challenges new drilling and sampling are required to obtain high-quality fresh samples critical for microbiological and biogeochemical study. Research on the deep subseafloor biosphere has the potential to address urgent questions about energy creation, climate change, and the nature of evolution of life on Earth over geologic time.

Important emerging fields within paleontology are the study of systems ecology and biotic response to major environmental forcing (such as climate change). Drilling is needed to better understand how ecosystems influence and respond to their environment on different timescales in order to predict how populations will respond to present and future global change. High temporal resolution records across paleogeographic gradients and through time can thus be used to study the processes that generate and destroy biodiversity.

Earth-Human-Earth Interactions

Geohazards: A top priority for the new drilling program should be the study of geologic hazards. Geology touches society directly through earthquakes, tsunamis, and landslides, and drilling can provide key constraints. Ocean drilling can be combined with other onshore and offshore national and international geohazards programs to provide knowledge for hazard assessment and mitigation of earthquakes and tsunamis that have the potential to directly impact the majority of the world's population, as well as for submarine slides that are of great concern to subsea and coastal infrastructure.

Research over the past decade indicates that old models of only two types of failure, stick-slip and creep, are incorrect. Slow-slip events, very low frequency earthquakes, and tsunami earthquakes are part of the stress-strain cycle (see Fig. 5.1 in section 5.1.1), and with the recent Haiti earthquake (moment magnitude (M_w) 7.0) there is recognition that even modest events can potentially cause a devastating loss of life. Specific queries for a drilling-based study of earthquake geohazards include the following. What is the nature of large-slip zones in earthquakes? What controls the size of earthquakes? Are very large destructive earthquakes governed by the same processes as small earthquakes? What are the characteristics of the earthquake repeat cycle? What causes tsunami earthquakes? What controls the range of tsunami efficiency generated by different earthquakes? Are earthquakes on different types of faults (*e.g.*, subduction megathrusts *vs.* plate-boundary strike-slip faults) fundamentally the same or different? To answer these questions requires drilling using a range of platforms, sampling, and logging strategies, integration with observatories and modeling, and collaboration with onshore studies.

Submarine landslides occur at a wide range of scales and settings. They often comprise distinctive mass-transport deposits recognized on the seafloor or in seismic reflection profiles. Small-scale submarine landslides are relatively frequent. They have displaced oil rigs, damaged pipelines, broken deep-sea communication cables, and devastated segments of coastline. Large- and small-slide events along coastal zones also create local, destructive tsunamis. A variety of triggers have been implicated in the initiation of submarine landslides, including earthquakes, sea-level change, and gas hydrates. There are important questions for examining this geohazard. How safe is the ocean floor? What causes and triggers submarine landslides? What are the frequencies and magnitudes? Is there a size-frequency relationship to submarine landslides? What is the relationship between climate change and submarine landslides? What is the tsunamigenic potential of past and future slides? Can and do gas hydrates cause seafloor instabilities? Can submarine slides cause significant hydrate dissociation? To study these processes requires drilling into past slides and into slide-prone areas to examine rheologic, hydrologic, lithologic, and geotechnical controls on slope stability through sampling, logging, and monitoring.

Exploring the Future, Anticipating the Transition to a High pCO_2 World: Increasing atmospheric carbon dioxide content (pCO_2) is the main driving force for projected future climate change. One of the primary goals of climate-change research is to quantify the Earth's equilibrium climate sensitivity, which is a measure of the climate-system response to sustained radiative forcing caused by changes in atmospheric greenhouse gas contents. Although it is defined as the equilibrium global average surface warming following a doubling of CO_2 and greenhouse gas equivalent concentrations, a broader definition would include the sensitivity of the entire Earth system to feedback processes that operate over a wide range of timescales. Phenomena that affect these processes include the carbon cycle, cloud cover, albedo, glacial processes, deep-ocean circulation, weathering, and acidification. Climate sensitivity may be non-linear (feedbacks affected by feedbacks), may differ regionally (such as at high latitudes where sea-ice albedo and other feedbacks may amplify climate change), and may affect the characteristics of climate variability (*e.g.*, the response of climate to perturbations or external forcing in a warm-climate compared to a cold-climate state).

Ocean drilling can deliver unique data necessary to quantify climate sensitivity in the past (see Fig. 5.3 in section 5.2.1) and contribute to understanding the feedback processes that need to be included for successful modeling of this topic of great societal relevance. Ocean sediments contain records of past temperatures, ocean chemistry, and pCO_2 from a wide range of boundary conditions and timescales inaccessible by modern, historical, or ice-core records. In particular, continuous high-fidelity records from times with pCO_2 levels higher than today are only obtainable through drilling ocean sediments deposited during warm intervals of the past. As such, ocean drilling provides the means to answer some of the key questions related to the quantification of climate sensitivity.

Increasing atmospheric CO_2 levels will not only cause climate to change, but will also lead to ocean acidification, known as "*the other CO_2 problem*". Acidification will affect biocalcification, oceanic ecosystems, and carbon-cycle feedbacks. But, in the face of increasing pCO_2, carbon-cycle feedbacks are as uncertain as the climatic response. Ocean drilling has already played a major role in framing the current concern about ocean acidification. Although ice-core records indicate that atmospheric pCO_2 changes have only varied within a very narrow range during the past ~800,000 years, archives from times of significantly higher pCO_2 can only be obtained through ocean drilling. These records provide the means to answer some key questions about the acidification process and the timescales over which the ocean is buffered. Ocean drilling will deliver key records of lysocline shoaling, atmospheric pCO_2, carbonate ion concentrations, and biotic responses to changes in ocean acidity in order to quantify the feedbacks and enhance predictions of ocean acidification and its impacts. As such, ocean drilling can make a substantial and unique contribution to this field of immediate societal relevance.

Another urgent avenue of climate-change research is the study of factors that impact rates and amplitudes of sea-level change. The response of ice sheets (and thus sea level) to climate change is difficult to constrain because of the complexity, size, and relatively slow response of ice sheets. Since instrumental records of sea level extend back only about 150 years, refinement of predictions of sea-level rise clearly rely on past high-resolution records of the rates and magnitude of rapid sea-level change.

During glacial-interglacial transitions known as terminations, ice volume decreased and temperatures, greenhouse gas concentrations, and sea level (magnitude >100 m) increased abruptly. Those periods are therefore regarded as potential analogues for future rapid sea-level rise and coeval abrupt climate change. The reconstruction of rates and magnitudes of sea-level rise during several terminations may help to model ice-sheet dynamics, clarify the mechanisms and sources of catastrophic ice-sheet collapse, understand suborbital climate variability, and determine the timing and volume of meltwater release under varying thermal regimes during deglaciations. In addition, gaining a much better understanding of the dynamics and sensitivity of Greenland, West Antarctic, and East Antarctic ice sheets to climate change during past warm periods is only attainable through ocean drilling, and is critically important to validating and improving ice-sheet and climate models used to predict future sea-level changes.

Cross-Disciplinary Research Frontiers

Extreme Events: Earth history, on the human and the geologic timescales, is punctuated by extreme events. Increasingly, we have discovered that intermittent, abrupt departures from stable, steady-state conditions can have major impacts on the Earth’s environment, the evolution of life, and global biogeochemical cycles. The study of extreme events links many high priority science goals, crosses several broad themes, and will answer fundamental questions about evolutionary processes, and thresholds in the Earth system that, if passed, lead to dramatic ecosystem responses. For example, the processes that dictate changes in biodiversity, the oceanographic and climatic drivers of ecosystem assembly and change, speciation, and extinction can be studied through drilling of extreme events such as mass extinctions and hyperthermals. Bolide impacts and episodes of catastrophic volcanism are examples of abrupt perturbations that have left geologic records whose study will address these issues.

Future drilling can play a vital role in improving our understanding of impacts and their role in Earth’s history, particularly through comparison of impacts that caused mass extinction events (*e.g.*, the 65.5 Ma Chicxulub impact) to other large impacts that only caused minor perturbations (*e.g.*, the 35 Ma Chesapeake Bay impact). Identifying the critical factors that lead to global environmental devastation (*e.g.*, the energy of impact, the chemistry of the target rocks, additional environmental stresses, or the vulnerability of life at the time of impact) is possible through ocean drilling of the impact structures and the sediments containing critical fossil and environmental-proxy evidence.

A fundamental process within the solid Earth is intermittent whole-mantle overturn that results in periods of eruption of LIPs (see Fig. 6.8 in section 6.1.2), high seafloor spreading and associated arc collisions, and sea-level highstands. This mode was last prominent during the Cretaceous to early Tertiary Periods (135–55 Ma) when extraordinary eruption rates produced large igneous systems on both continents and in ocean basins. The rate, volume, and duration of these events need to be constrained to understand the geodynamic mechanisms for their origin and their potential environmental impacts, including mass extinctions, rapid global warming, ocean acidification, and oceanic anoxic events. LIPs are extreme mantle-melting and volcanic events that can be studied to answer questions about geodynamic models whose critical distinctions are magma flux through time, geochemical variability, and internal architecture—all of which are best addressed by drilling to obtain direct volcanic samples and far-field, high-resolution marine sedimentary sections.

Hominin Evolution: Scientific ocean drilling can transform our understanding of how African climate change affected early human evolution. Key evolutionary events occurred near 3.0–2.5 Ma and 2.0–1.5 Ma that effectively shaped the characteristics that define us as human: bipedalism, exceptionally large brains, and the construction of increasingly sophisticated stone tools. Environmental hypotheses for early human evolution suggest that changing African climate altered the ecological composition of a landscape, which led to specific faunal adaptation or speciation pressures that resulted in genetic selection and innovation. Where hypotheses differ is in the proposed role of climate change in natural selection. The Savannah Hypothesis states that the evolution of African mammalian fauna, including early hominins, was primarily linked to the progressive expansion of more open grassland conditions. The Turnover Pulse Hypothesis is a variant of this idea that focuses on bursts of biotic change initiated by progressive shifts toward greater African aridity at approximately 2.8 Ma and 1.8 Ma. The Variability Selection Hypothesis suggests that changes in the amplitudes of orbitally controlled African climate variability, linked to the eccentricity modulation of precessional monsoonal cycles, may have been an important genetic selection criterion. To test these hypotheses, fundamental questions concerning the timing, nature, and causes of African climate variability must be answered. Drilling targets are margin sediments that reflect the subtropical African geographic domain where hominin fossils are found, including South Africa, Tanzania, Kenya, and Ethiopia. Ocean drilling to obtain records from these regions will likely revolutionize our understanding of the timing and causes of African climate changes and allow us to test the hypothesized role of past climate changes in shaping the course of human evolution.

Climate-Tectonic Linkages and Feedbacks: Climate and plate tectonics are two forces that shape the Earth in concert; examining the interplay between climatic and tectonic processes will advance our understanding of both. Fundamental questions regarding tectonic-climate linkages can be answered by ocean drilling in conjunction with continental studies. Future studies should focus on how the changing configuration and topography/bathymetry of the continents and oceans influence ocean and atmospheric circulations and biogeochemical cycles, as well as how orogens respond to significant climate shifts such as the onset of Northern Hemisphere glaciation, the Mid-Pleistocene Transition, and the development of the Indian monsoon. Other avenues of research should investigate how tectonics influences discharge of freshwater, nutrients, and sediment from the continents to the ocean and how these affect the biota and biogeochemical cycles on continental margins and in marginal seas. The potential impact of small rivers, groundwater, and aeolian transport on global freshwater, nutrient, and sediment budgets also needs to be quantified. Future ocean drilling should focus on capturing a complementary array of continental margin and fan records, including Arctic and Antarctic deposystems; exhumation history; terrestrial climate/vegetation changes; sediment, nutrients, and carbon budgets; and freshwater discharges for the areas of the Earth with the highest fluxes. Such a strategy will undoubtedly advance our understanding of the feedbacks between tectonics and climate and their combined influences on the Earth's surface.

Technological Needs and Development

To achieve novel scientific ocean drilling objectives will depend on improved drilling capabilities such as enhancing depth penetration, improving core recovery and quality, coring in high-temperature and high-pressure environments, coring in shallow water margins, coral reefs, and sea-ice covered regions (*e.g.*, such as with the planned Research Icebreaker *Aurora Borealis*), and preventing magnetic, chemical, and microbiological contaminations. Overall, the next phase of the scientific drilling program will require significant and even more coordinated engineering efforts.

One of the most significant technological requirements is the measurement of the intrinsic and/or ephemeral properties of cores and boreholes. *In situ* measurements of redox state, chemical compositions, physical parameters, pH, and microbial populations and their activities are absolutely necessary. Newly developed (or improved) logging sensor tools, *in situ* sampling/monitoring devices, and *in situ* microbial colonization systems will be needed to achieve multidisciplinary scientific objectives through borehole observatories and experiments. Real-time hydrocarbon gas monitoring systems that include stable isotope measurements should also be deployed in platform laboratories. Novel and/or improved analytical technologies for quick, high-resolution measurements of temperature-, redox-, and oxygen-sensitive chemical and microbiological components must be developed for use on recently acquired cores, since exploration of high-temperature hydrothermal systems and the deep, hot biosphere has great potential to increase our understanding of the co-evolution of life and the planet. In addition, onboard measurements of physical, chemical, and biological properties of cores are extremely useful for real-time decisions necessary to meet drilling goals.

The development of a high-pressure- (and -temperature) coring system is required for various geochemical and biological reactions because the pressure limit of the currently available high-pressure-coring system is up to 25 MPa, which is not enough for high-pressure gas fields or deep coring (>2500 meters below the sea surface). Furthermore, once core under high pressure and temperature reaches the surface, an onboard high-pressure core transfer system equipped with multiple (micro-) sensors, gas and fluid extraction ports, tracer injection systems, and a mini-core sub-sampling system is needed.

Subseafloor microbes proliferate in narrow niches and vary over local fluid-flow pathways used to transport energy and nutrients, hence high-resolution microbiological sampling is necessary. We need to develop onboard sub-sampling strategies for quick identification of microbially interesting zones and high-resolution sampling capabilities while monitoring and minimizing contamination. Furthermore, the non-destructive identification of core quality and structures (through X-ray CT scanning) is a high priority for future microbiology/biogeochemistry-dedicated drilling expeditions. For high-throughput and high-resolution onboard analyses, computer automated systems, such as the auto-extractor and the automated cell-counting microscope system using fluorescent image analysis, should be deployed.

Penetration through a complete ocean crust section, the so-called project 'Mohole', will require advances in drilling capabilities that include riser drilling capability in 4000 m or more water depth, deep penetration and recovery of crustal rocks of all lithologies, and borehole and drill bit cooling technology for high temperature (>250°C) environments. Technological issues include improvement of riser-pipe quality and casing strings, the blowout preventer, and the mud-circulation/recovery system. The newly developed Riserless Mud Recovery (RMR) system has great potential for use in various environments in future drilling, especially for borehole controls (*i.e.*, stability and cooling). Combining the dual-gradient technology with RMR enables environmentally friendly drilling (*i.e.*, clean without mud-pollutants to seawater) access to deeper environments and areas previously not drillable by riserless drilling. The RMR technology is directly applicable to all Integrated Ocean Drilling Program (IODP) platforms.

Improving core recovery and quality is the fundamental challenge for all drilling environments. Core recovery and quality depend on factors such as depth, temperature, fluid pressure, and lithology, as well as the design and performance of drilling and coring tools. In previous drilling experiences, poor core recovery has plagued (1) chert and/or shales, (2) sand and gravel layers, (3) hydrothermal deposits, (4) rubble basalts and sheeted dyke complexes, and (5) fault and fracture zones. Anticipated improvements include more accurate compensation of drill bit motion, torque, and type of cutting shoe, and operational technologies such as a feedback system of real-time drilling parameters. Other strategies, such as cuttings and side-wall coring, will increase sampling of unrecovered intervals. Borehole management (*i.e.*, stability) requires cuttings removal and compensation of lithostatic and pumping pressures in both riser and riserless drilling modes. In addition, large diameter pipes may provide more opportunities to conduct various geophysical measurements such as pore pressures and resistivity.

Monitoring while drilling using downhole logging tools has greatly expanded our understanding of *in situ* pressure and stress conditions in the borehole. The use of logging tools during drilling or in Circulation Obviation Retrofit Kit (CORK) boreholes is likely to expand in the new drilling program. Multiple-hole experiments are recommended, including injection tests and cross-borehole communication studies. Broadband and high-sensitivity sensors such as fiber-optic seismo-sensors combined with continuous data recovery should be developed and installed in active subseafloor environments. To study *in situ* conditions of high-temperature and/or high-pressure environments, the durability of logging systems to high temperature and pressure must be improved. Development of new slim-line multi-logging tools and borehole equipment is needed for all platforms. Current shipboard computational and dissemination capabilities should be more effectively integrated between software programs, database mining, and accessibility and be easily interfaced among the multiple drilling platforms and core repositories.

Outreach, Education, and Branding

Outreach refers to activities that target the general public and funding agencies. Education and educational outreach are aimed at students in primary, secondary, undergraduate, and graduate school realms. Continued coordination through IODP-MI or its successor organization is essential to achieve the best results in the arena of public outreach. A successful branding campaign will be vital to ensure ongoing public recognition of the scientific discoveries and technological achievements of scientific ocean drilling.

Branding the science and accomplishments of ocean drilling should elucidate the linkages to broader objectives or themes, and not necessarily focus on individual expeditions. As visual impression is the key for branding, web sites across the program must have a common layout to promote the impression of a truly integrated program to the scientific community and the public, and to facilitate access to information. A series of bold, clear key messages should be an important element in any branding campaign. For example, the main messages of the drilling program should emphasize the following.

⇒ The program investigates a dynamic Earth; it is a changing, not static, planet.

⇒ Basic science is always valuable to society.

⇒ Scientific ocean drilling is particularly relevant to society, providing knowledge about geohazards and climate change.

⇒ Scientific ocean drilling is on the edge of the science frontier. By exploring Earth through scientific ocean drilling, we make novel and fundamental discoveries.

Outreach and education are vital in raising the profile of the future drilling program. The program needs to employ a full-time science 'translator' (scientist or science educator with requisite skills) that can effectively communicate drilling science to non-scientists. Because many ocean drilling scientists are also geoscience educators, there should be mechanisms for them to be closely involved in framing the science to be easily accessible to students and the general public. Consideration should be given to expanding successful current programs to include all international partners and to serve all audiences (undergraduates, graduates, faculty, young scientists, science teachers, *etc*.). Specific recommendations are (1) the development and dissemination of an archive of basic images documenting the history and goals of the drilling program; (2) admitting science educators, in addition to school teachers, on expeditions; (3) providing communications training for younger scientists on board; (4) offering early career workshops sponsored by the new ocean drilling program; and (5) developing a mentoring plan for young career scientists who go to sea on expeditions and site survey cruises. Generally, the ocean drilling program should make greater use of Google Ocean and GeoMapApp to provide the public with images and video for education and outreach. Finally, in planning the new drilling program, there should be a workshop dedicated to formulating a plan that employs innovative cutting-edge methods of science education, communication, and outreach.

Recommendations for the New Program

Scientific planning in the new ocean drilling program should be driven from the 'bottom up', with scientists playing key roles in defining specific scientific short- and long-term goals and in advising and working directly with management, ship operators, and engineering development to execute the drilling program. The direct involvement of world-class students and scientists will keep the international ocean drilling program fresh and focused on emerging transformative topics that define the frontiers of life and earth sciences. As such, a strong science advisory structure should be a central component of the new program architecture. Furthermore, transformative science is often born from cross-disciplinary perspectives, and the drilling program must have multiple mechanisms to proactively engage scientists and students from disciplines outside of the traditional drilling community, from both academia and industry.

Because of the complex nature of an international drilling program with multiple operators and stakeholders, effective management should focus on fostering stronger international partnerships, well-integrated collaborations with other large geosciences programs, effective fundraising, and creative and efficient coordination amongst the national offices and implementation/ship operators. By working with the science advisory committees and scientific community, management should facilitate the formulation of visionary and innovative scientific goals through the life of the program.

Meeting the scientific goals of the drilling program will require flexibility. Multi-expedition, long-term missions will be required to achieve these ambitious goals. At the same time, many of the highest impact ocean drilling projects may be unanticipated and/or concise and focused. Thus, there must be mechanisms by which the new ocean drilling program can quickly respond to, nurture, and execute brilliant new ideas (identified through a peer-review system) that require ocean drilling. To implement the projects necessary to achieve transformative science will require a new ocean drilling program architecture that, by design, will have the flexibility to react quickly to new opportunities, but also to make decisive commitments to long-term complex, technically challenging projects.

1 Introduction

The INVEST conference, an international meeting to define the scientific goals and technology needed for a new ocean drilling program, was held at the University of Bremen between the 22nd and the 25th of September 2009. Based on the large attendance and vigorous engagement of scientists in the discussion of new science/technology ideas, INVEST was extremely successful. Initially 400 participants were expected, but the INVEST steering and organization committees were thrilled to see a much larger number of scientists flock to Bremen to demonstrate their support and enthusiasm for the continuation of an international scientific ocean drilling program. In all, 584 participants, including 64 students, from 21 nations and >200 institutions and agencies attended the INVEST conference. Contributions to INVEST included 103 submitted white papers that are posted on the INVEST webpage (http://www.marum.de/iodp-invest.html), and breakout discussions in 50 working groups that focused on a range of topics during the course of the conference. In addition, students and early career scientists, as well as national funding agency managers and platform providers, presented a total of 86 posters. Interspersed with the working group and plenary sessions were 12 keynote lectures, chosen to highlight overarching themes and new research directions.

The conference was sponsored by the Integrated Ocean Drilling Program Management International (IODP-MI), the Deutsche Forschungsgemeinschaft (DFG) and MARUM research center. The National Program Offices supported travel for many participants.

Nation	Participants
Australia	7
Belgium	3
Brazil	1
Canada	6
China	24
Denmark	6
France	44
Germany	110
Italy	4
Japan	109
Korea, Rep. of	12
Netherlands	6
New Zealand	1
Norway	10
Portugal	3
Russian Federation	1
Spain	7
Sweden	3
Switzerland	7
United Kingdom	53
USA	167
Total	584

Keynote lectures

Vincent Courtillot – Ocean Drilling: A 21st Century Endeavor to Understand the Earth System

Hans Christian Larsen – Future Program Planning Process and Facilities

Terry Plank – Down and Back Again: Cycles and Growth at Convergent Margins

Jim Zachos – The Potential and Promise of Studies of Past Warm Worlds

Dave Hodell – Paleoclimate Opportunities to Constrain Abrupt and Rapid Climate Change

Kiyoshi Suyehiro – Ocean Borehole Observatories: Scanning and Sounding the Earth in Motion

Tori Hoehler – The View from Space: What Ocean Drilling can Tell us About Habitability, Life's Limits, and the Possibilities for Life Beyond Earth

Andrew Fisher – Achievements and Challenges in Subseafloor Hydrogeology during Scientific Ocean Drilling

Bo Barker Jørgensen – Microbial Life in the Deep Seabed – The Starving Majority

Naohiko Ohkouchi – Future Directions in Probing Global Biogeochemical Cycles

Peter Kelemen – Future IODP Studies of CO_2 Capture and Storage: Focused Research and Synergies with other Science Goals

Jeff Kiehl – Paleoceanography: Providing Critical Knowledge to Improve Climate Model Predictions

Greg Myers – Engineering to Support Transformative Science in Ocean Drilling

Working group sessions

The working group sessions were organized within six conference themes. Each meeting attendee was given the opportunity to participate in three working groups: one within conference themes one through three (days 1 and 2), one within conference themes four and five (days 2 and 3), and one within conference theme six (day 3). Up to 18 working groups met in parallel sessions. All working groups within one conference theme met to report to each other the results of the working group discussions. The conference theme co-chairs then met with the working group chairs and scribes to prepare a plenary presentation of the conference theme.

List of conference themes (CT) and working groups (WG) *with the names of chairs and scribes in brackets*

CT1: Co-evolution of Life and Planet (Rick Colwell, Richard Norris)

WG1.1: Extent and habitability of subseafloor life and the biosphere (Steven D'Hondt, Jennifer Biddle)

WG1.2: Biogeochemical function, activity, and ecological roles of subseafloor life (Wiebke Ziebis, Timothy Ferdelman)

WG1.3: Limits and evolution of life on Earth and beyond (Ken Takai, Eric Gaidos)

WG1.4: Extreme environmental events and punctuated evolution (Mitchell Schulte, Ellen Martin)

WG1.5: Paleo-ecosystems: biodiversity and biogeography (Andy Purvis/Paul Pearson, Mark Leckie)

WG1.6: Co-evolution of ocean chemistry and the surface/subsurface biospheres (Rachel James, Richard Murray)

CT2: Earth’s Interior, Crust, and Surface Interactions (Donna Blackman, Susumu Umino)

WG2.1: Behavior of the geodynamo (Toshitsugu Yamazaki, Joseph Stoner)

WG2.2: Mantle flow and interactions with the lithosphere (Nicholas Arndt, Kaj Hoernle)

WG2.3: Variability in ocean crust composition and structure (Chris MacLeod, Barbara John)

WG2.4: Plate aging: ridge to trench (Robert Harris, Geoff Wheat)

WG2.5: Subduction zones and volcanic arcs (Lisa McNeill, Eli Silver)

WG2.6: Initiation of plate boundaries (Dale Sawyer, Gianreto Manatschal)

CT3: Climate Change – Records of the Past, Lessons for the Future (Yusuke Yokoyama, Alan Mix)

WG3.1: Extreme and/or rapid climatic events (Junichiro Kuroda, Terrence Quinn)

WG3.2: High latitude regions and stability of ice sheets (Carlota Escutia, Rüdiger Stein)

WG3.3: Rates and amplitudes of sea-level change (Jody Webster, Peter Clift)

WG3.4: Ocean-atmosphere circulation dynamics (Michael Schulz, Matthew Huber)

WG3.5: From Greenhouse to Icehouse worlds (Henk Brinkhuis, Mitchell Malone)

WG3.6: Sensitivity of the climate system (Jeffrey Kiehl, Mitch Lyle)

CT4: Earth System Dynamics, Reservoirs, and Fluxes (Damon Teagle, Peter Clift)

WG4.1: Ocean-crust-mantle cycles (Richard Arculus, Pat Castillo)

WG4.2: Controls and feedbacks on hydrocarbon storage and emissions (Ian MacDonald, Evan Solomon)

WG4.3: Carbon cycle and redox budget (Klaus Wallmann, Peggy Delaney)

WG4.4: Fluid-flow, heat-flow, and hydrothermal systems (Andrew Fisher, Marvin Lilley)

WG4.5: Continent-ocean fluxes, weathering processes, and linkages (Hongbo Zheng, Liviu Giosan)

WG4.6: (Bio)geochemical element cycles (Nao Ohkouchi, Jan Amend)

WG4.7: Tectonic-climate interactions (John Jaeger, Gabriele Ünzelmann-Neben)

CT5: Earth-Human-Earth Interactions (Pinxian Wang, Achim Kopf)

WG5.1: Geohazards: earthquakes (Shuichi Kodaira, Harold Tobin)

WG5.2: Geohazards: submarine landslides and mass movements (Angelo Camerlenghi, Sebastian Krastel)

WG5.3: Geohazards: volcanic eruptions and bolide impacts (Julia Morgan, Joanna Morgan)

WG5.4: Ocean acidification: past and future (Hodaka Kawahata, Ellen Thomas)

WG5.5: Subseafloor resources (Tetsuro Urabe, Bramley Murton)

WG5.6: CO_2 sequestration (Margot Godard, Peter Kelemen)

WG5.7: Improving sea-level change predictions (Gregory Mountain, Craig Fulthorpe)

WG5.8: Climate, human evolution, and civilization (Peter deMenocal, Stefan Mulitza)

WG5.9: Ultrahigh-resolution records to improve climate change prediction (Terrence Quinn, Robert Dunbar)

CT6: Science Implementation (James Cowen, Susan Humphris, Clive Neal)

WG6.1: Observatories (Earl Davis, Craig Moyer/Peter Girguis, Robert Harris)

WG6.2: Subseafloor laboratories and experiments (Beth Orcutt, Adam Klaus/Elizabeth Screaton, Dave Smith)

WG6.3: Platform, drilling, and logging tools: needs and opportunities (Hiroshi Asanuma, Alberto Malinverno/Peter Flemings, Yasuhiro Yamada)

WG6.4: Site characterization and integration with the borehole (Gail Christeson, Chun-Feng Li/Nobukazu Seama, Nathan Bangs)

WG6.5: Analytical needs and development (Yuki Morono, Mike Lovell/Clive Neal, Steven D'Hondt)

WG6.6: Balancing long-term projects and single expeditions (Keir Becker, Jim Mori/Kiyoshi Suyehiro)

WG6.7: Program management options to optimize integration (Ulrich Harms, Gabriel Filippelli/Masaru Kono, Timothy Byrne)

WG6.8: Develop broad vision for outreach, branding, and education (Katherine Ellins, Mark Leckie/Tatsuhiko Sakamoto, Kristen St. John)

Steering Committee

The INVEST steering committee was charged with organizing the INVEST meeting, selecting keynote speakers, defining working group sessions and leaders, and writing the INVEST meeting report.

Sponsors:

University of Bremen
Meeting host: Gerold Wefer
MARUM – Center for Marine Environmental Sciences,
University of Bremen, Germany

IODP-MI
Contact: Hans Christian Larsen
Vice President of Science Planning
Head, IODP-MI Sapporo Office, Japan

2 Climate Change Impacts

2.1 Extreme Events

> *"Locating potential future tipping points requires some use of predictive models, in combination with paleodata and/or historical data."*
>
> Lenton *et al.* (2008)

This section reports INVEST findings about 'extreme events' in the context of Earth system, climatic, and biological events. A working definition might be that extreme events represent a significant and rare deviation from natural variability on the timescale under consideration, and are of a global scale or impact. Using this definition, such extreme events depend on the geographical scale and the temporal resolution over which the general continuum is sampled. Several recent workshops have identified detailed, urgent research questions of societal relevance that provide context to this problem (Stein and Coakley, 2009; DeSantis *et al*., 2009; Thurow *et al*., 2009; Anderson *et al*., 2009, Henderson *et al*., 2009) (Fig. 2.1).

The significance of extreme events arises from our curiosity about what extremes are possible; these define general climate and Earth system variability for different timescales (represented by instrumental, historical, and geological records; Mitchell, 1976). Perhaps more importantly they enhance modeling studies to help us gain a better understanding of how Earth system components react to large amplitude perturbations. Extreme event-related perturbations might originate in a specific component of the Earth system (*e.g.*, atmosphere, ice sheets, carbon cycle, volcanism, hydrological cycle, biosphere), but typically propagate through complicated feedback systems across some or all components, allowing us to gain a better understanding of these system interconnections. Extreme and rapid events also allow the investigation of dynamic system behavior, such as tipping points and thresholds (deConto *et al*., 2008; Lenton *et al*., 2008). In addition, these events stand out from noisy sediment-derived proxy time series and are thus easier to quantify. From an ecosystem perspective, large amplitude perturbations often mark epoch boundaries (*e.g.*, the Permian/Triassic boundary, the Cretaceous/Paleogene (K/Pg) boundary (formerly K/T), the Paleocene/Eocene Thermal Maximum (PETM), the Eocene/Oligocene climatic transition), and provide one of the primary means to investigate large-scale ecosystem turnover and biodiversity evolution.

Ocean drilling has been the only means to reconstruct, at medium- to high-temporal resolution, the climate evolution of the Earth system throughout the Cenozoic and beyond. One such proxy-derived record is the compilation of oxygen- and carbon-isotope records that demonstrate the long-term temperature and ice-volume evolution during the past 66 m.y. (Zachos *et al.*, 2001, 2008). This remarkable success story of documenting global background climate and climatic extremes resulted from over 43 ocean drilling expeditions.

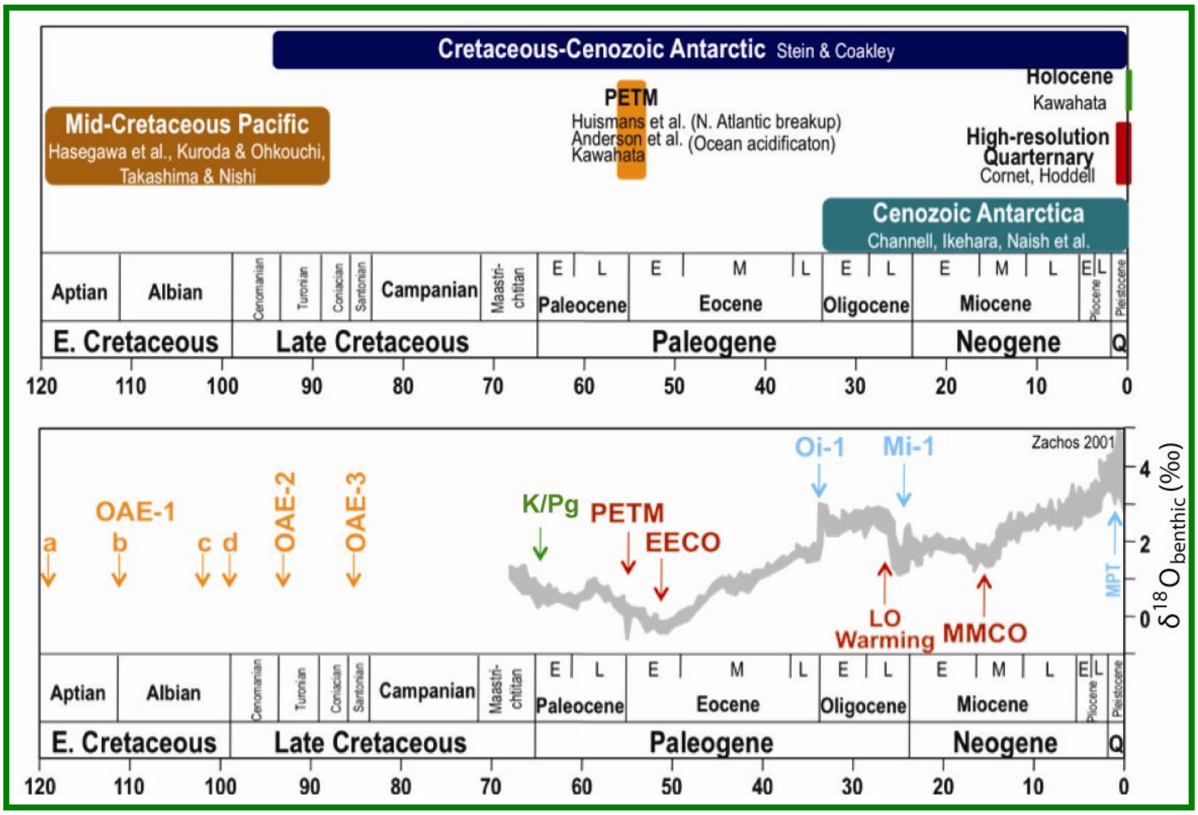

Figure 2.1 Summary of extreme and rapid climatic events during the Mesozoic and Cenozoic and associated INVEST white papers. The oxygen isotope curve in the lower graph is from Zachos et al., 2001. OAE = oceanic anoxic event; K/T = Cretaceous/Tertiary boundary; PETM = Paleocene/Eocene thermal maximum; EECO = early Eocene climatic optimum; Oi-1= Oligocene isotope excursion 1; Mi-1 = Miocene isotope excursion 1; LO = late Oligocene; MMCO = middle Miocene climatic optimum; MPT = mid-Pleistocene transition.

Individual studies have generated high-resolution records of extreme events, documenting a rapid shift in oxygen-isotope values of benthic and planktonic foraminifera across the PETM (Thomas *et al*., 2002; Zachos *et al*., 2007), at a transient warning event in the late stages of the Eocene Greenhouse (Bohaty *et al*., 2009), across the onset of major Antarctic glaciation at the Eocene/Oligocene boundary (Coxall *et al*., 2005; DeConto *et al*., 2008), and across the Earth's final transition into the Icehouse world during a middle Miocene global cooling (Holbourn *et al*., 2005). Oxygen isotope shifts have also documented the onset of Heinrich events before the last glaciation (Hodell *et al*., 2008), demonstrated the possibility of permanent El Niño-like states during the Pliocene (Wara *et al*., 2005), and allowed a global compilation of climate proxy data for the past ~5 Ma (Lisiecki and Raymo, 2005). More recent climatic events and their relationship and frequency with respect to climatic boundary conditions and global mean temperatures are additional high-priority targets for this research, including the Younger Dryas (YD), the possible manifestation of Dansgaard-Oeschger (D-O) cycles in the Southern Hemisphere, and El-Niño Southern Oscillation (ENSO) and El-Niño behavior during warm climates.

During INVEST, key aspects of extreme and rapid climatic events discussed included cryosphere dynamics, ecosystem response and feedbacks, tropical climate dynamics of rapid/extreme climate events and ENSO, causes of extreme or rapid climate events, as well as model-data interactions within these fields. The following key questions were identified during the meeting, and in the preparatory workshops and white papers.

2.1.1 Cryosphere dynamics

Major extreme climatic shifts occurred during the Cenozoic (Zachos *et al.,* 2001), including dramatic reorganization, waxing, and waning of the West and East Antarctic ice sheets. Major questions that need to be answered by ocean drilling and through links to other polar research initiatives include:

⇒ What is the contribution of continental ice to the rate and magnitude of sea-level changes both in the past and projected into the future? Will sectors of marine-based ice sheets experience 'runaway collapse' as climate warms? Can ocean drilling provide constraints on past rates of this process? Models hypothesize unpredictable and rapid deglaciation of marine-terminating ice sheets as they retreat into deep basins below sea level. Ice equivalent to three meters of sea level within the West Antarctic ice sheet (WAIS) is potentially susceptible to 'runaway retreat' capable of producing sea-level rise of 1-3 m per century. A numerical ice-sheet modeling approach calibrated with drill-core evidence of past WAIS collapses is required to address this issue.

⇒ How did paleo ice sheets respond when Earth's atmosphere had 400 ppm CO_2? The early Pliocene Epoch represents the last time Earth's climate was as warm as it will be in the next century. It is an important geological analogue for the initial stages of global warming, when atmospheric pCO_2 was known to be 400 ppm and other climatic boundary conditions were similar. The Antarctic Geological Drilling (ANDRILL) 1B record suggests ice-sheet variability in the western Ross Sea was not directly influenced by West Antarctic ice, but has provided some critical insights suggesting a dynamic WAIS collapsing during past warmer-than-present interglacials (Naish *et al.,* 2009). This record needs to be confirmed with a more WAIS-proximal record.

⇒ How did ice sheets respond the last time Earth's atmosphere contained 600-1000 ppm CO_2? The Oligocene Epoch is characterized by dynamic ice sheets on both East and West Antarctica (Naish *et al.,* 2008; Zachos *et al.,* 2001; Pälike *et al.,* 2006) when atmospheric pCO_2 was between 600 and 1000 ppm. We know the ice sheets form when pCO_2 concentrations are below 2-3 times pre-industrial levels (DeConto and Pollard, 2003); however, removing significant terrestrial sectors of the East Antarctic ice sheet (EAIS) may require significantly more greenhouse gas induced warming (DeConto *et al.,* 2008). The hysteresis and history of this response needs to be evaluated using spatial coring coverage around Antarctica, complementing the drilling on Wilkes Land (IODP Expedition 318, Jan./Feb. 2010).

⇒ What did a 'Greenhouse Earth' look like in the polar regions? Can Antarctica sustain any ice sheets when the atmospheric CO_2 concentration is above 1000 ppm?

⇒ Can ice-volume and sea-level records be reconciled with far-field deep ocean oxygen-isotope and temperature proxy records? How much of EAIS is vulnerable to marine melting? The Eocene-Oligocene climate transition in Antarctica is poorly known from proximal geological evidence, yet models (DeConto and Pollard, 2003) and far-field paleoceanographic proxy data (Liu *et al.,* 2009) suggest that the Earth cooled by 3-4°C and the first large permanent ice sheets formed on Antarctica when atmospheric pCO$_2$ concentrations dropped to about 1000 ppm during a cooling trend in the late Eocene. Recent studies calibrating the ice-volume/sea-level component (Coxall *et al.*, 2005; DeConto *et al.*, 2008) of the Cenozoic oxygen-isotope record require the existence of 20% more polar ice on Antarctica and/or the northern hemisphere continents during major glacials than is considered possible by both models (DeConto *et al.*, 2008) and geological evidence (Naish *et al.*, 2008). Drilling in the Ross Sea would address these questions. In addition, ocean drilling in the Indian Ocean is required to generate proximal records of the East Antarctic Ice Sheet during past extreme events.

⇒ Southern Ocean drilling will enable us to delineate behavior of several major climate cycles and climate shifts such as YD/Antarctic Cold Reversal (ACR), D-O cycles, the mid-Brunhes climate shift, late Miocene cooling, major Antarctic glaciation around the Oligocene/Miocene boundary and first ice sheet inception around the Eocene/Oligocene boundary.

⇒ Did the dramatic millennial-scale D-O climate cycles of the Northern Hemisphere manifest themselves in the Southern Hemisphere? If so, what was the amplitude of the response, and was the Southern Hemisphere in-phase or out-of-phase with the D-O cycles?

To meet the cryosphere dynamics objectives, new results from the ANDRILL Program (Naish *et al.* 2009; Pollard and DeConto, 2009) provide an important example of how paleoclimate records integrated with climate and ice-sheet modeling can help constrain future change. The ANDRILL-1B drill core reflects an unstable WAIS during the Pliocene (5-2 Ma ago); a time when Earth's average surface temperature was 3-4°C warmer than present and oceans around Antarctica were 5°C warmer – driving global sea-level changes of up to 7 m above present. The size of these ice-volume changes was a surprise and causes concern as they occurred when atmospheric CO$_2$ levels were no higher than ~400 ppm, only slightly higher than present day levels. Other research findings include a recently reported study of the Greenhouse world of ~50 Ma ago that implies a higher 'climate sensitivity' than currently accepted (Huber, 2008), suggesting additional positive feedbacks (climate amplifiers), perhaps pre-conditioned by CO$_2$ levels. Moreover, our knowledge of Antarctic ice-sheet behavior in a high-CO$_2$ world (2-4 times pre-industrial levels, which may be reached by 2100), still remains one of the greatest uncertainties. This is important as atmospheric CO$_2$ reconstructions from microfossils for the past 100 m.y. (Pagani *et al.*, 2005) and global climate models show CO$_2$ as the major influence on Antarctic ice-sheet stability (DeConto and Pollard, 2003). There is also an immediate need to recover Antarctic geological records beyond the age-range of ice cores and the current ANDRILL projects. These records need to extend back to 30-50 Ma ago when Earth's atmospheric CO$_2$ was 2 to 4 times higher than present – the high end of the Intergovernmental Panel on Climate Change (IPCC) projections for 2100. It is imperative to obtain sediment cores from the Indian sector of the Southern Ocean, which is a sensitive recorder of EAIS variability. Other specific requirements include:

⇒ Integrated inner-outer shelf to slope-rise-abyssal plain drilling transects are required across key sectors of the Antarctic margin using different platforms (IODP, the International Continental Scientific Drilling Program (ICDP), ANDRILL, Shallow Drilling on the Antarctic Continental Margin (SHALDRIL), the Meeresboden-Bohrgerät (MeBo)).

- ⇒ Better knowledge about sub-ice-shelf basins that trap Neogene sediments are needed to identify drill sites that can complement the new ANDRILL records and that can be used to validate and test hypotheses explored by models.
- ⇒ These drill sites should be coupled with multi-disciplinary marine-process studies (*e.g.*, biological ecosystem-scale, physical oceanography, sea ice, *etc.*) and non-marine studies (subglacial drainage and hydrology).
- ⇒ Ocean drilling should strive for high recovery of fine-grained, soft sediment (biogenic and fine-grained terrigenous) alternating with overcompacted glacial diamicts that preserve records of glacial advances and retreats in water depths up to 1500 m – which may require a riser system, mud recirculation system for riserless drilling, a seafloor wireline drill system, or a combination of these approaches.

The highest research priorities for the next decade were identified by Stein and Coakley (2009), DeSantis *et al.* (2009) and Thurow *et al.* (2009). In the Arctic Ocean, despite the success of IODP Expedition 302 – Arctic Coring Expedition (ACEX), major questions related to the climate history of the Arctic Ocean and its long- and short-term variability during Mesozoic-Cenozoic times cannot be answered from the ACEX record due to the poor core recovery and, especially, a major mid-Cenozoic hiatus. This hiatus spans the critical interval when prominent changes in global climate took place during the transition from the early Cenozoic Greenhouse world to the late Cenozoic Icehouse world. Nevertheless, the success of ACEX has certainly opened the door for further scientific drilling in the Arctic Ocean during the next decade, and the 2008 Bremerhaven workshop report provides details of specific Arctic targets that have already fed into the current proposal system. The ACEX results will frame the next round of questions to be answered from new drill holes to be taken by a series of drilling legs during the next decade and beyond. In the Antarctic, DeSantis *et al.* (2009) and INVEST identified a list of priorities that include urgent drilling in the Indian sector of the Southern Ocean and proximal to Antarctica, as well as integration with ANDRILL, SHALDRIL and other efforts.

2.1.2 Ecosystems response and feedback

Extreme environmental events and punctuated evolution can be defined as geologically rare intervals of rapid environmental and/or biotic change that have a global significance. Ocean drilling provides unique datasets of past biotic change that allow an ecosystem approach to be applied in order to evaluate biotic response to large environmental perturbations. Important events include the Cretaceous oceanic anoxic events (OAEs) and large igneous provinces (LIPs), the K/Pg boundary impact and Deccan Traps, Paleocene-Eocene hyperthermal events (*e.g.*, PETM) and the North Atlantic volcanic province, the Eocene-Oligocene transition, and intervals of anomalous cosmic dust input. Not all biotic evolutionary events are associated with extreme environmental conditions. For instance, important evolutionary steps also occur during intervals of environmental stability (Jurassic/Cretaceous (Jr/K) boundary, early Aptian OAE1a (Ontong Java Plateau (OJP)), Aptian/Albian boundary, late Albian, Campanian). Important questions include:

- ⇒ How do biota respond to rapid events? How do ecosystems function during extreme conditions, how do they recover, and how do they survive transient conditions? Why are recoveries different? Why do biotic systems recover from some events, whereas other events lead to thresholds and a new equilibrium? Can the rate of change be too great for the system to adjust? Is there a role for genetic memory?

⇒ What is the role of environmental change in biotic evolution? Why do different organisms respond differently to rapid environmental change? For instance, planktonic *vs.* benthic, carbonate *vs.* siliceous, primary producers *vs.* zooplankton during the K/Pg boundary crisis? Moreover, some originations occur under stable conditions rather than extreme events. During OAEs organisms start to change well before the major record of environmental change (thresholds). What is the trigger for changes during stable environments?

⇒ Is there a kill curve for impact events that cause significant biotic changes (*e.g.*, K/Pg *vs.* Eocene)? Comparing consequences of other large impact events, does the biosphere respond?

⇒ What is the sequence of ecosystem events during repeated or cyclical changes (glacial-interglacial, D-O cycles, Bond cycles, Heinrich events)? What are the dynamic relationships between different organisms under varying conditions?

2.1.3 Tropical hydrology, monsoon, and ENSO variability

Nearly four billion people rely on the regular return of the monsoon (Clift *et al.*, 2008) in Asia.

⇒ Will an increase in greenhouse gas concentrations disrupt this regular monsoonal cycle?

Past warm climates such as Pleistocene interglacials, the PETM and hyperthermals, and other Neogene hothouses might provide insight into future high CO_2 climates and monsoon behavior.

The basic need for water and food to sustain populations means that predicting extrema of the hydrological cycle (*e.g.*, droughts, floods, and cyclones) and their impact on water supplies and agricultural sustainability during climate change are pressing concerns. Extremes in the hydrological cycle occur regionally, are a feature even of the last 10 kyr of stable warm climate, and have changed civilizations (deMenocal, 2001). The IPCC Fourth Assessment Report (AR4) states that "*substantial uncertainty remains in trends of hydrological variables because of large regional differences, gaps in spatial coverage and temporal limitations in the data* (Huntington, 2006)", and that "*Tropical cyclones, hurricanes and typhoons exhibit large variability from year to year and limitations in the quality of data compromise evaluations of trends*."

Ocean drilling, together with ICDP lake drilling, can contribute to collecting the ultrahigh climate records required to assess the sensitivity of ENSO and monsoon processes to changes in climatic boundary conditions. Records of Pleistocene glacial periods and prior warm periods are needed to understand the mechanisms of monsoon variability and ENSO. Archives with sufficient resolution to capture extreme events (*e.g.*, stalagmites, rapidly accumulating sediments) are reaching sufficient maturity to allow assessment of relationships between storm events and climate state.

⇒ Was past ENSO and El-Niño behavior different during warm climates?

The weak ENSO variability of the early to mid Holocene (6-9 kyr ago) recorded in tropical corals (Tudhope *et al.*, 2001) and other paleoclimate records suggest that ENSO is sensitive to modest variations in seasonality caused by changes in Earth's orbit.

Efforts to understand the ability of ENSO to weaken in this way have examined a number of different hypotheses and models and helped to understand the behavior of ENSO in altered boundary conditions.

The so-called mid-Pliocene 'permanent' ENSO state (Bonham *et al.,* 2009), more accurately described as a mean warming of the east Pacific relative to the west, has motivated theoretical and modeling studies (Fedorov *et al.,* 2006), which need to be linked to actual observations of ENSO behavior from ocean drilling (Davies *et al.,* 2009).

2.1.4 Causes of past climatic extremes and rapid change

The climate system can respond abruptly to what appear to be gradual changes in forcing (*e.g.*, orbital, greenhouse gases, global temperature). This phenomenon is consistent with the notion of thresholds or tipping points in the climate system (Lenton *et al.,* 2008) that might be related to physical feedbacks involving ice sheets, ocean circulation, or geochemical feedbacks from surficial carbon reservoirs. Several extreme climatic shifts have been identified, partly by ocean drilling, over the last few years, which can provide insights into a better understanding of the causes of past climatic extremes and rapid changes. One such example is the PETM (Zachos *et al.,* 2005). Urgent research hypotheses that can be addressed by ocean drilling include:

⇒ One proposed positive feedback associated with the PETM is the dissociation of methane hydrates. These hydrates might have been concentrated in the Arctic Ocean with gradual warming initiating decomposition at depth. Modeling suggests that the hydrates in this region alone would have contained as much as 1500 Gt C.

⇒ With rapid warming of the high-latitude ocean, the thermohaline circulation slowed considerably, thereby slowing the uptake of carbon by the ocean. Slow diffusion of heat eventually restored thermohaline circulation.

⇒ Onset of the PETM was caused by the volcanically driven degassing of carbon rich sediments in the North Atlantic associated with the plume driven unzipping of the rift zone.

For the Eocene/Oligocene climatic transition from Greenhouse to Icehouse (deConto *et al.,* 2008), a specific hypothesis to be tested by ocean drilling is:

⇒ Gradual cooling of Antarctica crossed a threshold initiating rapid ice-sheet expansion around the Eocene/Oligocene boundary. Models suggest that the pCO_2 threshold lies at 700 to 800 ppm for rapid expansion of ice sheets. Ice-albedo feedbacks contribute to the rapid expansion.

Additional extreme events that have important unanswered questions include the YD event and Cretaceous OAEs. Several theories have been proposed to explain the rapid onset of carbon burial that defines OAE2 (Caribbean volcanism, circulation changes, gateway opening, orbital changes, greenhouse climate, or some combination of all of these), but none yet suitably explain the breadth of the event. It appears that other basins may hold some of the keys to understanding OAE2.

⇒ Is the YD a unique event or an 'extreme' Heinrich event? Do we see other similar events in previous terminations? If not, then is this a resolution issue or different deglacial processes?

- ⇒ The theories that are used to explain the origin of the YD (*e.g.*, orbital control, freshening in the North Atlantic) do not suitably explain the breadth of climatic change.
- ⇒ The most important question remains: What caused OAE2? How does the marine biogeochemical system respond to major, rapid redox perturbations?
- ⇒ What is the paleoceanographic record of OAE events outside the North Atlantic (South Atlantic, Indian, or Pacific Oceans)?

2.2 Ice-Sheet Stability, Sea-Level Change, and Shoreline Retreat

2.2.1 Records, processes, and effects of sea-level change

One of the most societally-relevant objectives within the earth sciences is to understand the history and impact of global sea-level (eustatic) fluctuations at different timescales. Sea-level fluctuations result from changes in the volume of water in the ocean or the volume of ocean basins as a consequence of the complex spatial and temporal interplay of a spectrum of intertwined forcing processes. Reconstructions of the magnitude and timing of sea-level movements can therefore provide clues to the complex interactions between the cryosphere, the oceans, the atmosphere, and the lithosphere that drive global climate change (Fulthrope *et al*., 2008).

Over the past 100 m.y., sea-level change reflects global climate evolution from a time characterized by ephemeral Antarctic ice sheets (100 Ma to 33 Ma), to a time when large ice sheets occurred primarily in Antarctica (33 Ma to 2.5 Ma), and finally to a world with large Antarctic and Northern Hemisphere ice sheets (2.5 Ma to present) (Miller *et al.,* 2005a) (Fig. 2.2). Over the last 2.5 m.y., the structure of the sea-level curve shows greater high-frequency fluctuations than does the insolation index. The lack of an overall correlation indicates that, in addition to summer insolation at 65°N, other parameters have influenced global climate. By the time ice sheets became long-term features of the Northern Hemisphere landscape, reaching the continental shelves and becoming unstable, the subtle interplay between Milankovitch cycles, ice-sheet dynamics, and shifts in ocean circulation had begun to drive the climate system (Lambeck, 2004). Eustatic changes on the 10^4 to 10^6 year scales are controlled primarily by the cyclic growth and decay of continental ice sheets. Over the past ~800 kyr, major rapid eustatic changes occurred at intervals of ~100 kyr with maximum amplitudes of 120–140 m (Fig. 2.3), and involved changes in ice volume of 50–60 million km^3; lesser cycles of a few tens of thousands of years and shorter duration are superimposed on these. Sea-level fluctuations during the last glacial cycle, from about 130 kyr to present, have responded to the dominant oscillations in insolation, with periodicities of ~40 kyr and ~20 kyr, but the relative amplitudes and phase relationships show no consistent match.

The evolution of high-latitude global ice volumes, as inferred from observations of far-field sea-level change, serves as a fundamental constraint on climate models for the last 3 m.y. (Lambeck *et al.,* 2002a). Although the correlation between ice and ocean volumes is incontrovertible, the causal link is commonly obscured. Local effects change the position of the sea surface relative to the land and impose additional signals that overprint the record of global sea level. Apart from tectonic movements, they include a variety of processes resulting from ice-sheet unloading and the redistribution of water masses between ice sheets and the global ocean: glacio-hydro-isostatic adjustments, the changing gravitational potential of the ice sheets, and equatorial ocean-siphoning effects. The resultant relative sea-level change is therefore a function not only of the change in ice volume but also of the planet's rheology. A number of attempts have been

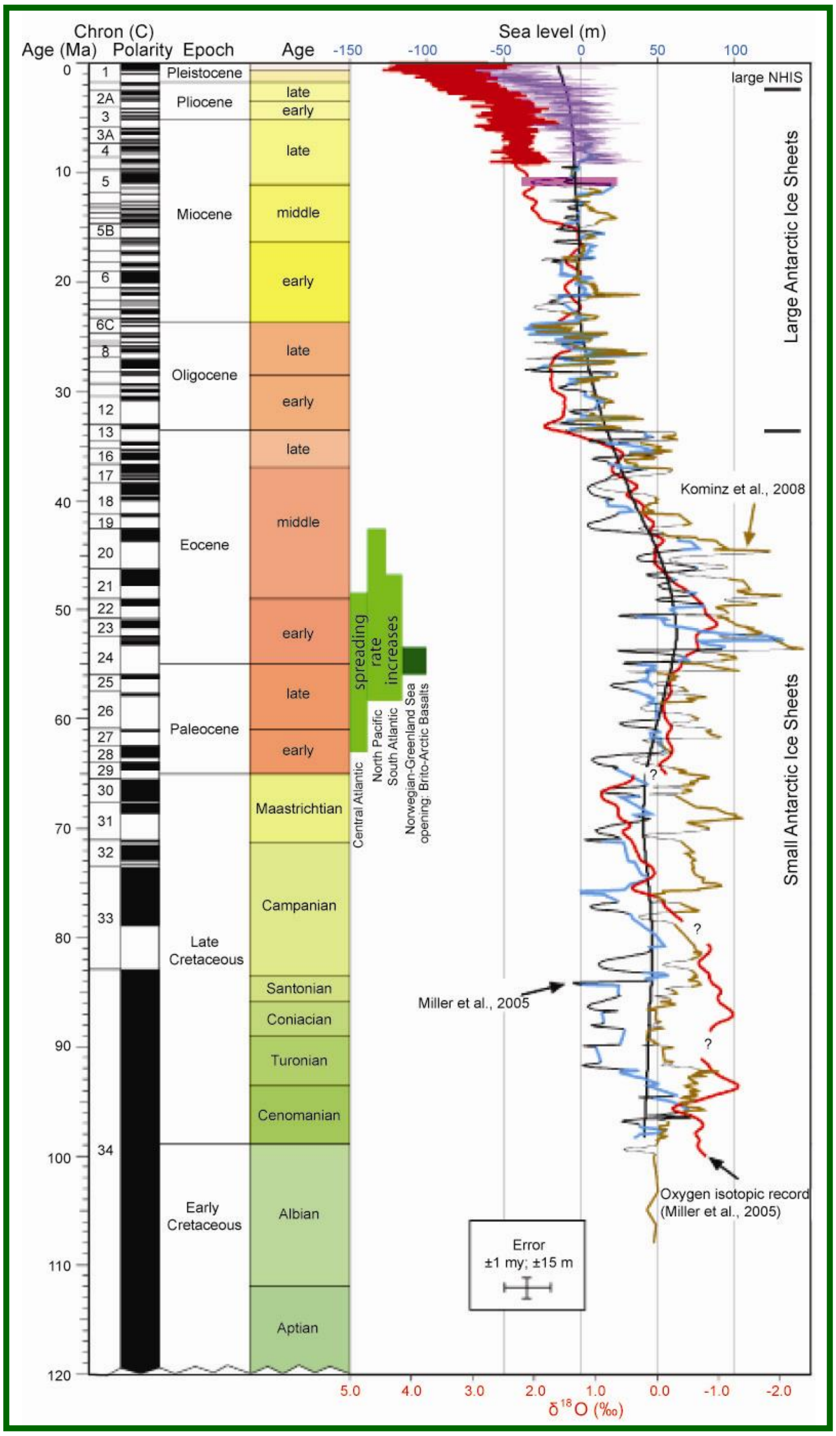

Figure 2.2 Global sea level (light blue) for the interval 7 Ma to 100 Ma derived by backstripping data. Revised backstripped sea-level curve (plotted in brown) is based on 7 new wells and new age and paleoenvironmental data for the 5 holes used to derive the light blue curve(Kominz *et al.*, 2008). Global sea level (purple) for the interval 0 Ma to 7 Ma derived from a benthic foraminifer $\delta^{18}O$ synthesis from 0 to 100 Ma (red) (Miller *et al.*, 2005a). The Miller *et al.* (2005a) backstripped sea-level curve was smoothed with a 21-point Gaussian convolution filter (black). The pink box at ~11 Ma is a sea-level estimate derived from the Marion Plateau (John *et al.*, 2004). Light green boxes indicate times of spreading rate increases on various ocean ridges (Cande and Kent, 1992). The dark green box indicates the opening of the Norwegian-Greenland Sea and concomitant extrusion of basalts (modified from Browning *et al.*, 2008).

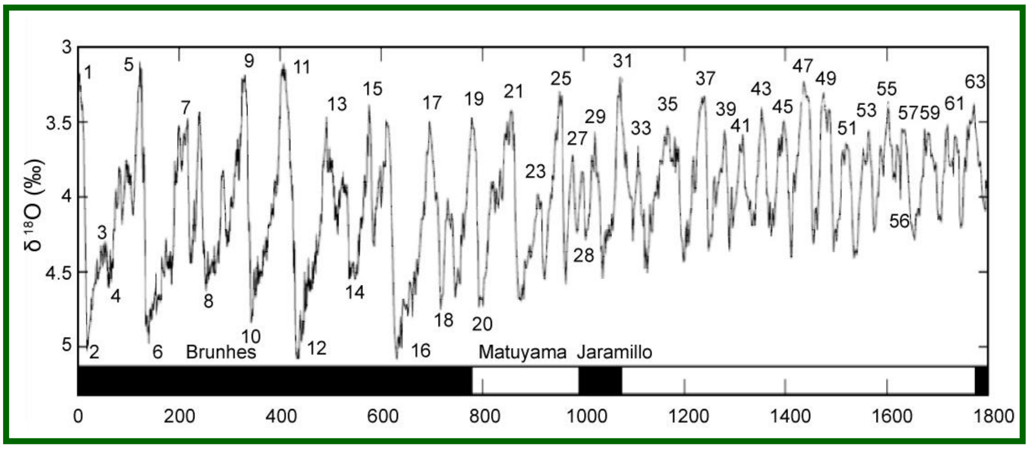

Figure 2.3 A Pleistocene stack of 57 globally distributed $\delta^{18}O$ records (from Lisiecki and Raymo, 2005).

made to model both global hydro-isostatic adjustments and equatorial ocean siphoning (*e.g.*, Lambeck *et al.,* 2002a; Milne *et al.,* 2002; Peltier, 2002) to simulate the lithospheric response to specific deglaciation histories and predict the general shape of local sea-level curves; however, aspects of these models remain controversial and significant deviations between model predictions and coral-based sea-level records have been noted in several regions (*e.g.*, Bassett *et al.,* 2005). New records are therefore needed to constrain and validate rheologic models of the mantle that predict the Earth's response to surface loads.

The discrepancies between ice-sheet models and far-field sea-level records must be tested to improve our ability to model past ice-sheet behavior and dynamics and enhance predictions of future changes. Central to this aim is the requirement to obtain accurate records of sea-level change on a regional scale, at various latitudes, in different tectonic settings, and at variable distances from former glaciated regions. Observations from sites distal to glaciated regions (*i.e.*, the 'far-field') are less affected by isostatic deformation and therefore better suited to constrain glacial eustasy. In contrast, sea-level data from sites proximal to former ice sheets (*i.e.*, the 'near field') provide information on local ice sheet dynamics.

Quantitative studies of sea-level change and ice-sheet fluctuations coupled to global climate variability have not been undertaken so far. The range and rate of temporal and spatial variability of various ice sheets (*e.g.*, ice extent, ice volume and contribution to global sea level, thermal conditions) and the sensitivity of various parts of the cryosphere to changes in Earth's climate (*e.g.*, atmospheric greenhouse gas concentrations, sea-surface and land temperatures, orbital cycles) are poorly constrained, and thus the causes of the climate fluctuations that repeatedly built up and destroyed ice sheets remain unclear. In particular, the timing and magnitude of past rapid ice-sheet collapses need to be documented and the driving mechanisms clarified. Ice-sheet responses for different climate backgrounds remain uncertain due to the difficulties of establishing reliable geophysical ice models that take into account the basal conditions of the ice sheets. The behavior of individual ice sheets needs to be investigated, including the thermal characteristics of Antarctic ice sheets during past warmer-than-present climates and the response of the Antarctic ice sheets to orbital forcing.

Past eustatic variations can be estimated from shoreline markers, reefs and atolls, oxygen isotopes ($\delta^{18}O$), and the flooding history of continental margins and cratons. Oxygen-isotope values provide a proxy for glacioeustasy but the relationship between $\delta^{18}O$ and sea-level fluctuations is more complex than sometimes assumed due to uncertainties regarding the effects of temperature, diagenesis, and evaporation-precipitation processes on calcite $\delta^{18}O$ values. Tropical coral reefs are unique recorders of sea level and environmental changes and can provide unparalleled records of the timing and magnitude of Quaternary sea-level change by dating the 'fossil sunshine' (*i.e.*, shallow dwelling corals). They are therefore of pivotal importance to resolving the rates of millennial-scale eustatic changes, clarifying the mechanisms that drive glacial-interglacial cycles, and constraining geophysical models.

Because the magnitude of Pleistocene sea-level change was in the 120-130 m range, the relevant reef and sediment archives are mostly stored on modern fore-reef slopes and can therefore be investigated only by drilling. Direct, accurate, and high-resolution observations of coral reef-based Pleistocene and Holocene sea levels exist only for the last glacial cycle (from about 130 kyr ago to present) and are limited mainly to two snapshots: the period following the Last Glacial Maximum (LGM) and the last interglacial period, approximately 125 kyr ago. Existing coral-reef records are too limited to constrain accurately the Pleistocene sea-level fluctuations and therefore new drilling is necessary. Furthermore, most of the existing records concern uplifted and presently emerged parts of reefs and reef terraces in active subduction zones where vertical tectonic movements may be large and often discontinuous, implying that apparent sea-level records may be biased by variations in the rates of uplift. Hence, there is a clear need to obtain sea-level records in tectonically stable regions or in areas where vertical movements are slow and/or regular. The reconstruction of the evolution of high-latitude global ice volumes will primarily rely on far-field sea-level change during interglacial and glacial periods. Glacial terminations, which are critical to understanding ice-sheet dynamics and to determining the timing and volume of meltwater released during deglaciation events, are discussed in section 5.2.3.

2.2.2 Interglacial periods

Interglacial intervals account for less than 10% of the Pleistocene, and thus could be regarded as anomalies within the norm of glacial cycles, which display a classic sawtooth pattern of abrupt beginnings that gradually moderate towards interglacial conditions. Some valuable sea-level records have been obtained only on the last interglacial (Marine Isotope Stage (MIS) 5), whereas the existing records of older interglacial periods consist of a few isolated points corresponding approximately to relative highstands. Detailed studies of last interglacial reefs from Papua New Guinea and Barbados have demonstrated the occurrence of sea-level oscillations typified by periods of reef growth separated by relative low stands during Substages 5b and 5d. They point to a rapid transition from interglacial to cold conditions, with global ice volumes increasing to about 30% of the additional ice at the time of the LGM and with equally rapid decreases and re-growth of the ice (Lambeck, 2004). The transition to Substage 5d, for example, suggests that ice volumes of as much as $20x10^6$ km^3 can form in less than 10,000 years. This questions the stability of the Pleistocene interglacial periods, and this needs to be investigated in detail.

Other than for the last interglacial, it has not yet been possible to define with precision the timing of the onset and termination of interglacial periods or to establish in detail the phase relationship(s) between Milankovitch forcing, sea level, and oxygen-isotope signals for the same interval. Each interglacial is unique, and as such none can be used as a perfect analogue for the continued evolution of the present interglacial or for future climate change. Thus, it remains impossible to say with certainty whether there was more or less ice globally than today during any of the past interglacials and whether the behavior of the Greenland and West Antarctic ice sheets differed from interglacial to interglacial, especially during MIS 5e (Thompson and Goldstein, 2005), 11 (Droxler *et al.,* 2003), and 31 (Scherer *et al.,* 2008). One possible strategy is to compare all late Quaternary interglacials to generate a model for end-member states (Ruddiman, 2005). Although it is natural to focus on recent interglacials because of the similarities in non-anthropogenic forcing, much can be learned from the study of older but more extreme warm intervals in Earth's history. For example, determining how sea level varied in response to past intervals of global warming and elevated CO_2 levels (*e.g.*, mid-Pliocene warmth (Draut *et al.,* 2003; Naish *et al.,* 2008; Raymo *et al.,* 2009), the MMCO, the early Eocene (Zachos *et al.,* 2001), and the Late Cretaceous (Abreu *et al.,* 1998; Miller *et al.*, 2005a, 2005b; Bornemann *et al.,* 2008)) might provide a baseline for evaluation of the eustatic and societal impacts of future climate trends. Extracting the eustatic signal on these longer timescales will involve drilling on widely separated margins to demonstrate global synchrony, and will need to represent multiple timeframes and depositional settings, including carbonate (*e.g.*, atolls and guyots), siliciclastic, and mixed systems. This signal will need to be deciphered from a variety of interacting processes, including vertical tectonism, sediment type and rate of supply, ocean currents, physiography, isostasy, and compaction.

2.2.3 Glacial periods

Lambeck (2004) estimated that during the LGM, the ice sheets contained about 55×10^6 km^3 more ice than today and that sea level was raised by approximately 120 to 130 m during the subsequent deglaciation phase. Furthermore, sedimentological evidence has provided some rough estimates of sea levels during major glacials preceding interglacials, suggesting that global ice volumes during successive glacial maxima have been of similar magnitude to that of the LGM; however, the elevation of sea-level lowstands (that reflect total ice volume) and the timing and nature of coeval climate changes are (somewhat surprisingly) poorly constrained for the LGM in particular, but also MIS 6. There is therefore a crucial need to document accurately the timing and magnitude of maximum sea-level lowstands during the major glacial periods in order to constrain the phase relationship between temperature change and ice-sheet response (Yokoyama *et al.,* 2000; Kawamura *et al.,* 2007). In addition, the record of rapid millennial to centennial sea-level oscillations during glacial periods may reveal the degree of sensitivity of sea-level changes to variations in temperature.

The cold period of MIS 3, during which sea level was 60 to 90 m lower than present, was characterized by rapid oscillations in sea level, implying that ice-volume responses to fluctuations in climate were rapid and substantial, thus questioning what controls the sea level on millennial timescales (Fig. 2.4). The timing of the highstands at intervals of 6,000–7,000 yr between 30 and 60 ka BP recorded by reef growth at Huon Peninsula coincide with variations in ice-rafted debris (IRD) deposition noted in both the North and South Atlantic Oceans (*i.e.*, Heinrich events); in turn, the ages of the Huon terraces provide absolute timing for Heinrich Events and can be used as a calibration for ice-core data. The relevant sea-level rises were seemingly caused by the collapse of up to 20% of the mass of the Laurentide ice sheet during or at the end of cold periods (Yokoyama *et al.,* 2001; Chappell, 2002; Lambeck *et al.,* 2002a) but also suggest the involvement of the Antarctic ice sheet. Similar studies must be extended to glacial periods prior to the last glacial cycle as ice-core records from Antarctica reveal persistent millennial-scale fluctuations in climate.

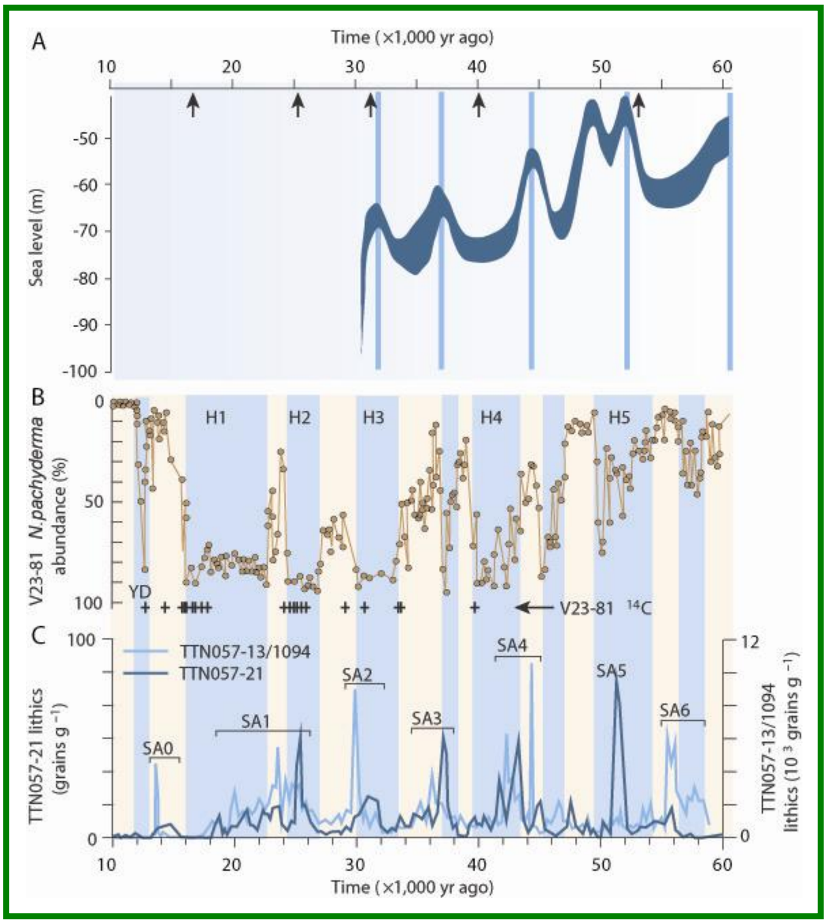

Figure 2.4 Comparison of MIS 3 sea-level oscillations and Atlantic sediment records. (A) Sea-level curve for MIS 3 coral terraces from Huon Peninsula, Papua New Guinea. Upper and lower bounds are shown. (B) *Neogloboquadrina pachyderma* (sinistral) abundances from the North Atlantic core V23-81 (Bond, *et al.,* 1993) plotted on the same calendar timescale. The original radiocarbon ages (Lund, and Mix, 1998; Bond, *et al.*, 1993) from the depths in the core marked by (+) have been converted to calendar ages. The extent of major Heinrich events identified in the North Atlantic cores, corresponding to cold periods, are within the color bands. The arrows identify the mean timing of Heinrich events (Chapman *et al.*, 2000). (C) IRD from two South Atlantic cores TTN057-21 and TN057-13/1094 (Kanfoush *et al.*, 2000). Within the uncertainties of the calendar age determinations, the South Atlantic IRD peaks correspond to the cold events in the North Atlantic (figure from Lambeck *et al.*, 2002a).

2.3 Hydrological Cycle

Understanding the processes that control changes in the hydrological cycle is one of the most pressing issues in climate-change research because changes in precipitation and evaporation impact the salinity/density distribution in the surface ocean, ecosystems on land, floods, aridification, water resources, and climate-vegetation feedbacks. Although discussed in the context of extreme events (see section 2.1.4), a comprehensive examination of the climatic controls on the hydrological cycle requires the study of long-term trends and variability over a range of climatic states. In fact, even small global temperature changes impact the energy balance in tropical regions, resulting in changes in evaporation and storm and hurricane activity. In the mid-latitudes, changes in the atmospheric thermal gradients can impact atmospheric circulation, the location of storm tracks, and the intensity of storms. For example, recent global trends in surface humidity (Willett *et al.,* 2007), precipitation rates including an intensified hydrological cycle with more rainfall in tropical and temperate regions and lower rainfall in the subtropics (Zhang *et al.,* 2007), and changes in large-scale atmospheric circulation, specifically the widening of Hadley circulation (Johanson and Fu, 2009), have been attributed to anthropogenic influences. In addition, trends in extreme events (storms and hurricanes) have also been observed (Trenberth and Fasullo, 2008) and modeled for future global warming scenarios (Emanuel *et al.,* 2008).

> *"**Testing models** with paleoclimatic data is important, as not all aspects of climate models can be tested against instrumental climate data."*
>
> IPCC (2007; Ch. 6)

The current generation of climate models needs to be improved to more accurately predict changes in the hydrological cycle. For example, both the prediction of changes in horizontal temperature gradients (Gastineau *et al.,* 2009; Karnauskas *et al.,* 2009) and the treatment of tropical atmospheric convection (O'Gorman and Schneider, 2009) have a large impact on the ability of models to accurately predict changes in the hydrological cycle and regional precipitation patterns, and need improvement. As such, records of past climate and oceanic changes provide the necessary data to validate climate-change models and to provide the needed context of natural variability, particularly for changes that occur on decadal or longer timescales. For example, in a study of megadrought in North America, Cook *et al.* (2010) make a strong argument for the use of paleoclimate data to understand the global context of North American megadroughts in order to better predict future changes. This is true at all timescales. In fact, paleoceanographic and paleoclimatic studies using older drilled ocean sediments, from times when Earth's climate was different than today, provide the only opportunity we have to study the processes that control precipitation across a large dynamic range of conditions.

There was not an INVEST working group that focused explicitly on the hydrological cycle; however, because of the strong impact of precipitation on the environment and its habitability (*e.g.*, water resources, floods, *etc*.), and thus the urgent need to develop a deeper understanding of the factors that control regional precipitation, many of the climate-related INVEST working groups emphasized the need to study the hydrological cycle. Specifically, discussion in many working groups emphasized the need to understand controls on the Intertropical Convergence Zone (ITCZ), to study climate oscillation modes and their behavior during different mean climate states, to focus on wind-driven upper ocean circulation and its coupling to atmospheric forcing, to understand the relationship between precipitation patterns, density stratification, and biogeochemical processes, to examine past changes in monsoons, among other topics. Pressing questions that can only be answered by studying geological archives of past climate change are focused on three large-scale climatic features that influence continental patterns of precipitation.

2.3.1 The Intertropical Convergence Zone

What controls the position of the ITCZ? The ITCZ, the tropical zone of deep atmospheric convection and rainfall, is highly variable in character and seasonal behavior in each ocean basin. While the seasonal migration of the ITCZ is dictated to a large extent by seasonal change in the temperature gradient between low and high latitudes, its location, variability, and intensity is also strongly controlled by other processes whose importance varies depending on ocean dynamics and land-sea distribution. In the Indian Ocean, land-sea interactions have a dominant control on monsoons, which strongly influence the seasonal position of the ITCZ. In the Atlantic Ocean, the position of the ITCZ is influenced by both oceanic processes and land-sea temperature contrasts, whereas in the Pacific Ocean, the position of the ITCZ is dominantly controlled by global and regional tropical sea-surface temperature spatial patterns. Contrasting the behavior of the ITCZ in different ocean basins during periods with different global boundary conditions can shed light on the importance of global versus regional processes on the tropical hydrological cycle. In addition, the detailed examination of how the position of the ITCZ in one region varies through time as solar heating, greenhouse gas forcing, and global climate changed in the past can provide time series of hydrological changes needed in order to apply statistical tools to deconvolve multiple mechanistic sources of variability.

Studies of the response of the ITCZ to climate conditions during periods of warmth relative to today are particularly critical for making predictions of changes in precipitation patterns when the hydrological cycle is enhanced during globally warm periods. The strategies for studies of the ITCZ involve drilling north-south transects of sites to trace north-south shifts in the ITCZ; however, to gain insight into the mechanisms of changes in the ITCZ, drilling must also focus on key locations (which may be remote) where changes in temperature could have a profound influence on the position and intensity of the ITCZ. To devise such a drilling strategy would involve a detailed planning group with deep knowledge of tropical climate models and theory who could help define locations and predict the amplitude of change that would be diagnostic of each mechanism of change. The strategic planning would also involve geologists and geophysicists with expertise in tropical sediment distributions, possible drilling targets, and the newest methods and techniques for determining past changes in tropical precipitation and temperature patterns of the sea surface and on land.

2.3.2 Monsoons

What controls the strength the monsoons, and therefore seasonal rainfall in low-latitude continental regions? Monsoon strength is strongly dependent on subtle differences in ocean and continental temperatures and/or the land-sea temperature contrasts. As there is a plethora of climatic and oceanic processes that can cause changes in land and sea temperatures, an examination of the major controlling factors of monsoon strength requires a comprehensive approach that would start with reconstructions of rainfall strength and sea-surface temperatures, but would also need to include strategies for using changes in spatial patterns of multiple oceanic variables to identify underlying ocean dynamical causes. In addition, there are clearly orographic influences on the monsoon, such that the evolution of continental mountains must play a role in the large-scale development and establishment of the modern-day monsoon system.

As with studies of tropical rainfall changes associated with variations in the ITCZ, investigating the causes of changes in the monsoon requires an examination of past time periods with climate forcings different than today. To make major advances, sediment records from continental margins where sediments of continental origin contain needed information regarding changes in precipitation, run-off, and continental climate need to be collected. Strategies for studying the evolution of Asian, Indian, and African monsoons should be designed by multi-disciplinary detailed planning groups with knowledge of monsoon climate dynamics, continental mountain tectonics, river basin and geomorphological evolution, continental margin, slope, and river delta sedimentological processes, and technological and analytical advances in reconstructing continental climate, sea-surface salinity and precipitation-evaporation balances.

2.3.3 Mid-latitude storm tracks

What controls the strength and position of mid-latitude storm tracks? Climate models predict that with warmer climate due to greenhouse gas forcing, extratropical rainfall including extreme events should increase and storm tracks should move poleward as the Hadley Cell expands. In addition, this enhancement in the hydrological cycle includes intensification and poleward expansion of subtropical arid desert zones. Changes in large-scale extratropical precipitation–evaporation patterns are linked to warmer sea-surface temperatures and concomitant increases in water-vapor content of the atmosphere, but they are also strongly controlled by changes in the low–high latitude temperature gradient. As such, the regional processes that determine the sensitivity of temperature changes to radiative forcing play a big role in controlling the intensity and position of mid-latitude storm tracks.

Past changes in the spatial extent of climate zones can be detected using geologic proxies; thus, the geological perspective that is provided by ocean drilling is one of the most powerful ways to test model predictions of the mechanisms that control Hadley Cell dimensions and associated precipitation patterns. Regional geological studies can be further applied to studying the interdependence between regional climate and large-scale global precipitation patterns. As with geological studies of the tropical hydrological cycle (ITCZ and monsoon), studies of extra-tropical climate change need to be approached with a drilling strategy that integrates climate system model predictions with knowledge of the best localities on continental margins to find continuous sections with well-preserved fossils of continental and oceanic origin. The biggest challenge will be to find locations and analytical strategies to extract information about seasonal or extreme precipitation events; however, even information on how climate zone boundaries evolve over longer timescales will provide valuable insight into the behavior of, and fidelity of models of, the hydrological cycle.

2.4 Science Strategies

2.4.1 Transect concept

New ocean drilling is required because it is the only way to obtain past records of large amplitude extreme and rapid climatic events that are required to fully understand and model the climate system on long-term and societally relevant timescales. All of the specific problems listed above require spatial data coverage to allow for a comprehensive approach whereby data and models supplement each other and advance both model/theory development and future data collection strategies. In addition, high temporal resolution is needed to investigate climate behavior on shorter timescales relevant to societal needs over the next few hundred years, both from recent climatic shifts, as well as climate extremes in the Cenozoic and Cretaceous. Most importantly, coordinated latitudinal and depth transects could be designed to meet multiple scientific objectives. To answer most high priority climate change questions defined at the INVEST meeting requires an array of drill sites to capture basin-wide or global-scale changes in water-mass distributions, to monitor shifts in climate and oceanographic fronts, and to integrate land-to-sea environmental changes across continental margins. A comprehensive strategy to obtain transects of sites that could be drilled as either focused expeditions or as sets of single sites drilled during ship transits is needed. More than ever, because of the emphasis on deciphering continental climate change and continental ice-sheet fluctuations, there is a need for targeting riverine and glaciomarine sediments found at continental margins.

Examples of specific transects identified as important to examine:

⇒ Southern Ocean – southwest Atlantic ocean-atmosphere dynamics (carbon cycle, ocean-atmosphere gas exchange, nutrient distribution, multidecadal variability).

⇒ ITCZ, Hadley and Walker cell dynamics, ENSO, western Pacific Warm Pool (meridional/zonal transects in the equatorial Pacific, Atlantic, and Indian Oceans; sediments + corals).

⇒ Hydrological cycle in semi-arid regions (deltaic sequences and continental-margin sequences; *e.g.*, off East Africa).

⇒ Monsoon variability (deltaic sequences and continental-margin sequences; platform carbonates), achievable through Mission Monsoon.

⇒ Sea level studies (offshore, shallow-to-deep, and onshore drilling transects involving global retrieval of cores representing multiple timeframes and various tectonic (*e.g.*, active *vs.* passive margins) and depositional settings, including siliciclastic, carbonate and mixed systems on both icehouse and greenhouse targets). There is a clear need to obtain a global coverage of sea-level records in different settings worldwide on widely separated margins to deconvolute tectonic and isostatic processes, and to demonstrate global synchroneity. The proven strategy of drilling transects of proximal to distal sites must be expanded by incorporating shore-parallel transects. This will provide new understanding about how sediment depocenters shift during transgression, which is of direct relevance to the stability of barrier islands and preservation of the coastline during the coming century.

The IODP consultation in preparation for INVEST (CHART report, 2009) identified the urgent need to conduct the strategic collection of high-resolution data in a geographically distributed fashion, following the Geochemical Ocean Sections Study (GEOSECS) approach (‘PALEOSECS’), to provide a spatially distributed baseline for past climatic changes.

2.4.2 Land-sea linkages

To understand the Earth system and its evolution, information on not only the oceanic but also on the terrestrial component of paleoclimatic reconstruction is necessary, and the results should be integrated and synthesized to achieve a comprehensive view of Earth system dynamics. Although reconstruction of terrestrial paleoclimatic changes using marine cores has been conducted in previous phases of scientific ocean drilling, neither specific emphasis was put nor were systematic attempts made to promote research on land-sea linkages. In the new phase of IODP, the land-sea linkage gathers increasing attention of the community, and continental margins are becoming the most important and promising target area for scientific ocean drilling. Thus, strategy for integration of land-sea drilling should be made.

From a scientific view point, cooperation with terrestrial paleoclimate and tectonic communities is necessary and coordination and integration with terrestrial drilling programs such as ICDP are essential to maximize ocean drilling results and create breakthroughs. In both IODP and the Ocean Drilling Program (ODP), such efforts were made. Among them, one of the most successful examples was a series of Antarctic drilling campaigns initially motivated by coordination with the Antarctic Stratigraphy (ANTSTRAT) group. In this example, the ANTSTRAT group made a presentation of their idea of a long-term drilling campaign in the marginal areas surrounding the Antarctic continent. Afterwards, a detailed planning group was formed and a series of drilling proposals (4 or 5 in total) were submitted. In this case, the terrestrial part of the research was conducted in parallel as an individual subcomponent of ANTSTRAT. There are also several other drilling proposals that try to coordinate IODP with ICDP, such as Chicxulub drilling and East China Sea drilling; however, such efforts were made by an individual proponent or a small proponents group and very little support and/or service was provided by IODP other than organizing a workshop or DPG.

To effectively promote research on land-sea interaction and linkage, we need to establish a new system that supports coordination and integration between IODP and ICDP (or other terrestrial drilling projects). A new system should allow for the proposal of drilling both on land and under the sea within one proposal, or at least under one umbrella proposal. With the ICDP, proponents have to also help raise substantial funding for continental drilling. Such a requirement makes it difficult to promote land-sea integration of drilling, so a new system is desired that would provide support to proponents to more easily obtain funds for the continental drilling component of the overarching project.

Drilling continental margins may also require riser drilling and consequently good coverage of seismic data (preferably 3-D seismic) is desirable. Thus, close coordination and cooperation with industries (especially the oil industry) and local governments should be promoted from a logistical point of view.

Furthermore, Antarctic ice-core records now extend back to 0.8 Ma and will very soon reach to 1 Ma or even older. Antarctic ice cores also have their own orbitally-tuned chronology, and correlation of their CH_4 record with millennial-scale Asian summer monsoon variability preserved in Chinese stalagmites seems promising. Thus, high-resolution correlation between land and sea and examination of phase relationships between marine proxy records and the records of atmospheric CO_2, CH_4, and other gas concentrations will become possible very soon. It will be fruitful and important to promote communication and collaboration between paleoceanographic, ice core, and stalagmite communities.

2.4.3 Model – observation integration

Paleoclimate data obtained by ocean drilling are indispensable for reducing the uncertainty of current climate models used to predict climate over the next few centuries (IPCC Report: Solomon *et al.*, 2007), and are thus of extreme societal relevance. The significance and importance of ocean drilling to improve models of past and future climate lies in the generation of datasets from different past boundary conditions that can challenge and improve existing climate models (see sections 2.1, 5.2.1 and 5.2.3), which can then use the data to better understand how Earth system components react to large amplitude perturbations. In addition, paleoclimate data provide estimates of underlying climate variability on multiple timescales ranging from annual through millions of years.

The INVEST meeting highlighted a number of specific recommendations for the future integration of modeling and observational components, including the necessity for integrated latitudinal and land-ocean transects, targeted time slices for data-model comparison, and the recovery of exceptionally preserved carbonate material for climate proxy application, for example from a Tanzania land-ocean transect (Pearson *et al.*, 2009).

Climate models currently used to predict future conditions can be evaluated and tested by their ability to reconstruct past climatic conditions. One simple approach involves forward modeling of climate under relevant changes in estimated boundary conditions and comparison of the output with paleoclimatic observations, such as proxy records of past temperatures and pCO_2. INVEST discussions highlighted the difficulty of using paleoclimate data to provide quantification of past ocean circulation, windfield, and changes in the hydrological cycle, in contrast to more established temperature and sea-level reconstructions. When significant mismatches occur, this might indicate structural error in the model (missing or incorrect processes), poor parameterization in the model, errors in the data (or their interpretation), or a mis-specification of the appropriate experiment. When applied to a specific aspect of the climate system this approach can be used to assess the relative robustness of future predictions from different models. For instance, an ice-sheet model that fails to reasonably predict past Greenland ice volumes is not likely to predict future conditions on Greenland. A more statistical approach to quantify the uncertainty in future climate change predictions is to assess those predictions in the form of probability distribution functions. This technique involves the production of an ensemble of possible model predictions of the future, often by varying uncertain parameters in the model that control the strength of physical, biological, and chemical feedbacks.

Multiple overarching themes were identified where observation-modeling integration is likely to play a major role over the next decade: (1) using ocean drilling and other paleoclimate data to reduce uncertainties for IPCC climate models and predictions; (2) using ocean drilling data to improve modeling of ocean-atmosphere circulation dynamics; (3) using ocean drilling data to provide test scenarios for Earth system models under extreme boundary conditions; and (4) using ocean drilling data to improve the understanding of the global carbon cycle.

There are a number of key uncertainties in the current modeling of climate that need urgent integration with paleoclimate data to reduce the uncertainty boundaries of future predictions (Solomon *et al.*, 2007; Henderson *et al.*, 2009; Huntingford *et al.*, 2009). Henderson *et al.* (2009) summarized the key IPCC uncertainties where paleoclimate data are able to reduce model errors and where paleoclimate data have contributed:

⇒ Paleoclimate archives show coherent regional changes in precipitation in different climate boundary conditions, including many regions where models disagree widely about precipitation change.

⇒ Dated marine terraces provide clear evidence that sea level was 4-6 m higher than today at the last interglacial under conditions slightly warmer than today, and recent data have suggested the rate at which sea level can rise to this height from modern levels (Rohling *et al.*, 2008).

⇒ Diverse paleoclimate records have demonstrated the existence of large and rapid switches in Atlantic overturning, and the climate response to these switches on hemispheric and even global climate.

⇒ Corals and other paleoclimate records have demonstrated the sensitivity of ENSO to modest changes in boundary conditions during orbital change (Pleistocene) and warming (Pliocene).

⇒ Arctic temperatures have been quantified for many times in the past, demonstrating extreme polar warmth during the Cretaceous, Eocene, *etc*. and the conditions during the last interglacial that led to significant melting of Greenland.

⇒ Past records of variations and perturbations of the global carbon cycle provide estimates of climate sensitivity that are quite different to those estimated by the IPCC.

Other emerging and important themes in climate model-data integration that need further verification include: an ice-free Arctic Ocean and interactions with adjacent continents, changes in meridional and zonal gradients in tropical sea-surface temperatures (SST), the unexpected amplitude of interdecadal-to-centennial scale climate variability in 'warm' climates, and the sensitivity of the tropical rainbelt to high-latitude forcing. All of these topics require testing of the robustness of climate projections and the underlying assumptions. This will complement ongoing work of new proxy development, particularly for the climate and hydrological cycle, and the inclusion of 'proxies' in inverse modeling approaches. Currently, the spatial and temporal coverage of paleo datasets is often too sparse to fully constrain probabilistic inverse modeling approaches.

The following specific approaches were suggested during INVEST:

⇒ Snapshot equilibrium simulation (atmosphere/ocean/biosphere general circulation model) is very accurate for 6 ka (mid-Holocene), 21 ka (LGM), 115 ka (last interglacial), and 3 Ma (Pliocene). Comparison between these model results and well-dated climatic records from the continent, ocean, and ice will provide critical insights into climate dynamics. Sites proposed during an ultrahigh-resolution ocean drilling workshop would contribute towards these aims (Thurow *et al.*, 2009).

⇒ A transient experiment of several tens of kyr with a simpler model (Earth system Model of Intermediate Complexity coupled with ice model) can be used to investigate climate variability (such as D-O/Heinrich events compared with marine temperature reconstruction). The proposed 'Shackleton sites' off the Portuguese margin would contribute significant datasets to this enterprise (Hodell and Abrantes, 2009).

⇒ A global mapping approach with the analysis of widely distributed records and their integration into an Earth system modeling study to identify teleconnections around the globe. This will foster interactions and collaborations with other research communities (ICDP, International Marine Past Global Change Study (IMAGES), *etc*.).

⇒ Past ocean acidification and carbon cycle extrema provide the possibility to reduce uncertainty within the climate sensitivity parameter (see section 5.2.2). Recent work (Panchuk *et al.*, 2008; Zeebe *et al.*, 2009) has shown the opportunities and challenges provided by direct model-data comparison, including the lack of any pre-PETM constraints of the carbonate compensation depth (CCD) in the Pacific (Fig. 2.5).

⇒ Past extreme glaciation and de-glaciation events offer the opportunity to link coupled climate models with observations (deConto *et al.*, 2008; deSantis *et al.*, 2009; Merico *et al.*, 2008), and require additional targeted drilling data from around high-latitude regions.

The Arctic polar regions (Stein *et al.*, 2009) and the Antarctic Peninsula (deSantis *et al.*, 2009) have been among the fastest warming regions of the globe in recent decades, and the IPCC projects the high northern latitudes to show the most warming in the next century. As a result, sea ice is projected to shrink in both polar regions, and an ice-free Arctic in late summer is projected by many models by the end of the 21st Century or even sooner. Warmer polar regions may also impact the extent of permafrost and marine hydrates in these areas. This has implications not only for climate feedbacks and ecosystems, but also in the economic and geopolitical sphere. Recent studies (Bijl *et al.*, 2009) have shown that past climates might have experienced latitudinal temperature gradients very different from those of today during episodes of warm climates. These data need to be collected to test whether climate models are able to re-create these climatic states.

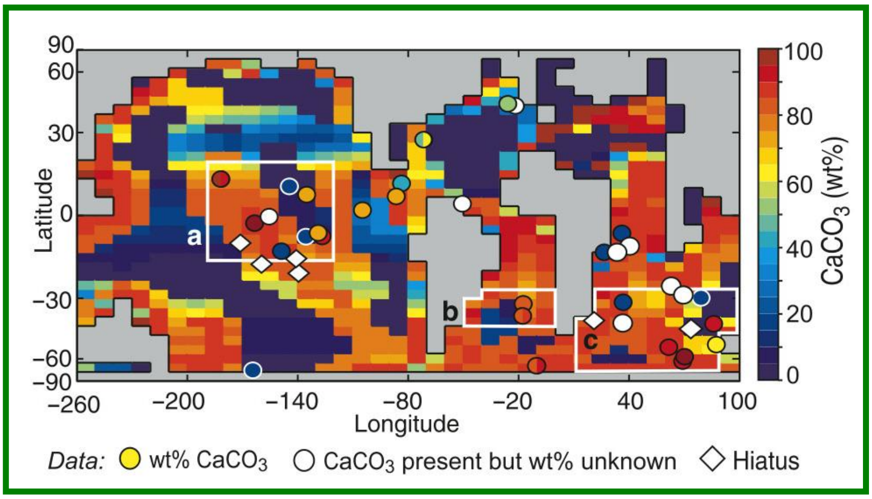

Figure 2.5 Forward modeling of carbon cycle perturbations by comparison of paleo datasets that represent past evolution of the CCD *vs.* modeled carbonate sediment concentration from Earth system models of intermediate complexity from Panchuk *et al.* (2008). White circles indicate unknown $CaCO_3$ wt%, whereas filled circles represent known $CaCO_3$ wt% values according to the scale at right.

2.4.4 Ultrahigh-resolution records

One of the great successes of ocean drilling has been the continuous increase in the available temporal resolution of sediment core generated climatic proxy data throughout the life times of the Deep Sea Drilling Project (DSDP), ODP, and IODP. Scientific drilling on land and at sea has played a key role in advancing our knowledge of climate change, for example by helping to demonstrate the effects of orbital variations on climate, by revealing evidence for extreme warm events in the past, by establishing the timing of Antarctic ice growth, and by providing insights into the hydrologic balance of lake systems around the world (Thurow *et al.,* 2009). A recent workshop identified key sediment sections that are available for generating societally relevant high-resolution records with a wide geographical distribution (Thurow *et al.,* 2009; Fig. 2.6); however, despite some long records in the oceans (*e.g.*, Santa Barbara Basin: Behl and Kennett, 1996; Hendy and Kennett, 2000; Cariaco Basin : Peterson *et al.,* 2000; Hughen *et al.,* 2004) and on land (Scholz *et al.,* 2007; Hodell *et al.,* 2008), high-resolution records generated by scientific coring and drilling is currently limited in both number and global coverage (Voelker, 2002; Clement and Peterson, 2008). Several studies have now shown the possibility to decipher short timescale climate variability by comparing sediment-derived records with ice-core records (Tzedakis *et al.*, 2009). In addition, the synchronization of high-resolution records has recently undergone significant advancements through the application of ultrahigh-resolution correlations of relative magnetic paleo-intensities determined from sediment cores (IODP Expeditions 303/306: Channell *et al.,* 2004). This method provides a significant new opportunity to fully exploit high- and ultrahigh-resolution records and provides the backbone for new drilling proposals of high societal relevance (*e.g.*, drilling near the West Antarctic ice sheet).

With the aim to better predict the likely manifestation of future climate change, it is critical to better understand the causes and consequences of rapid environmental/climate change at various timescales (annual, interannual, multi-decadal, centennial, millennial, Mitchell, 1976), including societally relevant ultrahigh-resolution,

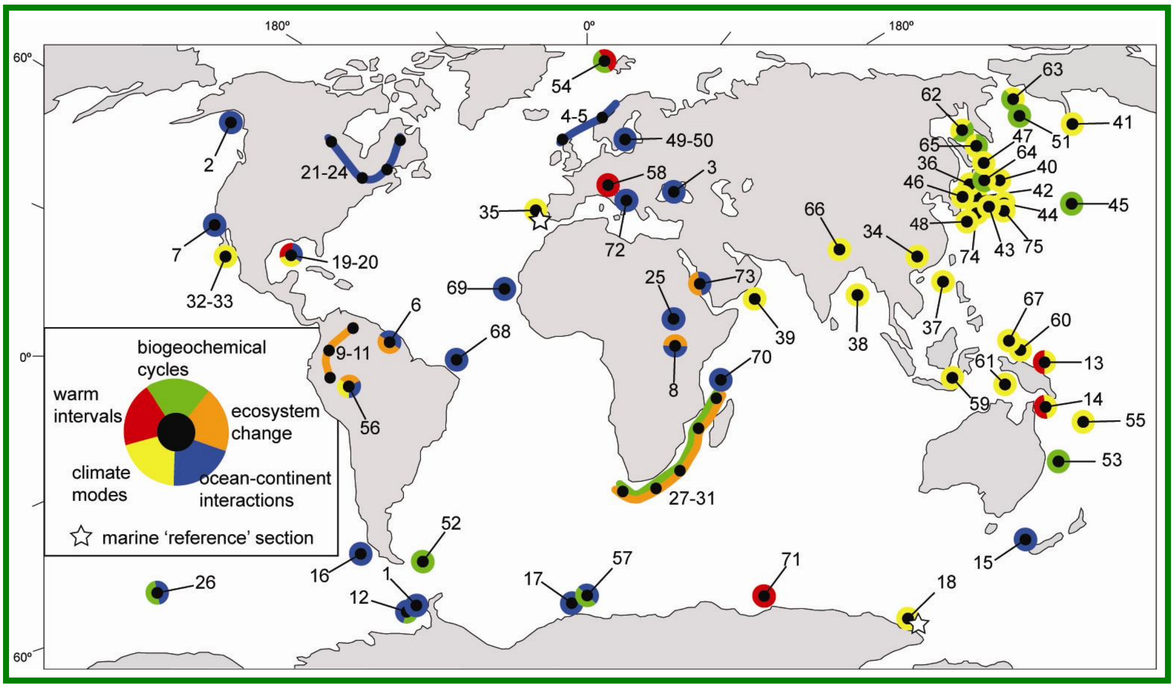

Figure 2.6 Compilation of potential drilling sites proposed by workshop participants to address the scientific themes 'Warm intervals through time', 'Ocean-continent interactions', 'Biogeochemical cycles', 'Ecosystem change', and 'Climate Modes'; from Thurow *et al.,* (2009). Site numbers are linked to information that can be found in Appendix 1 at http://high-resolution.icdp-online.org.

approaching those of instrumental records. Well-dated, well-calibrated sedimentary records (*e.g.*, sediments including varved marine and lacustrine muds, corals, ice cores, speleothems), with sub-annual to centennial resolution spanning different time intervals, provide an unparalleled opportunity to explore past natural climate variability by revealing the details and complexities of the climate system (*e.g.*, better definition of the climate norm and anomalies), and constraining rates and magnitudes of change.

Central to these aims is the acquisition of ultrahigh-resolution and multi-proxy records following a number of specific approaches:

⇒ A time slice approach whereby expanded sections and very high accumulation rate sites, including non-traditional sedimentary deposits (*e.g.*, drift deposits, fjord and semi-enclosed basin deposits, shelf deposits proximal to river systems, rapidly subsiding coral reefs) from key stratigraphic intervals are targeted. The IMAGES program and subsequent work identified regions in the Indo-Pacific Warm Pool with very high accumulation rates, some in excess of 100 cm kyr^{-1}, whereas additional natural synergies exist with lake records generated through ICDP (Thurow *et al.,* 2009).

⇒ Use ocean drilling to extend those records that have been demonstrated to be correlateable to high-resolution ice-core records throughout the Quaternary and beyond (Hodell and Abrantes, 2009). Few marine sediment cores have played such a pivotal role in paleoclimate research as those recovered from the Portuguese margin (referred to as the 'Shackleton sites' by Hodell and Abrantes, 2009). These cores preserve a high-fidelity record of millennial–scale climate variability for the last several glacial cycles and can be readily correlated to Greenland ice cores. Alley

(2003) suggested that paleoceanographers should consider following the ice core community's lead and organize a research effort to "*generate a few internationally coordinated, multiply replicated, multiparameter, high time resolution-type sections of oceanic change.*" These types of records were identified by IPCC community members as a crucial component of data-model integration. There is wide interest and support within the paleoceanographic community in seeing the Shackleton sites drilled. At a recent IODP-ICDP workshop (Thurow *et al.,* 2009), the Shackleton sites were identified as a key target for future IODP drilling to obtain marine sediment analogues to the polar ice cores, and this effort resulted in a European Science Foundation funded workshop on drilling the Iberian Margin held in November 2009 in Lisbon, Portugal.

⇒ The IODP consultation in preparation for INVEST (CHART report, 2009) identified the urgent need to conduct the strategic collection of high-resolution data in a geographically distributed fashion, following the GEOSECS approach ('PALEOSECS').

⇒ For several 'extreme' and large amplitude events throughout the Cenozoic, ultrahigh-resolution records are required to fully decipher the complex interplay of climate system components (see sections 5.2.1, 5.2.2, 6.1, 6.2 and 6.3). Of specific interest is the paleo-latitudinal gradient of SST (Bijl *et al.,* 2009; Fig. 2.7)

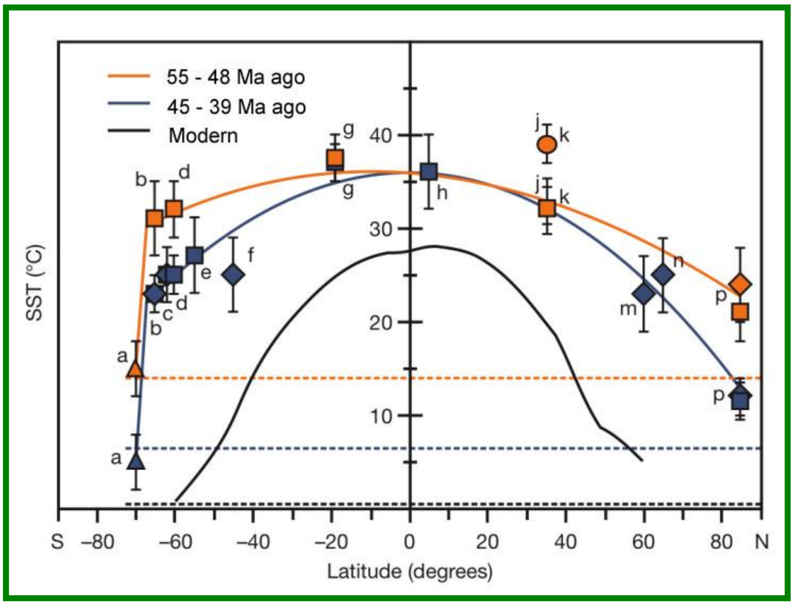

Figure 2.7 Early and Middle Eocene latitudinal SST gradients compared to modern values. SST gradients during the Eocene are much lower for latitudes south of 60°S and N than today, and challenge existing climate models (Huber, 2008), from Bijl *et al.* (2009).

High-resolution and ultrahigh-resolution records can address aspects regarding the causes and consequences of past climate variability, including the nature and origin of abrupt climate change at various timescales, thus providing the opportunity for immediate engagement with the modeling community. The causes of climate variability in the multi-decadal band is currently a key topic in climate prediction and accessible to the high resolution drilling/coring community. Those records are of prime importance to investigate past variability and potential teleconnections of the most important elements of the modern climate system, such as the ENSO, monsoons, the North Atlantic Oscillation, the Pacific Decadal Oscillation, the Arctic Oscillation, and the Southern

Annular Mode under different boundary conditions. High- to ultrahigh-resolution records can also address specific questions such as the timing and magnitude of ice-sheet change, impact of meltwater pulses in the oceans, changes in vertical mixing rates, and the variability of the bipolar seesaw during glacial and interglacial intervals.

High- to ultrahigh-resolution records of sedimentary archives deposited during previous warm intervals (*e.g.*, Early Holocene, Eemian, mid-Pliocene, MMCO, Eocene) over the widest possible geographical range may potentially document the Earth's hydrologic, atmospheric, and oceanic responses to past extreme warm events, including the potential occurrence of a seasonal sea-ice cycle, ocean productivity, and ENSO and monsoon variability.

2.4.5 Site characterization

Site survey cruises were raised as a critical tool for indentifying ultrahigh-resolution deposits that straddle critical climatic boundaries or fall within times of rapid climate change. Prospecting for these deposits requires an integration between the marine geophysical and paleoceanographic communities in order to identify the best opportunities for integration between seismic mapping with the ability to image the 3-D geometry of these deposits and ocean drilling to sample the identified optimal locations. Only through this integration can the best samples be gathered and analyzed using the range of existing and new proxies for studying paleoclimate.

3 The Lithospheric Membrane – The Key Interface and Processing Zone

Our tectonically active planet evolves by chemical and physical changes from the core and mantle, through the lithosphere, to the ocean and atmosphere. Flow of material and energy among these reservoirs drives both gradual changes in the Earth's structure and composition, as well as extremely rapid volcanism and other events that impact Earth's environment. Quantifying the fluxes between the major Earth reservoirs is crucial for understanding the state and evolution of our planet. The lithosphere is the major interface between the solid interior of the Earth and the exterior hydrosphere/atmosphere/biosphere. Ocean drilling provides a key tool for probing this processing zone of mass and energy flow. From direct sampling we can understand the fundamental, steady-state processes of ocean crust accretion, plate aging and recycling, and intermittent events such as eruptions of LIPs and rifting of continents.

Ocean drilling has played, and needs to continue to play, a central role in answering fundamental questions about solid Earth composition, structure, and processes. Examples include such basic discoveries as the confirmation of plate tectonics, the recognition that long-lived mantle plumes may not be stationary, that portions of subducted slabs are recycled through the deep mantle and return to the surface after billions of years, and that the long-term behavior of the magnetic field is linked to the thermal regime of the deep mantle.

> *"**The ocean lithosphere** is the principal process zone for interplay between the deep Earth and our planet's surface envelopes, and hosts key environments for fundamental magmatic, thermal, hydrologic, and biological exchanges in the Earth system".*
>
> Melting, Magma, Fluids, Life Workshop Report (2009)

Many questions still need to be answered for us to better understand the Earth system. To address these we need to quantify fluxes and interplay within the mantle-crust-ocean system (physical, chemical, and biological) and monitor fault-driven processes. We also need to obtain a better understanding of the components of a subduction zone system that control seismic behavior, which in turn affects the level of hazard posed by the plate boundary. Ocean drilling will continue to significantly contribute to our understanding of these processes.

Topics discussed at INVEST considered processes in all three solid Earth layers. Furthermore, it was noted by several working groups that the ocean lithosphere provides resources in the form of hydrocarbons, metals, biodiversity, and pore space for CO_2 storage. The principal results of these working group discussions are summarized in this section, with focus on: (1) core-mantle-crust interactions, (2) crust-ocean-atmosphere interactions, (3) ocean-floor resources, (4) basement biosphere and hydrology, and (5) plate boundary initiation, subduction zones, and volcanic arcs.

Prior to INVEST, three international workshops – "Scientific Drilling of Large Igneous Provinces" (Coleraine, Northern Ireland, 23-25 July 2007), "Melting, Magma, Fluids and Life – Challenges for the Next Generation of Scientific Ocean Drilling into the Oceanic Lithosphere" (Southampton, UK, 27-29 July 2009), and "Scientific Ocean Drilling of Mid-Ocean Ridge and Ridge-Flank Settings" (Austin, USA, 27-28 August 2009) – were held to discuss the role of ocean drilling in examining oceanic lithosphere processes within the Earth system. The reports of these workshops provide details that go much beyond what is summarized here.

The intense interest in lithosphere research through ocean drilling is reflected in the number (~50%) of white papers submitted for INVEST. As defined in the INVEST working groups and white papers, several overarching questions, cross-disciplinary frontiers in lithosphere research, and new directions for a future drilling program common to all subthemes are:

Ocean-Lithosphere

Understanding the hydrothermal transfers of heat and mass between the lithosphere and hydrosphere/atmosphere on a global scale has been identified as high-priority overarching research question. Answering it requires making full use of synergies in the investigation of the coupling between hydrogeological, geochemical, thermal, mechanical, and biological processes and their relation to the architecture and physical nature of lithosphere below the ocean. Of primary importance is addressing the nature of the Mohorovičić discontinuity (Moho), a first-order geophysical interface within our planet whose origin is uncertain in slow-spreading mid-ocean ridge environments. It could be an igneous boundary or a serpentinization front – a difference with profound consequences for the chemical and rheological properties of the lithosphere.

The temporal and spatial scales of seawater circulation and coupled transport processes need to be explored to establish the nature, distribution, and significance of fluid exchange with the seafloor (sediments, volcanic crust, and upper mantle). Seawater circulation facilitates microbial growth within the ocean floor and is critical to the transport and distribution of microorganisms. Yet, the size, activity, and connectivity of the intracrustal oceanic biosphere are unknown, as is their influence on global geochemical and biogeochemical cycles.

The recent recognition of the extent of heterogeneity within slow-spreading lithosphere raises several new questions and provides exciting opportunities. As much as one-quarter of the seafloor exposed at slow-spreading mid-ocean ridges is a heterogeneous assemblage of peridotite and gabbroic lithologies. In hydrothermal processes, this heterogeneous crust is more reactive and the changes in physical properties are much more drastic than in layered crust. We do not know how this difference affects tectonic, geochemical, and geomicrobiological processes and what the consequences are for global lithosphere-ocean exchange fluxes.

Geodynamics

Ocean basins themselves are not permanent features. They open and close over intervals of 100s of millions of years, which may be related to timescales of heating of the core-mantle thermal boundary layer (D") and episodic triggering of 'superplume' events with mantle overturn. The most recent of these began with the breakup of Pangaea, which resulted in the opening of the Atlantic, the closing of the Tethys, and the shrinking of the Pacific basins. Research questions that need to be addressed include: How do continents rift to form a new ocean? How does subduction begin within an existing ocean basin? Are the locations of new plate boundaries largely controlled by pre-existing geologic features or by external forces (*e.g.*, extreme volcanic events)? How do fault systems form and evolve during plate boundary initiation? What controls the temporal and spatial role of volcanic and mechanical processes during rifting and formation of a new ocean? How does continental rifting transition to steady-state seafloor spreading?

Subduction

Oceanic lithosphere is formed at mid-ocean ridge spreading centers and evolves over millions of years through interaction with the asthenosphere and hydrosphere; however, its lifetime is limited to ~200 m.y., after which the oceanic lithosphere is partially recycled during subduction and plate collision. This process is not wholly destructive, as subduction often includes offscraping of sediments and some ocean crust and their subsequent accretion to a continent or island arc. Interaction with asthenospheric mantle also results in melting of subducting sediments and sometimes upper crust to produce continental or oceanic volcanic arcs. Both of these processes can effectively transfer crustal material, fluids, and volatiles from the geologically transient oceanic lithosphere to continental or island arc crust that may remain permanently within the lithosphere. Additionally, subduction zones produce perhaps the most significant geological hazards to society including the highest magnitude earthquakes, the greatest transoceanic and local tsunamis, and the most explosive volcanic eruptions.

Solid Earth cycles

Formation, hydrothermal alteration, and subduction of ocean crust generate secular chemical and physical changes throughout the lithosphere and mantle, as well as in the ocean-atmosphere system. The genesis of two main lithospheric constructs involves deeply recycled components: arc systems and LIPs/hotspot trails. Ocean drilling in arc systems (including forearc, arc, and backarc) is critical for understanding seismicity in subduction zones and determining input versus output mass balances. Of crucial importance in determination of input fluxes are reliable estimates of the chemical and mineralogical state of the subducting ocean crust. Hence, a primary rationale for drilling ocean crust remains in understanding ocean-crust and mantle-crust exchanges and their variability in time and location. At brief, intermittent intervals in intraplate settings, extremely large ocean-crust and mantle-crust fluxes produced significant chemical effects in the ocean and atmosphere through the emplacement of oceanic plateaus and volcanic rifted margins. LIPs and hotspots are manifestations of temporal and spatial variations in mantle upwelling intensity. Particularly intense periods of LIP activity appear to correlate with long-term changes in geodynamo behavior, which could involve interaction between the core and the deep mantle. Chemical components in LIP and hotspot magmas appear to provide samples of ancient recycled lithosphere. Variability in the direction and intensity of the geomagnetic field provide age models for environmental records and unexplored opportunities for high-resolution paleoclimate research. This example highlights the synergies between geodynamics, geochemistry, tectonics, and paleoclimate that should become a cornerstone of the new drilling program.

Linkages, big picture

Many lithospheric processes are common to a range of geotectonic settings (mid-ocean ridges, intraplate volcanoes, rifted continental margins, subduction zones). These include deep (mantle flow, recycling, melting, melt segregation), intermediate (magmatic versus tectonic accretion, structure, composition of lithosphere), and shallow (seawater circulation, weathering, microbial colonization) processes. The geotectonic diversity is reflected in variable physical, geochemical, and biological processes found in these different tectonic settings. These processes likely influence and are influenced by the resulting biological systems that develop, but the nature of these ecosystems and geobiological processes are largely unknown. Some principal perturbations (*e.g.*, volatile flux) propagate through the system and lead to pronounced differences, for instance in the microbial community composition below the seafloor. The new drilling program should focus on examining these linkages and thus provide an understanding of the underlying processes. These insights will lead to both increased accuracy of exchange-flux estimates for the modern Earth and improved ability to examine gradual and punctuated variations throughout Earth history. Additionally, serpentinization was identified as a process of global importance operating in all major plate boundaries and playing a key role in ridge and subduction zone tectonics, Earth's geochemical cycles, and the deep biosphere, and yet it is a little understood process worthy of investigation.

Relevance

The questions centered on initiation of plate boundaries and evolution of plates are fundamental to understanding how the Earth works and how the continents we live upon were formed and evolve. Many of the things to be learned from systems and processes making up the 'lithospheric membrane' of the Earth are of great societal relevance. Subduction zone hydration-dehydration cycling affects earthquakes and volcanic hazards. During initiation of plate boundaries, volcanism has impacted past climate, and may yield information about agents of climate change. Hydrothermal systems form polymetallic sulfide deposits of potential economic interest, and also host microorganisms that may be exploitable in bioengineering. The ocean crust provides vast opportunities for CO_2 capture and storage, with areas of exposed mantle being particularly reactive and suitable for long-term storage of CO_2 in carbonates. Finally, rifted continental margins host major hydrocarbon reservoirs, which are an essential energy resource.

3.1 Core-Mantle-Crust

3.1.1 Core and mantle dynamics

The interior dynamics of our planet are expressed in temporal and spatial variability of the geomagnetic field, which is produced by convective motion in the outer core (geodynamo). It is important to better understand the nature and extent of geomagnetic field variations to assess true polar wander and long-term changes in the structure and intensity of the field. Why does the field reverse at irregular intervals? What are excursions? What is the true distribution of excursions and subchrons, and their relationship to secular variation? Developing magnetic stratigraphic tools useful for correlation within polarity chrons will be important for providing chronology for paleoclimate research that is independent of the environmental record (*e.g.*, oxygen isotopes). Understanding the interactions between the geomagnetic field and climate is an emerging area of research that should be addressed in the new drilling program. Paleomagnetic studies carry potential for synergies between geodynamics, tectonics, magmatism, paleoclimate, and geographical reconstructions that have not yet been fully utilized.

The deep mantle communicates with the surface of the planet in two fundamental modes, driven by the energy of radioactive decay (Fig. 3.1). In the first mode, steady-state convection of primarily the upper mantle results in the plate tectonic cycle of ocean basins opening, aging, and closing. Numerical models based on tomographic images of seismically fast (cooler) and slow (warmer) regions of the mantle, together with plate reconstructions, are producing ever-refined predictions of mantle flow, which can be tested with anisotropy measurements and chemical tracers.

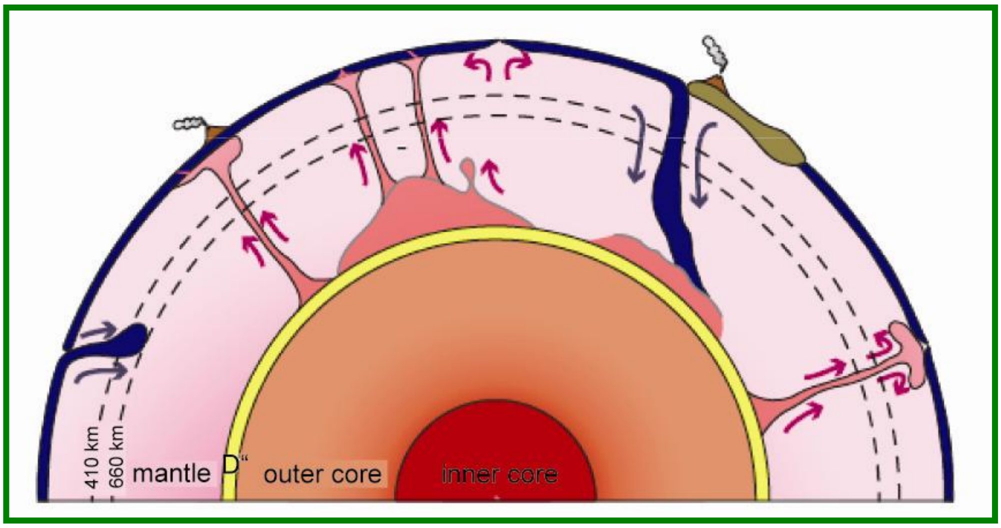

Figure 3.1 Schematic cross-section of Earth depicting upper mantle convection (upwelling at spreading centers and downwelling at subduction zones) and lower mantle convection (upwelling of LIPs and hotspots and deep penetration of subducting lithosphere). Transient LIPs are believed to originate from a thermal boundary boundary near the core-mantle boundary (D") or from thermal or mechanical boundary layers at the upper mantle-lower mantle transition (410 and 660km) (Farnetani and Samuel, 2005). From Coffin *et al.* (2006).

In the second mode, intermittent whole-mantle overturn results in periods of LIP eruption, faster-than-usual seafloor spreading and arc collisions, and sea-level highstands (Fig. 3.2). Strong evidence is accumulating that the second mode, last prominent in the Cretaceous to early Tertiary Periods (135-55 Ma), produced igneous systems that were constructed on both continents and in ocean basins at extraordinary eruption rates. This period nearly coincides with the long Cretaceous normal magnetic polarity, implying a possible connection between geomagnetic field behavior and deep-mantle thermal regime. The major hotspots appear to begin with LIP magmatism, but reconciling the melt volumes, eruption rates, and source compositions of the two manifestations of mantle plume activity is a challenge for dynamic modeling. Critical questions about LIP volcanism are: How rapid? What volumes? What total duration? What chemical exchange? These questions have huge implications for geodynamic mechanisms for their origin and for potential environmental impacts, including mass extinctions, rapid global warming, ocean acidification, and ocean anoxic events (see section 6.1).

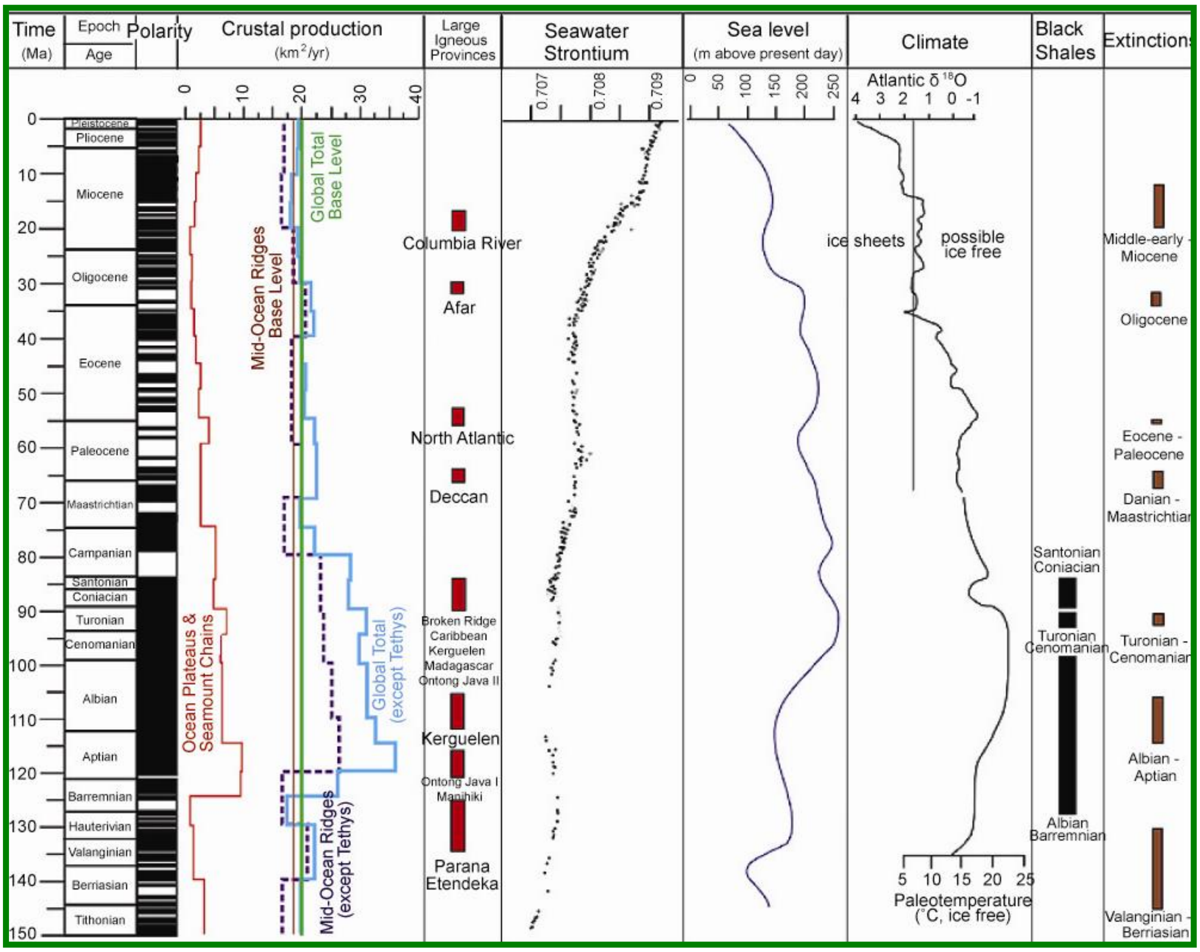

Figure 3.2 Temporal correlations among geomagnetic field polarity, crustal production rates, LIP construction, seawater strontium (Sr) evolution, sea level, climate, black shales, and mass extinctions. From Coffin and Eldholm (1994).

3.1.2 Crustal accretion

Two-thirds of the surface of the planet is continually renewed in the ocean basins through an ongoing process of upward flow of the mantle, partial melting, and emplacement of hot rocks as new seafloor. This relentless movement of material and energy from the mantle to the ocean and atmosphere is regulated through exchange of heat and chemical elements between the deep sea and new ocean crust. Cooling of new ocean crust through conduction of heat and convective circulation of seawater leads to thicker and denser lithosphere that ultimately sinks back into the mantle. Ocean crust creation, aging, and recycling is the foundation of the plate tectonic cycle that is unique to Earth among known planets. It is central to any understanding of the integrated Earth system, and in particular to the sources, sinks, and pathways of heat and chemical transfer between the solid Earth, oceans, atmosphere, and biosphere.

Major uncertainties about the creation of new ocean crust include the long-sought, but unattained goal of understanding the nature of the primary seismic discontinuity between ocean crust and the mantle, the Moho. Previously thought to be the boundary between rocks above formed from mantle melts (the crust) and rocks below from which melts are extracted (the residual mantle), it is now viewed as possibly an alteration boundary formed by fluids penetrating through the crust into the uppermost mantle (Blackman *et al.,* 2009). Seafloor accretion rates range from 1 to 20 cm yr^{-1}; however, the structure (including Moho) and internal composition of seafloor formed at slow and fast-spreading ridges do not appear to be the same (Dick *et al.,* 2003; Cannat *et al.,* 2006). Do differences related to spreading rates result in variable heat and chemical fluxes and hydrothermal circulation? What is the bulk composition of the ocean crust? Recent evidence from oceanic gabbros reveals that significant reactions occur between mantle melts and lower crustal rocks, which cast doubt on long-established ideas about mantle melting (Lissenberg and Dick, 2008). To answer these questions, it is essential to penetrate a complete crustal section across the Moho and into the shallow mantle at a fast-spreading ridge, coupled with shallow targeted drilling and *in situ* experiments elsewhere. Such a complete sampling is also necessary to provide *in situ* confirmation of geophysical imaging of much greater volumes of crust formed at fast-spreading ridges, and also to enable us to test limits concerning the greatest depth that biological ecosystems can exist in igneous ocean crust.

Twelve white paper submissions expressed strong interest in obtaining full crustal penetration and recovery of uppermost mantle material. Some of these cited ‘Mohole’ as one of a broader set of interests and several portrayed this objective as their main focus. Contextual studies are a crucial part of the Moho project, as excellent geophysical characterization and understanding of regional Moho structure is essential. This requires ground-truthing of geophysical data by geological sampling. It was acknowledged that there are several major scientific milestones that will be achieved by Mohole drilling: (1) investigating the nature of the Moho and upper mantle properties (composition, structure); (2) determining the structure and composition of ocean crust at a magma-rich spreading center, in particular the crust-mantle and intracrustal transition zones; (3) testing rival models of ocean crust accretion and cooling; and (4) assessing the extent of hydrothermal interaction on a full lithospheric scale.

Drilling is required to determine plate rheology and structure in crust formed at slow-spreading ridges, as well as the extent of seawater penetration into the lithosphere and the significance of serpentinization for geochemical fluxes. Although some of these goals can be achieved by taking advantage of tectonically exposed crustal sections, many of the first-order objectives will require technical development of riser drilling capability to 5-6 km crustal penetration in high-temperature conditions. Full penetration of crust through the Moho and into the uppermost mantle requires long-term commitment and special capabilities of drilling and logging technology (ultra-deep penetration, high temperatures, deep water); engineering to prepare the D/V *Chikyu* for these objectives has begun.

3.1.3 Intraplate and massive volcanic activity

While the vast majority of volcanic activity and mantle-crust interaction over most of Earth history have occurred as a result of plate tectonics (*i.e.*, crustal accretion and subduction), there are significant steady-state volcanic systems that develop in the interiors of plates or cross plate boundaries (hotspot tracks), and erupt intermittent, massive volumes of lava over geologically brief periods (*i.e.*, LIPs). Arguably, plate tectonics reveals how the shallow mantle operates, whereas hotspots and LIPs tell us more about deep mantle composition and dynamics. Drilling along prominent hotspot tracks (*e.g.*, Hawaiian-Emperor, Walvis Ridge) offers information about: (1) the drift of plumes in mantle flow; (2) the factors that control magma flux in plumes; and (3) the origin, continuity, and heterogeneity of plume sources (*e.g.*, recycled slabs, primitive mantle).

For submarine LIPs, the highest priority is to better understand the likely geodynamic conditions for mantle melting and lithospheric interaction through quantifying the composition and duration of magmatic events, thereby deriving a record of melting and magma flux with time. The most successful drilling implementation is thought to be through an array of 'off-LIP' high-resolution, contemporaneous sedimentary sections that record the environmental impact of submarine volcanic activity through several geochemical proxies (*e.g.*, paleontologic, isotopic, trace metal, biomarker; see cross-cutting theme section 6.1). Direct sampling of a LIP is also important to establish igneous compositions for modeling of mantle sources and melting, geochemical fingerprinting for environmental impacts, and discovering internal structure and response of the lithosphere to loading and extension. Given their enormous lateral extent and thickness, the best drilling strategy for maximizing sampling of internal structure and composition is proposed to be a transect of offset sites along a rifted margin, where a compositional range of rock types can be assured from surface sampling (*e.g.*, Manihiki Plateau).

3.2 Crust-Ocean-Atmosphere

3.2.1 Crust-ocean exchange

Thermal and chemical exchange between the solid earth and oceans, facilitated by hydrothermal fluids, is an important driver of global geochemical and biogeochemical cycles. We need to understand the processes that influence the vigor and extent of hydrothermal exchange. Pursuing this goal requires not only full penetration of a complete crustal section across the Moho and into the shallow mantle at a fast-spreading ridge, but also must be coupled with shallow targeted drilling and *in situ* experiments elsewhere. Specifically, how are coupled hydrogeological, geochemical, thermal, mechanical, and biological processes linked to the architecture and physical nature of lithosphere below the ocean? Important questions remain about the spatial and temporal scales of hydrothermal fluid movement and the advection of heat and materials. What processes influence the intensity of hydrothermal exchanges in a range of environments and can we develop predictive models for different tectonic/geologic settings? To what degree are hydrological regimes and microbial communities connected in the subseafloor? Recent research has highlighted strong linkages between microbial activity and hydrothermal fluid-flow (Perner *et al.,* 2009), but the controls on microbial growth, diversity, distribution, survival, and evolution remain poorly understood. All oceanic environments need to be considered from arcs to major ocean basins, ridge crests to the ancient flanks, sediment, basaltic, and serpentine-hosted systems, and important but hitherto unquantified hydrological systems operating on continental margins, ocean islands, and plateaus.

Many questions about axial zone processes can be addressed by the integration of drilling, monitoring, and sampling programs. We lack crucial information on the permeability structure of zero-age crust, although recent progress from seismic monitoring provides unprecedented details of hydrothermal flow patterns (Tolstoy *et al.,* 2008). Ocean drilling offers unparalleled opportunities for examining the controls of fluid pathways and the spatial and temporal variations in permeability and fluid-flow. The hydrogeology of axial hydrothermal systems greatly affects the biological systems that thrive in the ridge environment. We have little knowledge of how microbiological activity in the subseafloor varies spatially and temporally within axial hydrothermal systems. How is fluid-flow related to biota dispersal and the connectivity of microbial communities? What are the limiting factors (temperature, availability of chemical energy and/or nutrients) for subseafloor life in these environments?

Tackling these questions requires exploratory drilling and sampling, active experiments where environments are perturbed, and measurements, experiments, and sampling from long-term observatories. Although ocean drilling has established innovative approaches to investigate these systems, late stage scheduling decisions often make long-term planning challenging. For drilling crust in axial zones, the hard rock reentry system (HRRS) offers the ability to install casing with reentry capability on sediment-free and sloped seafloor. The HRRS establishes a hole for casing without coring and is a critical tool for hole initiation for deep drilling and borehole observatories. Sampling shallow crust in axial zones is perhaps best accomplished by the deployment of seabed drill rigs, of which several types are available with capabilities of coring down to 100-150 m subseafloor in 2000-4000 m water depth.

3.2.2 Plate aging – ridge to trench

In regard to the evolution of ocean lithosphere from ridge to trench (Fig. 3.3), we have so far been unable to determine the relative roles of spreading rates, lithospheric architecture, faulting, basement relief, and sedimentation; how do these processes influence patterns and vigor of fluid-flow? How does the crust – and the microbial communities it harbors – transition from the high-temperature axial region to the lower temperature flanks and beyond? How much are the rates of advective heat transport, fluid-flow, microbiological activity, and seafloor alteration changed as a function of plate aging? How does the evolution of oceanic lithosphere influence the dynamics of subduction processes? Systematic transect drilling in crust of different ages, spreading rates, and hydrological state is required to answer these questions, which are critical for developing a comprehensive and accurate picture of mass and heat exchange, present and past.

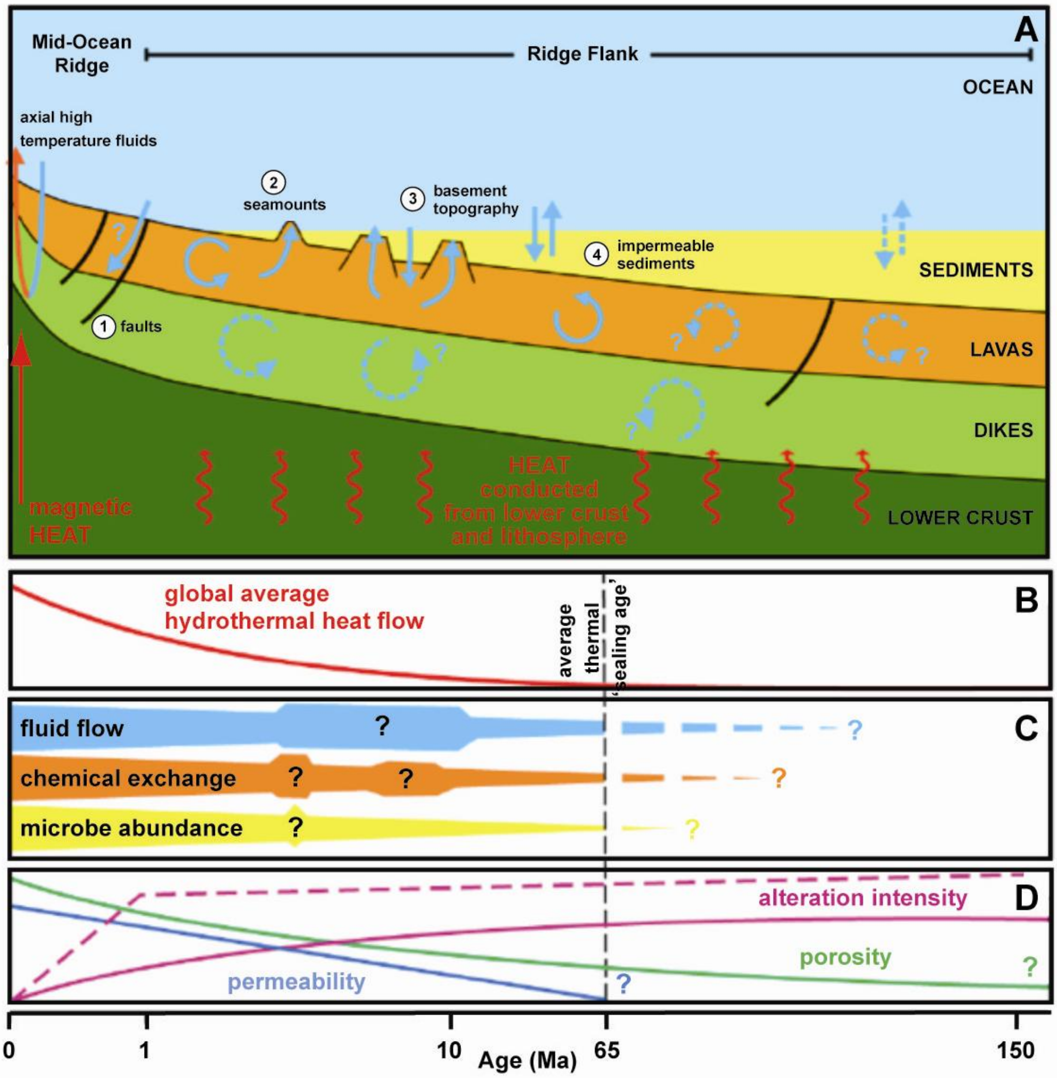

Figure 3.3 Diagram showing the predicted changes in crustal properties during aging (from Teagle et al., 2009). (A) Parameters that may influence the intensity and style of hydrothermal circulation through the ridge flanks, such as faults, seamounts, basement topography and impermeable sediments. Arrows indicate heat (red) and fluid (blue) flow. (B) The difference between the average measured conductive heat flow and that predicted from conductive cooling plate models. The calculated global hydrothermal heat flow decreases to zero, on average, by 65 Ma. At this age the crust is typically assumed to be 'sealed' to hydrothermal circulation. (C) How parameters such as basement topography and sediment thickness affect fluid-flow, chemical exchange, and microbe abundance in the crust during the aging process remain undetermined. The hydrological, physical, chemical, and biological evolution of hydrothermal circulation through the ridge flank could be investigated across a ridge flank. (D) The controls on the intensity and style of hydrothermal circulation could be investigated by the measurement of multiple parameters such as porosity, permeability, and alteration mineralogy.

Ultramafic seafloor (20–25% areal extent along slow-spreading ridges) is highly reactive and its presence has profound consequences for plate-scale rheology, crustal composition, and architecture, and implies geochemical and biogeochemical exchanges of global significance (Cannat *et al.,* 2009). Serpentinites are a major source of water in subduction zones and they play a prominent role in the hydrological cycle (Rüpke *et al.,* 2004). Moreover, study of the serpentinization process itself has taken on notable importance within the ocean lithosphere community with emphases on biogeochemical processes that are inherent where seawater encounters peridotite. Carbonation reactions (Andreani *et al.,* 2009; Kelemen and Matter, 2008) represent a critical and poorly constrained aspect of this and could become an additional focus area that has until very recently not received much attention.

A top priority for understanding crustal aging is a drilling transect of holes through the upper (~600 m) ocean crust along a 'flow line' within the Pacific basin. Ideally, the transect will be tied to a complete crustal section through the Moho at the young end and a trench-parallel array of sites to document the inventory and variability of material entering the subduction zone at the old end. Studies across a broad, representative range of sites will examine the relationships between hydrothermal circulation, permeability, geochemical alteration, hydrological systematics, and microbial communities as a function of crustal age, as well as enable the development of cross-hole experiments for longer term experimental constraints on biological and hydrological properties of the ocean crust.

3.3 Ocean-Floor Resources

3.3.1 Mineral carbonation and CO_2 sequestration in the oceanic lithosphere

The ocean crust is a natural sink for CO_2 (Alt and Teagle, 1999) and during hydrothermal alteration and weathering it releases Ca and Si, which increase the production of carbonate and biomass in the oceans and hence play a role in the carbon cycle. A new fundamental question is: How does natural mineral carbonation in previously little-studied lithologies such as mantle peridotite affect the global carbon cycle? Natural carbonation of peridotite could be an important sink for carbon from the ocean into subduction zones. Ocean drilling programs have played no role as yet in the study of natural mineral carbonation processes and conditions in the ocean crust. Yet, much of what we wish to know about natural mineral carbonation systems can be achieved via ocean drilling. Learning about mineral carbonation from natural analogues can take place within IODP expeditions even if their primary objectives lie elsewhere. The study of the deeper parts of active hydrothermal systems, particularly those where rapid, ongoing peridotite carbonation has been demonstrated, should be given a high priority. These include mid-ocean ridge systems (*e.g.*, Lost City, Rainbow), carbonated peridotite basement at rifted continental margins, oceanic lithosphere altered during the aging process, and carbonated peridotite in serpentine seamounts in western Pacific fore-arc settings. Of exceptional interest is sampling of actively forming, large (>1 m) bodies of fully carbonated peridotite (listwanites) in near-seafloor peridotites, because full carbonation is the goal of enhanced, *in situ* mineral carbonation processes and it is vital to understand the combination of pressure, temperature, mechanical properties, and fluid composition that lead to this outcome in natural systems.

In studying natural mineral carbonation in these environments, we need to characterize relevant mineral carbonation reactions (reactants, products, temperature, pressure, fluid composition). Theoretical and experimental work along these lines has just started (Andreani *et al.,* 2009; Kelemen and Matter, 2008), but we also need to determine mineral carbonation rates in ocean lithosphere by relating carbonate abundance to age in drill cores (*e.g.*, Alt and Teagle, 1999). Additionally, we need to understand the controls of oxygen fugacity buffers, pH, and the presence of chemical or biological catalysts on those rates. Finally, we need to determine fluid-flow rates and multi-scale porosity and permeability characteristics in the ocean crust.

There are many advantages to subseafloor geological capture and storage of CO_2, including the safe release of saline pore fluids displaced by CO_2 injection. Mineral carbonation is important for long-term storage of CO_2 during injection of the gas into pore space in sediments, but is the least well understood component of the overall process. We have much to learn from natural systems about favored geochemical and geomechanical pathways for mineral carbonation. Identifying and studying natural environments where rates of carbonation are increased will be critical in the evaluation of promising methods of *in situ* mineral carbonation. Ocean drilling can provide 'proof of concept' for these options, which may be complementary to, or even preferable to, injection of supercritical CO_2 into pore space in sedimentary rocks. Questions to be addressed include: What are the fundamental mechanisms of mineral carbonation in natural systems and how can they be utilized to design systems for enhanced, *in situ* CO_2 sequestration? What are the conditions of pressure, temperature, fluid composition, rock composition, and physical properties that maximize the rate of mineral carbonation processes in different environments proposed for geological CO_2 sequestration? How will changes to the natural system (increasing pCO_2, increasing fluid-flow rates) affect the natural system?

3.3.2 Subseafloor resources

CO_2 sequestration within pore spaces and reactive lithologies represents only one subseafloor resource exploitable for human society. Apart from hydrocarbons (including gas hydrates, which are more extensively covered in section 5.1.3), polymetallic sulfide mineralizations constitute a potentially important type of subseafloor resource. Others include geothermal energy and genetic resources (*e.g.*, enzymes from thermophilic microorganisms).

Gas hydrates

The largest fraction of hydrocarbons on Earth is stored in gas hydrates, but many details of the global distribution and abundance of gas hydrates have yet to be elucidated. What are the controls on gas hydrate localization and concentration? Progress on this front depends on our ability to determine the nature of bottom-simulating seismic reflectors (BSRs) as indicators of gas hydrate occurrences. Furthermore, the source of the carbon in gas hydrates and the rate at which these deposits form is relatively poorly understood. In terms of assessing the exploitability of gas-hydrate deposits, it is crucial to study the effect of mining of gas hydrates on continental slope stability.

Conventional oil and gas

Large hydrocarbon deposits form in rifted continental margin settings. It is uncertain to what extent igneous activity affects the maturation of conventional oil and gas deposits. Non-volcanic rifted margins constitute very favorable conditions for hydrocarbon formation, both in terms of their structure and thermal states. The basement underlying hydrocarbon-bearing sedimentary sequences is often inaccessible, but slow- and ultraslow-spreading ridges may be a good analogue that can be utilized by developing synergies between the hydrocarbon and lithosphere research communities.

Deep-seafloor volcanogenic-hosted massive sulfide deposits

From a research perspective, submarine massive sulfide accumulations have long been of interest because it is believed they represent modern analogues for volcanogenic-hosted massive sulfide (VMS) deposits on land, including many world-class copper and gold deposits. From studies of active seafloor hydrothermal systems, much can be learned about the formation of VMS deposits. Drilling is critical to examine the structure, thermal profiles, source rocks, fluid pathways, reaction/precipitation processes, and the controls on sulfide composition and abundance. Questions revolving around subseafloor sulfide mineralizations and their potential use as a metal resource include the following: What are the size and magnitude of massive sulfide accumulations and how can we detect them remotely and ground-truth them directly? Can massive sulfide accumulations form without creating a seafloor expression of high-temperature fluid upflow? What is the influence of the underlying volcanic crust/sediment composition and magma degassing processes on sulfide composition (base metal content)? What controls the sub-surface pathways of fluids and their precipitation/reaction products? What is the source of the reduced sulfur and how does it vary along the hydrothermal upflow path? What are the rates of formation of seafloor sulfide accumulations? What are the mechanisms for focusing, precipitating, and preserving seafloor and subseafloor sulfides? What is the role of biomediation in the formation and enrichment of metals in seafloor and subseafloor sulfide?

Further questions relate to specific settings. For instance, what is the heat source for ultramafic-hosted sulfide mineralizations and hydrothermal systems? Is it mafic intrusions or serpentinization? Are volcanic rifted margin sequences, including their intrusive bodies and their mineralization, analogues for other LIPs?

Sustainability issues need to be considered when entertaining thoughts about seabed mining of metal sulfides. How fragile are the seabed and sub-seabed ecosystems? What is the comparative environmental footprint of seabed mining compared with land-based mining?

Bio-prospecting

A key question related to bio-prospecting of the subseafloor biosphere is whether it is feasible and desirable. In any case, researching the biological involvement in massive sulfide formation and base metal concentration both at the seafloor and in the subseafloor should be considered a high priority. Of special interest in this regard are microbes, which can catalyze the dissolution or precipitation/immobilization of various elements and thereby mediate the extraction or recovery of desired metals and metaloids.

Sub-seafloor geothermal energy

While the thermal power output from ridges and arcs is immense (several Terawatts), a critical question is whether subseafloor geothermal energy resources are a viable future energy resource. A related question is over what time frames focused and potentially usable geothermal resources on ridges are sustainable.

Drilling is critical for ground-truthing geophysical methods of detecting subseafloor resources. Drilling is also required to access deeper portions of the seafloor beneath zones of mineralization. Moreover, drilling is the only means of assessing the thermal and permeability structure of the seafloor into and beneath zones of hydrocarbon or metal accumulations.

3.4 Basement Biosphere and Hydrology

To date, many exciting discoveries have been made about the nature of the deep microbial biosphere in marine sediments. In comparison, there is relatively little information about the nature, extent, and activity of microorganisms living in volcanic oceanic crust (see Edwards *et al.,* 2005). Seawater circulates through the porous and permeable upper oceanic crust, carrying seawater and microbes into the subseafloor where they may take up residence in the deep crustal biosphere. The potential for the oceanic deep biosphere to influence global biogeochemical processes scales with the size of the subseafloor as a habitat. Oceans cover over 70% of the Earth's surface, and 70% of the rock underlying the ocean represents an actively flowing aquifer system — the largest on Earth. Fluid-flow in the oceanic aquifer mediates elemental exchange between crust and seawater, and consequently affects global ocean chemistry. Because of the size and hydrodynamics of this potential biome, crustal life may have a profound influence on global chemical cycles and, as a consequence, the physical and chemical evolution of the crust and ocean. Microbial populations seek out high thermal and chemical gradients. Temporal variations in the geometry and nature of hydrothermal recharge and discharge are expected to determine the diversity of ecosystems. The subseafloor oceanic aquifer processing zone represents a realm where biochemical reactions, evolutionary processes, and elemental cycling and exchange occur with globally significant ramifications. Hence, it is imperative that the scientific community develops a more complete understanding of life in ocean crust.

Our understanding of the biosphere harbored in hard-rock settings is hampered by the difficulty in accessing high-quality, uncontaminated samples. For example, brecciated rubble zones in basaltic basement are rarely recovered, yet are of very high value for studies of indigenous microbial communities. Hence, in the next phase of ocean drilling, researchers must develop appropriate tools for studying this unique habitat. Recent engineering and methodological advancements make now a particularly opportunistic time to do so (see section 6.4).

3.5 Plate Boundary Initiation, Subduction Zones, and Volcanic Arcs

3.5.1 Initiation of plate boundaries

Since the advent of the plate tectonic theory one of the foremost questions has been: How do plate boundaries initiate? Current understanding of plate tectonics has shed light on how some plate boundaries formed. Examples include new transform boundaries formed through triple junction migration and plate rifting caused by mantle plumes; however, in many cases the current understanding is based on extrapolation of limited data, from case studies focused on specific processes, to formulate broader hypotheses and models. Some cases are especially problematic due to the question of how the first boundary formed; for instance some models for subduction initiation require a neighboring subduction zone to propagate subduction into a new boundary, so how did the first subduction zone form?

There is a need to investigate how both divergent and convergent boundaries form, as well as how one boundary type evolves into another. Divergent plate boundary initiation includes both rifting of a continent to form a new ocean basin and new divergence in a back arc. Multiple models exist for convergent boundary formation, including a subduction zone that steps out or propagates from an existing subduction system, possibly through a reversal of subduction direction (Stern, 2004; Gurnis *et al.,* 2004); initiation of a new subduction zone along a passive margin (Niu *et al.,* 2003); or forced initiation along a fracture zone (Hall *et al.,* 2003; Gurnis *et al.,* 2004). Spontaneous subduction at passive margins has yet to be demonstrated by geodynamic modeling or data, and yet the lack of any oceanic crust older than ~200 Ma seems to require some mechanism by which passive margins can become the nexus for a new subduction zone.

Given these considerations about fundamental processes creating plate boundaries there are several unifying, overarching questions. Are the locations of new plate boundaries largely controlled by pre-existing features? Are new plate boundaries generated largely by external forcing processes (magma, 3-D boundary propagation, or something else)? Formation of a plate boundary requires breaking a plate, yet fundamentally lithospheric plates are strong, leading to what has been known as the Strength Paradox. Thus, mechanisms to thermally weaken a plate have been suggested (Buck, 1991), whereas other suggest rifting takes advantage of pre-existing weaknesses (Dunbar and Sawyer, 1988; Gueydan *et al.,* 2008). How fast must a new plate boundary form in order to succeed? Alternative mechanisms have been proposed that rely upon strain rate to provide the necessary weakening (Kusznir and Park, 1987). How do fault systems form and evolve during plate boundary initiation? How do local plate boundary initiation and plate reorganization affect plate configurations and motions globally? How do plate boundary tectonic processes affect intracrustal microbial communities (*e.g.*, by hydrogen production)?

An additional series of questions were asked about the earliest stages of convergent plate boundary initiation. What is the sequence and timing of magmas reaching the surface after subduction initiation? How do the early magmas build the foundation for the arc platform? What is the role of early arc crust in forming new continental crust? What is the relationship between initiation of subduction boundaries and global plate reorganizations? Subduction zones are particularly vital to consider in this context as it is generally accepted that the dominant tectonic force is slab pull, and thus the addition of another slab-pull force in the global tectonic framework should have far-reaching implications.

There are additional questions that specifically pertain to divergent boundaries that can allow for testing of existing and competing models for formation of rifts and oceans. What controls the temporal and 3-D spatial role of volcanic and mechanical processes during rifting and formation of a new ocean? How is continental lithosphere thinned during rifting? What controls the transition from rifting to steady-state seafloor spreading? How does magma interact with sediment, the hydrosphere, and the atmosphere? What are the consequences of serpentinization of large areas of exhumed mantle at hyper-extended margins?

Specific locations were suggested for study of plate boundary initiation. For subduction initiation, the Izu-Bonin-Marianas Arc and the Aleutian Arc were highlighted for the purpose of investigating the magmatic/volcanic products from the earliest phases of subduction. Continental rifting examples discussed included the northeast Atlantic margin (magma-dominated rifting), the Gulf of Corinth (ongoing rifting), Iberia/Newfoundland (hyper-extended rifting), and the Marmara Sea (ongoing rifting).

These questions are clearly first order and global, but how can ocean drilling help? Ocean drilling is the only way to attach ages and rates to these processes. Drilling will also obtain sediment and rock samples for study of lithology, pressure and temperature conditions, and rheology, and can be used to calibrate seismic and other geologic data in the region. Testing of existing models and generation of new calibrated, ground-truthed models can only be done through drilling. To date, there has been little or no drilling to explore early arc crust or zones in an early stage of rifting. There have also been no drilling expeditions specifically targeting initiation of subduction or the evolution of a plate boundary from one type to another.

The questions centered on initiation and evolution of plate boundaries are societally relevant due to both the geohazards associated with convergent and transform boundaries and the linkage between tectonics and global climate. Learning about subduction systems may provide useful information for mitigation of hazards posed by earthquakes, tsunamis, and volcanoes. Initiation of plate boundaries is associated with plate reorganizations and often new volcanism. Both have impacted past climate and may yield information about agents of climate change. Plate reorganization ultimately modifies the distribution of landmasses and hence the movement of water masses; thus, understanding the feedbacks between plate boundary initiation and reorganization can aid in determining global ocean circulation and its impact on climate. Volcanic processes at new plate boundaries may release large volumes of greenhouse gases. Rifted margins are a major source of hydrocarbon fuels. It is certain that during the period from 2013 to 2023 and beyond, these sources of energy will be essential.

Research strategies require excellent site characterization using 2-D grids and sometimes 3-D seismic reflection profiling. Good velocity control using ocean bottom seismometers may be important for deeper targets. Drilled samples including oriented cores, samples useful for age dating, and *in situ* stress measurements will help aid study of subduction initiation. To examine early products of subduction at a volcanic arc, deep drilling may be required (using *Chikyu*) for some sites, but shallow offset drilling can accomplish many objectives. Rifted margins need deeper penetration requiring either a longer riser for the *Chikyu* or a riserless mud delivery system. These goals will require a mix of short- and long-term projects with inherent flexibility should unexpected results necessitate a change in strategy.

Interactions with other programs that would be beneficial include US MARGINS, INTERMARGINS, ICDP, and the energy industry. Rifted margins are a major source of hydrocarbon fuels. Understanding their origin and occurrence with respect to temperature-depth paths and structures in developing ocean basins i of interest to potential partners in the energy industry. Outreach opportunities include the concept of the birth of continental crust (*e.g.*, Bonin Islands) and the issue of rifted margins as a source for future energy.

3.5.2 Subduction zones and volcanic arcs

In the new drilling program, we envision studying subduction zones and volcanic arcs holistically within the context of the Earth's processing zone to answer some fundamental questions of interest to the fields of plate tectonics, geo- and atmospheric chemistry, and geohazards. Four themes concerning the combined subduction-volcanic arc system are: (1) arc growth and growth of continents, (2) forearc structure and evolution, (3) fluxes, fluids, and volatiles, and (4) controls on earthquake processes at subduction zones. The latter is reported on in section 5.1.

Arc growth, mass fluxes, and links to growth of the continents

Volcanic arcs are a direct product of subduction and important for assembly of continents, as recorders of past subduction, and for their hazard potential (Kay, 1985). One set of key questions about arcs is centered on their formation and growth (Jicha *et al.*, 2006; Nikolaeva *et al.*, 2008). Does steady state or episodic growth dominate arc production? How and over what timescales does arc production vary? What controls the across- and along-arc variation in arc crust, arc magma, and mantle wedge composition and structure? How do subduction inputs control these variations? How does arc growth contribute to the growth of continents? Which processes can transform arcs into parts of continents?

The rate of arc crustal growth is a fundamental parameter towards which arc research should be directed within the new program and in allied programs. This topic requires acquiring samples through upper arc crust, determining crustal thickness, and developing an understanding of middle arc crust composition and formation. Additionally, the role of serpentine in transferring fluids from the subducting plate to the overriding plate and how it influences arc growth are unknown. To study these processes, we need to drill an early/young arc to understand growth and evolution. Examining the history of crustal growth from arc initiation through extinction requires transects as crustal growth is not uniform and may vary through time and along arc.

There are clear connections among subduction inputs, magma production, and arc heterogeneity but these processes need to be studied in detail. Subduction inputs and volcanic/arc output therefore need to be researched in concert both along-strike and across-strike. Drilling strategies to address these arc questions should include a combination of shallow drilling transects and a deep hole for crustal sampling targeting age and chemical composition. Shallow transects should be devised for along- and across-arc variation in crustal composition and volatile emissions. Integration of the geophysical images and models with drilling data should allow for quantitative estimates of the variability. Technological challenges to be overcome for these goals include the ability to drill and log at high temperatures.

Forearc structure and evolution

Beyond studies of the earthquake cycle in subduction zones, there are numerous key questions regarding the forearc structure and evolution of active continental margins (Kukowski and Oncken, 2006; Clift *et al.*, 2009; Scholl and von Huene, 2009). What are the mechanisms and products of tectonic erosion (in contrast to accretion)? What factors control this process, at what rates does it occur, and over what timescales? What occurs when a seamount subducts? How do forearc basins in accretionary or erosive active margins develop? Is their formation related to deformation, rheology, or basal taper changes? How do the mechanisms of stability that produce forearc basins relate to or contribute to growth of continents and arc magmatic processes? What are the links between the forearc, arc, and backarc?

Scientific drilling is the only method that can access and sample the submarine forearc. To help understand the process of tectonic erosion, drilling can provide forearc slope paleobathymetry, lithologies, and rheology of non-accretionary forearcs; however, to examine basal erosion mechanisms deeper drilling is required. To study forearc basins, basin sediments can be used to determine the timing of events and may give clues about the evolution of the forearc (Gulick and Meltzer, 2002; Gulick *et al.*, 2002; Melnick and Echtler, 2006). Shallow sub-basin sampling or drilling near the flanks of basins may provide tests of varying basin formation mechanisms. For both forearc structure and basin studies, along-strike transects could highlight lateral variations and elucidate how subducting plate characteristics influence arc development. Site characterization is critical for site selection and knowledge of the structural framework will allow results at the borehole to be interpolated between boreholes and correlated regionally.

Fluxes, fluids, and volatiles

Considering the forearc to backarc as a continuous system requires investigating fluxes of mass, fluids, and volatiles through the lithosphere. A number of key questions were highlighted at INVEST. What is the hydrogeology of the subducting plate and the role of faults within this system? What are the rates and distribution of fluid-flow within the subduction system? What is the significance or role of serpentine in different parts of the subduction system and what is its contribution to the hydrogeology of the system and earthquake generation process? What is the role of hydrothermal systems in arc volcanic systems and what are their contributions to the biosphere and mineralization (significant resources)? How do diagenetic and metamorphic processes evolve within the subduction system? What is the effective stress distribution (pore pressure, stress magnitude) in space and time? What is the feedback to other systems, *e.g.*, ocean, atmosphere, biosphere, mantle?

In previous drilling efforts these processes have been largely studied in singular settings such as in the context of sediment accretion and dewatering in the forearc or in magma generation within the arc. In the new program we plan to examine these fluxes and the critical processes that control them through the entire system. To accomplish these goals and answer these questions with drilling is likely to require either new transects across the system, or non-standard drilling implementation allowing these processes to be investigated in differing settings across multiple drilling expeditions.

Arc research has very strong linkages to other programs; thus, focus for the new phase of ocean drilling can build on the US MARGINS program "The Subduction Factory", EarthScope, previous ODP/IODP results, seafloor networks and observatories, as well as geophysical data and terrestrial studies. Drilling in forearc environments provides linkages with major existing and planned geophysical datasets, as well as with the numerical modeling community studying margin development and the importance of the subduction erosion process. There is a clear need to combine evidence from land investigations with ocean drilling in arcs. For instance land/sea combined investigations could allow study of the chemistry of volcanism through time including studying lithologies that fingerprint arc initiation, linkages between modern arcs and ophiolite formation, and ash stratigraphy to help establish temporal records and bridge significant stratigraphic gaps in the record of the lavas.

3.6 Science Strategies

3.6.1 Transect concept

For many of the highest priority science objectives regarding the solid Earth (mantle, lithosphere, crust), heterogeneities in composition, structure, material properties, and evolution with time require arrays or transects of drilling sites to capture three-dimensional and four-dimensional variability. These may be modest penetration sites coupled with deep penetration holes, as in the current NanTroSEIZE program, or long transects of modest penetration holes along a crustal flowline to assess aspects of plate aging. Other examples include:

- ⇒ Arc-parallel transect of sites on the down-going plate to assess variability in slab inputs to the subduction zone 'factory';
- ⇒ Offset drilling transects of sites to assess variability in ocean crust (particularly that formed at slow-spreading ridges) and ocean plateaus through sampling of composite sections exposed in tectonic windows;
- ⇒ Cross-hole experiments to determine hydrogeological behavior of the ocean crust;
- ⇒ Arrays of marine sedimentary sections to examine near- and far-field environmental effects of ocean plateau (LIP) construction; and
- ⇒ Transects of sites along hotspot lineaments to discover the temporal and spatial scale of mantle source heterogeneities delivered from the deep mantle by plumes.

3.6.2 Land-sea linkages

Processes within the 'lithospheric membrane' by definition cross the boundary between land and sea. Ocean drilling has traditionally focused exclusively on the deep-sea or continental shelf record of these processes and in general on the marine processes themselves; however to fully understand the interactions between the mantle, crust, ocean, and atmosphere we need to integrate the records of these processes from terrestrial deposits, shallow water and marginal basin sites, continental shelf records, and deep-sea depocenters. These transects from land to sea can be integrated through provenance studies, use of proxies, and thermo-chronology, calibrated with a suite of dating techniques, and mapped using onshore-offshore geophysical methods. Some major research programs now exist that are attempting to cross the shoreline and the new drilling program should integrate with these research endeavors to gain the most complete picture of lithospheric processes and fluxes from mantle to oceanic and continental crust, from crust to atmosphere, and then by erosion from continental crust and basins into the marine environment.

3.6.3 Model – observation integration

Our understanding of crustal growth and cooling is hampered by a near complete lack of direct evidence for the mechanisms of lower crustal accretion. Competing, but untested, conceptual models of crustal accretion have very different predictions for the extent and nature of hydrothermal circulation and for heat and chemical flux (Kelemen *et al.*, 1997; Maclennan *et al.*, 2005). These models provide robust predictions that can be tested by deep drilling of intact lower crust or rare tectonic windows. Sampling of *in situ* shallow mantle and an associated lower crustal cumulate section would lead to major paradigm shifts in planetary geochemical models. Similarly, we do not yet understand the controls on seawater penetration into the lithosphere and its importance for melt emplacement, plate rheology, and lithospheric architecture. *In situ* sections of lower crust are needed to determine the penetration depth and flux of seawater in the lower ocean crust and assess its role in crustal cooling.

In terms of crustal evolution, we need tighter constraints on the interrelationships among hydrology, geochemistry, and microbiology. Detailed and comprehensive combined studies involving observatory components are critical for understanding how the transport of heat and solutes are coupled. The development of coupled models of heat and reactive mass transport require a firm knowledge of the rates of geochemical reactions, which is currently missing. Better constraints on the timing of hydrothermal alteration and veining processes and their relation to changes in the hydrological state of the crust are dearly needed.

3.6.4 Drilling observatories

INVEST discussions prominently focused on the use of subseafloor borehole observatories (Circulation Obviation Retrofit Kits (CORKs)) as a means of accessing crustal fluids and microbiological samples, and reducing the extent of contamination associated with drilling, coring, and other operations. CORKs may be used, for example, to test specific hypotheses regarding the role of microbes in ocean crust alteration, serpentinization, hydrocarbon generation, elemental cycling, and VMS deposition and reworking. These processes can now be studied quantitatively, enabling the possibility that future ocean drilling can further integrate data that is generated by observing stations into predictive models; for example, by developing coupled hydrological, reactive transport, and bioenergetic modeling approaches to understand processes in the lithosphere (see also section 4.5.5).

Similarly, mineral carbonation and CO_2 sequestration can be tackled only by an approach that includes active experimentation that will require alternative platforms for characterization of shallow water test and long-term storage sites, as well as use of the complete arsenal of hydrogeological tools, including CORKs, packer tests, push-pull tests, *etc.* (see Fisher *et al.,* 2005). It will be necessary to develop better tools to measure/monitor the chemistry of fluids (pH, alkalinity, conductivity, high temperature gas content, speciation) and sample biological material in boreholes. In addition, older data (especially pH measurements) could be examined to develop understanding of, and correct for, systematic bias in measurements. There is also a need for passive seismic experiments and other long-term geophysical and geochemical monitoring, including microgravity, detailed bathymetry, fluid chemistry, EM, *etc*. Though this is standard practice in the oil and gas industry, we are not aware of any past ODP or IODP hydrofracture experiments, and we think that this may require moderate technical modifications and specialized safety measures. Similarly, in large-scale field tests, it will probably be desirable to inject CO_2 at 100 to 300 bars. Again, this is standard industry practice but to our knowledge is unprecedented in ODP and IODP, and will require new techniques including specialized safety procedures and perhaps supplemental ships.

3.6.5 Site characterization

Seismic reflection and refraction data are both vital tools for examining the 'lithospheric membrane'. To understand the processes happening locally, regionally, and globally requires mapping of deformed and undeformed strata, identifying faults, directly imaging fluids in these faults or strata, measuring the velocities of sediments and crust, and placing every sample site into a 3-D regional context. Goals for the new program involving sampling, logging, experimenting with the seafloor, and monitoring all necessitate geophysical site characterization. Discussions need to be raised as to how to plan for and fund integrated international studies requiring site characterization and drilling to answer the most compelling solid Earth questions.

4 Co-Evolution of Life and the Planet

Scientific ocean drilling has historically yielded some of the most transformative advances in the Earth sciences, cross-cutting many of its disciplines and providing fundamental advances to our knowledge of how the Earth works. Today, ocean drilling is poised to offer these same transformative advances to disciplines within the life sciences and to provide insight into how life operates and interacts with Earth's processes at and below the seafloor – both today and in the distant past.

INVEST attendees addressed the co-evolution of life and planet in six thematic breakouts sessions: (1) Extent and habitability of subseafloor life and the biosphere; (2) Biogeochemical function, activity, and ecological roles of subseafloor life; (3) Limits and evolution of life on Earth and beyond; (4) Extreme environmental events and punctuated evolution; (5) Paleo-ecosystems: biodiversity and biogeography; (6) Co-evolution of ocean chemistry and the surface/subsurface biospheres. Many of the topics discussed in these breakouts were further addressed in other breakouts at INVEST, indicating how interwoven the life sciences are now with most other major scientific topics being addressed in ocean drilling.

Approximately one-third of the submitted white papers had a major focus on topics that revolved around the co-evolution of life and the planet. Many of these white papers addressed issues relating to technology; either microbiological or molecular technologies for advancing our analytical abilities or technologies for experimentation in microbiology and geochemistry associated with microbiological and biogeochemical observatories through boreholes. At the heart of topics relating to the co-evolution of life and the planet is the juxtaposition of modern life processes operating within sediments and rock in the deep biosphere and records of past life recorded in deeply buried sedimentary sequences.

Deep subseafloor biosphere studies seek to answer questions that range in nature from exploratory and census-level to the most complex and fundamental in the Earth and life sciences. Deep subseafloor habitats are vast in scale — it is estimated that one-tenth to one-third of the Earth's biomass is harbored in the marine subsurface (Whitman *et al.*, 1998; Parkes *et al.*, 2000; Lipp *et al.*, 2008; D'Hondt *et al.*, 2009) — and are physically and chemically diverse. Energy and carbon cycling in the deep subseafloor biosphere are potentially important issues in solving global redox and carbon budgets; however, quantification of the magnitude and activity of this dark biosphere and its organic versus inorganic energy and carbon sources is difficult owing to a dearth of data concerning the nature of these deep ecosystems.

Fundamental questions that have far reaching consequences for life on Earth and beyond include: What is the nature and extent of life on Earth? What are the physio-chemical limits and the constraints of life on Earth? How metabolically active is the deep subseafloor biosphere and what are the most important redox processes? Are there exotic metabolic processes occurring? How are microbes dispersed in the deep subseafloor biosphere? How does life evolve in deeply buried geological deposits beneath the ocean floor? These questions are diverse and demand interdisciplinary research approaches in microbiology, molecular biology, geology, geochemistry, engineering, hydrology, and more. Research on the deep subseafloor biosphere has the potential to impact major current questions about energy creation, climate change, and the very nature of evolution of life on Earth.

Study of past life on Earth is concerned with emerging themes such as systems ecology and our understanding of the biotic response to major environmental forcing such as climate change and geologic events. What are the critical terrestrial-marine connections across shelf-basin transects at continental margins? How do ecosystems influence and respond to their environment on different timescales, including critical extreme events in Earth history? To understand past biotic ecosystems and their responses to environmental change, it is critical to evaluate ecosystems fully within their paleogeographic context. Processes of evolution can be revealed by analysis of high-resolution records of speciation and extinction and can reveal information about processes that generate and destroy biodiversity.

These topics and considerations can be considered along four major themes concerning extant and past life on the planet: activity, extent, limits, and evolution.

4.1 Activity of Life on the Planet

Understanding of the activity of life on Earth relates principally to revealing the role that extant microbiological ecosystems in the deep biosphere play in major biogeochemical cycles. Subseafloor microbial processes exert fundamental influence on the biogeochemistry of the ocean and atmosphere. For example, sulfate reduction coupled to metal sulfide (*e.g.*, pyrite) precipitation in sediments is a major sink of sulfate from the world ocean and potentially a significant source of ocean alkalinity on geological timescales (ka to Ma). Oxidation of organic carbon is a major source of dissolved inorganic carbon (DIC) to the ocean. Because the geographic distribution of organic carbon degradation, sulfate reduction, and sulfide precipitation is poorly quantified, the global effect of these coupled processes is not well known. As another example, water-rock weathering reactions in the ocean crust impose significant negative feedback on atmospheric CO_2, accounting for ~30% of the silicate drawdown globally. Microbes are known to promote these reactions in the laboratory and at the seafloor, but the degree to which they influence these processes *in situ* in the subseafloor remains unknown.

Despite our awareness at a rudimentary level that microbes exert fundamental influence on globally relevant processes, the extent of the subsurface biosphere, its influence on global biogeochemical cycles, and the relative importance of abiotic versus biotic processes remain unquantified and poorly understood. In most hard-rock oceanic environments, there are only very limited observations in many frontiers (*e.g.*, very young crust, peridotites, convergent margins). The biogeochemical cycles of carbon, nitrogen, other redox-sensitive elements, and many standard and non-traditional tracers of chemical and biological exchange and activity remain poorly quantified because of a lack of measurement apparatus and appropriate sampling. Rates of transport (advection versus diffusion) and the nature of exchanges remain unclear. It is now widely recognized that there is a blurring of the boundaries between inorganic and organic chemical and biological processes and this has wide ranging influences on the maturation of organic matter, the transport of trace elements by organic ligands, microbial diversity, and population stabilities. Establishing the frontiers of life in both sedimentary and lithospheric environments and the ecological roles that microbes play in biogeochemical cycles is paramount. The nature of this research requires careful sampling and storage protocols and the development of new methods to identify the biogeochemical agents operating.

The carbon cycle with its related redox budgets is a particularly important biogeochemical cycle operating in the Earth system; however, the linkages between the cycles of many important elements (*e.g.*, C and S, P and N) are poorly understood. Even the burial and maturation of organic carbon remain poorly quantified beyond the benthic boundary layer and earliest diagenesis. This precludes understanding and modeling of the deep subseafloor carbon cycle and quantification of rates of exchange with the oceans, hindering our understanding of nutrient and metal cycles and secular Earth's processes such as the rise of atmospheric oxygen. Related issues include the processes, budgets, and kinetics of organic matter degradation and the geophysical and geochemical constraints of methanogenesis and gas hydrate formation. Recent recognition of the importance of microbial activity in these processes exemplifies the need for further research. Key objectives include the quantification of organic matter turnover at different depth levels (0-10 m, 10-100 m, 100-1000 m) in both common and frontier environments to assess the fluxes of solids and solutes at these levels. The details of the chemical reactions and microbial processes controlling sedimentary turnover of organic carbon and the redox budget need to be understood and quantified.

The paradigm of the global carbon cycle, distilled to its most simplistic form, involves the net balance between photosynthesis (water column primary production), subseafloor microbial activities, and what escapes this efficient cycle via export from the upper ocean to deep subseafloor environments. As a first-order bookkeeping approach, this paradigm works well for establishing mass balances; however, the apparent success of such simplifications does not establish their adequacy as the magnitude and consequences of a viable and active deep subseafloor biosphere have not been considered. For example, estimates based on a few types of respiration rates suggest the occurrence of significant cycling of carbon in the subseafloor, but the balance between production and respiration is poorly constrained for solid implications to be inferred. The global redox state of the near Earth's surface (*i.e.*, atmosphere, oceans, and upper lithosphere) is also considered to be unbalanced; however, processes in the deep subseafloor biosphere, such as ocean crust alteration, remain largely unknown, with consequences for the evolution of both the near surface (atmosphere) and deep Earth (upper mantle).

Pore water chemical profiles in sediments of low productivity regions in the Pacific suggest a range of diffusive, advective, and diagenetic influences, including evidence for upward fluid seepage, sea-water intrusion, and flow along basaltic aquifers. The upward flux of electron acceptors may invoke a paradigm shift in our understanding of sediment biogeochemistry. For example, do autotrophic pathways play a much greater role in the generation of energy and biomass than is currently recognized? How open or closed are these ecosystems? We do not understand the basic plumbing of the subseafloor ocean or the mass transport processes that impact microbial communities and biogeochemical processes. Since most subseafloor microbial components are phylogenetically distinct from physiologically known isolates (Fig. 4.1), novel biogeochemical processes and metabolic pathways may also exist in the deep biosphere.

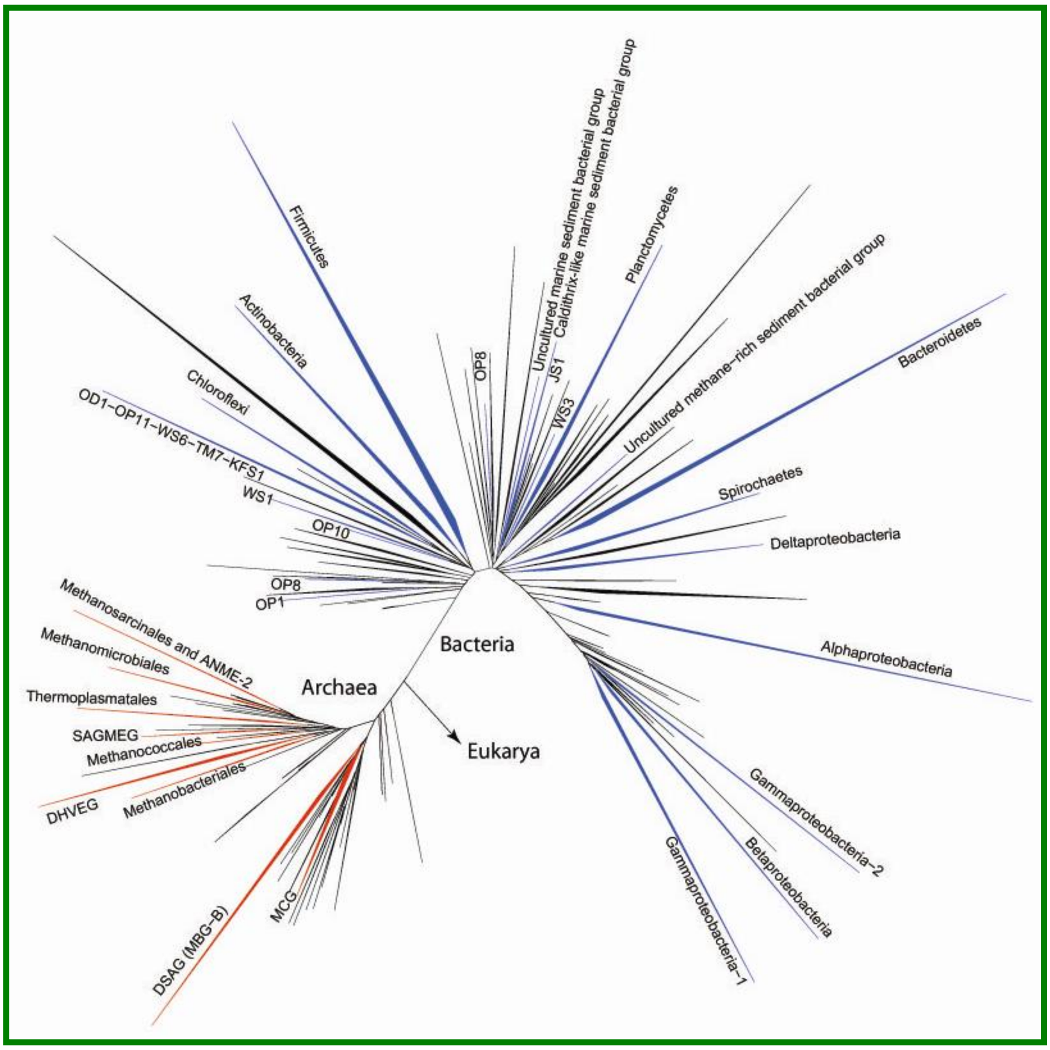

Figure 4.1 Phylogenetic tree of Archaea and Bacteria based on 16S rRNA gene sequences (from Inagaki, 2010). The red and blue branches represent archaeal and bacterial phyla, respectively, and include sequences frequently detected from the deep subseafloor biosphere.

Although some important elemental fluxes have been measured in a few areas of the oceans, we still lack global coverage even at the level of sampling and making measurements across a suite of core reference sites. There is pronounced variability in space and time that needs to be captured. The relationship between extant microbial ecosystems and past oceanic or geological processes has not yet been addressed in previous studies from scientific drilling. For example: How does the modern and/or past deep subseafloor biosphere vary with glacial-interglacial and lithological changes? Are there changes in past ocean chemistry that drive current microbial populations? What is the coupling between extant microbial communities and past sedimentary events such as Cretaceous black shales? Without information on the extent, limits, and biogeochemical processes occurring in the deep subseafloor biosphere, conceptual models cannot be developed and expanded holistically to quantitative models. This is critically necessary to develop true predictions about the consequence of biogeochemical activity in the deep subseafloor biosphere and the role microbes play in global sulfur, carbon, iron, and other biogeochemical cycles.

During the INVEST meeting, it was also noted that the potential influence of the deep subseafloor biosphere, which may play a role in global biogeochemical processes, is one of the most provocative concepts in ocean drilling today; this is a topic that should be exploited for education, outreach, and ocean literacy campaigns in the next ocean drilling program.

4.2 Extent of Life on Earth

Discussions relating to the extent of life on Earth were considered for both extant subseafloor ecosystems and paleoecosystems. Here we address these discussions separately but note that groups also discussed that the linkages between the extant biosphere and paleoecosystems are largely unknown and have not previously been addressed in scientific ocean drilling. There are large and unaddressed questions regarding ecology in the past and microbial life in the present as they relate to the carbon and nutrient cycles and microbial biogeography.

4.2.1 Paleoecosystems – biodiversity and biogeography

Major hypotheses relating to paleoecosystems present challenging topics that need to be addressed in the next phase of scientific ocean drilling. Of timely topical relevance is the issue of resolving the planetary-scale biotic response to global change – both in terms of biogeography and biodiversity. It remains unclear what climate feedbacks should be used in concert with other geochemical proxies to address issues of biodiversity and biogeography as they relate to global change. The biotic feedbacks that may affect climate are poorly constrained; what types of data are needed and what are the proxies? Model systems must be developed in order to understand how organisms respond to global change. Furthermore, developing an understanding of the biotic response to global climate change will provide new insights to the nature and dimensions of climate forcing and the response of the biosphere. This will have important societal consequences that should be actively promoted in the new scientific ocean drilling program.

In addition to studying paleoecosystems in the context of climate change, other environmental factors can be examined and revealed through ocean drilling. Responses to tectonics-driven events such as the development of gateways, circulation changes, *etc.*, need all be examined in the context of extinction and radiation of paleoecosystems.

Fossils recovered from deep-sea sections are typically abundant and diverse, providing an exceptionally complete record that is unparalleled from any other environment (*e.g.*, terrestrial realm). Ultra-high-resolution sampling is needed for all timescales to study processes and response of ecosystems to environmental change. Despite the potential for exceptionally complete records, the spatial distribution of paleoecosystems recovered by ocean drilling is incomplete and patchy. Complete records are lacking in many key regions, among specific taxal groups, as well as specific time intervals *(e.g.,* the early Paleocene biosiliceous record).

4.2.2 The deep subsurface biosphere - biogeography and dispersal

We are now aware that there is a deep subseafloor biosphere — intra-terrestrial microbial life that represents a significant biomass in sediments and rock below the ocean floor. The biogeography of microbes and how they are transported and dispersed in the deep subseafloor biosphere remain intriguing problems that speak to the most fundamental questions in microbiology, *e.g.*, the Baas-Becking hypothesis that *"Everything is everywhere, but, the environment selects"* (Bass-Becking, 1934).

Tremendous volumes of seawater infiltrate the ocean crust where it outcrops at the seafloor; hence, seawater is likely a source of inoculums 'seeding' subseafloor biomes. The transport time for fluid to travel through different crustal aquifers varies enormously, as do the physical and chemical conditions of these fluids and any microbiological components they carry. Deep-sea sediments remain in exchange with seawater via the overlying water column and deep crustal aquifers. Questions that need to be addressed include: What microbes take seed and why? What are the most significant physical and chemical controls for adaptation to different environmental regimes? How similar or different are the seawater-driven crustal and sedimentary ecosystems from indigenous deep subseafloor ecosystems? It is hypothesized that geochemical and physical conditions will shape the patterns of archaeal and bacterial diversity (Inagaki *et al.,* 2006; Parkes *et al.,* 2005), but too few sites have been examined to resolve this major question. Drilling objectives that get at questions of biogeography in the deep subseafloor biosphere should be a cornerstone component of the new scientific drilling program.

Although we recognize the pervasiveness of fluid-flow on a global basis, on a more regional scale (*e.g.*, within a biome) the degree of hydrological connectivity and hydrothermal vigor is poorly constrained. This fundamentally limits our ability to understand mechanisms of dispersal and patterns of biogeography in the subsurface. Hence, the future scientific drilling program must develop coherent interdisciplinary projects in which hydrological studies are conducted in concert with microbiological and biogeochemical experiments, such as the expedition currently being planned at Juan de Fuca that includes borehole observatories for multidisciplinary purposes.

Deep-biosphere studies in future scientific ocean drilling also need to address microbial taxa that have thus far nearly wholly been ignored – viruses and microbial eukaryotes. To address the question of the extent of life and the nature of biomes, it is critical that we consider all microbial life comprehensively and not exclude taxa that like in the other environments (*e.g.*, water column), play critical roles in the diversity of extant ecosystems and subseafloor food webs. As noted above, we do not yet know the extent of *de novo* synthesis of cellular matter in the deep subseafloor biosphere via chemosynthesis, but we also do not understand the other end member in this process – the recycling of cellular matter for maintenance and/or growth of living microbial components. Also, it is currently unknown how viruses or other molecular interactions contribute to lateral gene transfer and subsequent functional mutations in the deep subseafloor biosphere. Studies of viruses and protists will gain insights on these processes.

Integrative and cross-comparative studies at multiple sites are critically needed to understand biogeography and transport of microbes in the deep biosphere as these fundamentally vary with the environmental setting. For example, comparisons between deeply buried sediment communities that are in similar carbon/nutrient regimes or comparisons between ocean crust and overlying sedimentary biomes are necessary. The new scientific drilling program should encourage cross-comparisons so that critical global and regional issues relating to biogeography and dispersal in the deep subseafloor biosphere can be resolved.

4.3 Limits of Life in the Deep Subseafloor Biosphere

During the INVEST meeting, 'extreme life' was discussed from both the paleoecological and the extant life perspective. On the paleoecological front, extreme events were considered for their role in driving ecosystem responses and records. As these responses were discussed mainly from an evolutionary perspective they will be discussed in the next section. For extant life, the extremes of life were considered in terms of how current extreme geophysical and geochemical constraints impact the physiological state of life and how they limit microbial habitat and activity in the deep biosphere.

The fundamental factors that limit the existence and diversity of life within seafloor sediments and ocean crust are poorly explored, both theoretically or via drilling. High temperature is commonly thought to be a critical limitation in many areas, although the impact of temperature on the distribution of life is likely to be convolved with other factors such as depth (pressure), energy-yielding chemical reactions, and fluid-flow, which have not been explored. For example, survival at high temperatures may depend on the capacity of organisms to repair the damage caused by thermal and radical degradations of cellular components. Thus, it may be possible for microbes to temporarily exist or survive in nutrient- and energy-rich conditions, even at temperatures exceeding the limit of cell growth. Most sedimentary subseafloor environments exhibit relatively low thermal gradients (~30°C per km); hence, defining the boundary between abiotic and biotic realms will require sensitive and objective technology able to detect subtle changes in biomass and activity. The highest temperature recorded for cell growth is 122°C at 20 MPa (Takai *et al.,* 2008), which is exceeded at shallow depths in certain sediment-covered ridge flank hydrothermal circulation systems, such as at the Juan de Fuca, Okinawa Trough, and Guaymas Basin. Drilling along a temperature gradient in deeply buried, organic-rich sediments, where the availability of organic carbon and nitrogen should not be a crucial limiting factor, will enable us to answer questions relating to the thermal limits of active life forms in the future scientific drilling program.

In terms of the balance and constraints of nutrients and energy in the deep subseafloor biosphere, availability of electron donors may more positively limit the microbial population and metabolic activities than electron acceptors. In sediments, buried organic matter produced during photosynthesis in the surface ocean is the primary source of electron donors for microbial respiration (D'Hondt *et al.,* 2002; 2004; Lipp *et al.,* 2008). For example, in the South Pacific Gyre, where the burial rate of organic matter is two orders of magnitude lower than in other regions that have previously been explored for life in subseafloor sediments, analyses of shallow cores revealed that only 10^3–10^4 cells cm^{-3} are present in the sediments. The net rate of respiration is one to three orders of magnitude lower than rates at previously explored sites, even though there are electron acceptors (such as dissolved oxygen and nitrate) present in the porewater (D'Hondt *et al.,* 2009) (Fig. 4.2). If the low concentration of bio-available organic matter as a carbon source and/or electron donor ultimately sets one of the limits for microbial population and activity in marine subsurface sediments, metabolically active cells may be absent or nearly absent in deeper sediments. If hydrogen production via radiolysis of porewater can sustain a certain population in such organic-poor deep habitats, the conceivable metabolic pathways will be either chemolithoautotrophic or mixo-trophic. Different unknown factors are likely to define the ultimate limitation to life in the subseafloor biosphere. In the young (approximately <10 Ma) crustal biosphere, chemical reactions between reduced ocean crust and oxidants in seawater-derived circulation fluids are considered to supply energy (*e.g.*, H_2, reduced iron) and carbon (CO_2) substrates to sustain chemolithoautotrohpic microbial community (Bach and Edwards, 2003); hence, sources of metabolic energy may not be a crucial limiting factor in subseafloor crustal environments. On the other hand, it remains to be determined if all upper ocean crust at temperatures below ~120°C can harbor metabolically active microbial communities based on the constraint of crustal age and fluid circulation. To address this globally significant fundamental issue, it is critically necessary to span nearly the entire age range of ocean crustal environments in the future scientific drilling program.

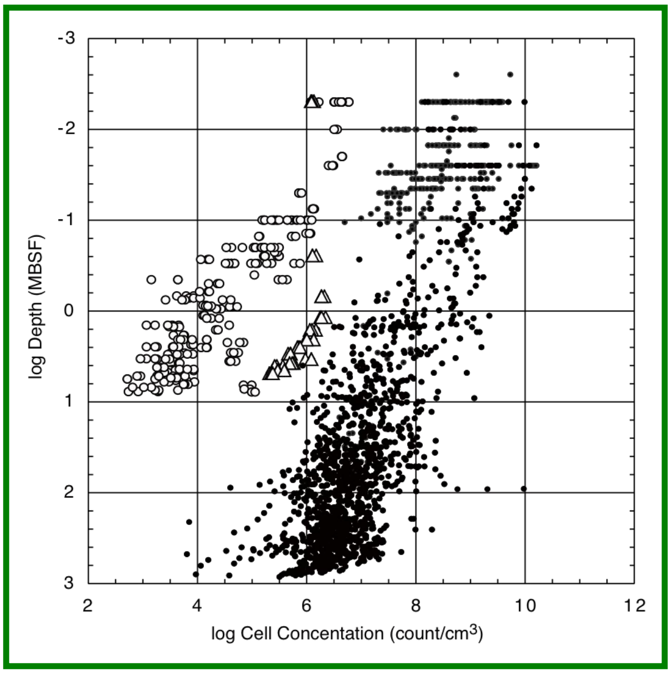

Figure 4.2 Cell abundance in subseafloor sediments (D'Hondt *et al.*, 2009). Data marked by open circles and triangles are derived from sediments in the South Pacific Gyre where surface photosynthetic production is significantly low. Data marked by black circles are from acridine orange direct count (AODC) by Parkes *et al.* (2000; 2005).

In addition to field observations, unraveling the limitations on growth and existence in the subseafloor will require contributions from both *in situ* and shore-based laboratory experiments combined with theoretical approaches (*e.g.*, thermodynamic calculation). The experimental and theoretical studies of chemical reaction rates and microbial energy requirements will provide constraints on the balance between supply and demand of sustainable energy in subseafloor environments. Questions about the role of pH, pressure, and physical parameters on limiting deep subseafloor life may similarly be augmented in this way. The new scientific drilling program should encourage the development of new insights into the defining drivers that affect the spatial distribution of active and surviving life forms in the subseafloor, which will significantly expand our knowledge of the extent of biogeochemical consequences for our planet and the evolution of life.

4.4 Evolution and Survival of Life on Earth

4.4.1 Buried alive

The subseafloor as a habitat presents challenges to life that are distinct from most other known environments on Earth. This raises questions of how microbes survive in the face of these challenges and what evolutionary forces are at work in the deep subseafloor biosphere.

The question of persistence of life from the perspective of metabolic processes and growth can be distilled to the concept of survival at the edge of bioenergetics and redox processes (Hoehler, 2004; Price and Sowers, 2004) (Fig. 4.3). The metabolic rates proposed for subsurface microbes (pmol cm^{-3} day^{-1}) are up to nine orders of magnitude below respiration rates observed in microbial cultures (mmol cm^{-3} day^{-1}) and in environmental microbes in surface sediments (mmol cm^{-3} day^{-1}), and are the challenge of our current understanding of the functioning of life (*i.e.*, having enough energy to maintain charge potential across a cell membrane). Observations of living cells with intact polar membrane lipids lead to the inference that subseafloor sedimentary microbes must persist at extremely low rates of activity per cell. Additionally, previous culture-independent molecular studies have shown that the subseafloor hosts extremely unique microbial communities that are distinct from surface habitats (Inagaki *et al.,* 2006; Biddle *et al.,* 2008). Why are these microbial components so prevalent in the subsurface? Are there distinct adaptations that are common to the subseafloor biosphere?

Questions regarding evolution and the interplay between paleoecological biotic responses and extant microbiological ecosystem properties should be addressed in the next phase of scientific ocean drilling. For example, as siliceous plankton evolved were there parallel changes in subseafloor microbial communities? Since most subsurface microbes are recalcitrant to cultivation, answers to questions about their adaptation, evolution, and survival need to be answered through improved molecular and biogeochemical analyses. Genetic-based studies of the deep subseafloor biosphere to date have used targeted polymerase-chain reaction (PCR) based approaches to examine phylogenetic genes and, on occasion, 16S ribosomal ribonucleic acid (rRNA) gene sequencing and analysis have been performed. More rarely, PCR-based approaches for looking at functional genes encoding for important biogeochemical processes (methanogenesis, sulfate reduction, *etc.*) have been targeted; however, research concerning questions about survival and evolution in the subseafloor has not yet emerged among the core foci in subseafloor biosphere studies, nor have research approaches that take a broader-scale view of the genetic content of microbes buried beneath the seafloor.

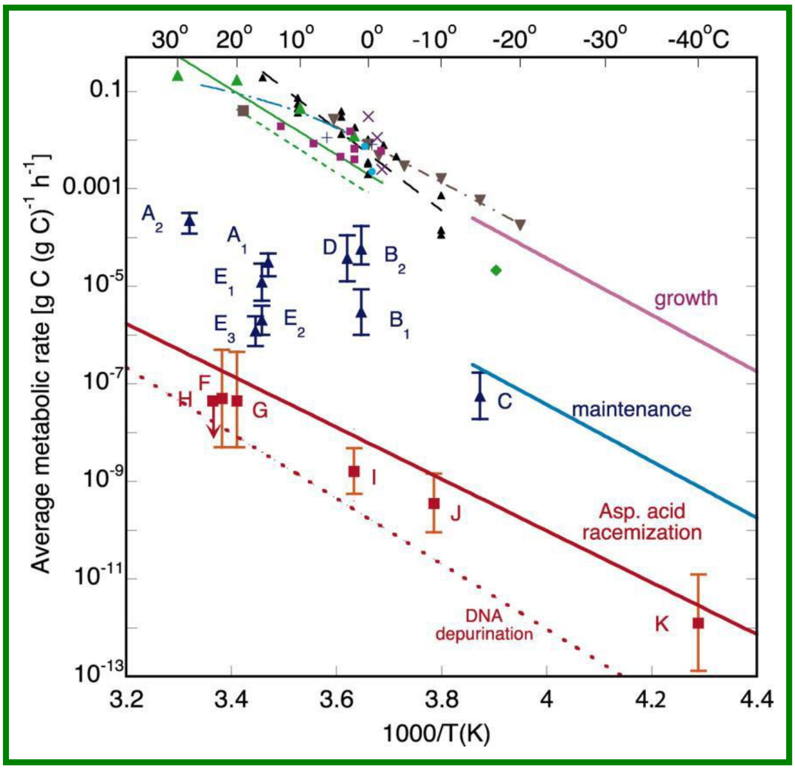

Figure 4.3 Carbon-metabolic rates of microbes as a function of temperature in various natural ecosystems. Points in the top group, labeled 'growth' and these labeled with letters A to K in the middle and bottom groups are specifically keyed in Price and Sowers, 2004. Lines at the bottom are extrapolated from rates of racemization of aspartic acid (solid line) and rates of DNA depurination (dashed line), both measured at high temperature. Plots E_1, E_2, E_3 represent the anaerobic respiration rates of bacteria in marine sediments from the Peru Margin (from Parkes *et al.*, 1990).Plot I represents *in situ* assessment of the metabolic activity of sulfate reducers and methanogens in marine sediments down to several hundred meters below sea floor (from D'Hondt *et al.*, 2002), showing the generally extremely low activities that maintain life function. Figure from Price and Sowers, 2004.

Through future explorations by scientific ocean drilling, the need to compare and contrast different sites through examining the total gene content of the deep subseafloor biosphere using metagenomics-based approaches should be achieved. The term 'metagenomics' includes a variety of whole-genome approaches such as shot-gun sequencing, vector-based library tools, whole-genome amplifications, and other specialized methods. Deep-biosphere studies in the new drilling program should embrace new cutting-edge technologies for gaining insights into the functional context for phylogenetically identified microbial components.

Our first glimpse at using metagenomics in the deep subseafloor biosphere illustrates its potential power to answer evolutionary questions (Biddle *et al.,* 2008). As part of the initial census of life in subseafloor sediments, it has emerged that cell abundances generally decrease logarithmically with depth (Parkes *et al.,* 1994; 2000) (Fig. 4.2). A consequence of this decrease is that with depth, microbes become increasingly isolated from each other owing to the fact that chemical exchange in sediments is dictated by diffusion, which operates slowly over long distances. Hence, we may hypothesize that an evolutionary consequence of this increasing isolation may be the loss of genes for functions such as chemotaxis and quorum sensing, which may not be needed as cells become isolated. Indeed, metagenomics surveys of sediments from the Peru Margin do show that genes for chemotaxis decrease with depth (Biddle *et al.,* 2008), hinting that further metagenomics surveys and cross-comparisons may yield exciting new insights about microbial evolution on Earth. These metagenomic trends need to be compared with other sites and in distinct biomes. For example, in the crust, where microbes exist in cracks, pores, and crevices through which seawater flows vigorously, there is less systematic isolation with depth. Comparisons across the range of crustal and sedimentary habitats may illuminate evolutionary trends that are a consequence of the increasing isolation of microbial cells. Are there systematic changes in gene content as a function of depth or distance from a spreading center? Are similar trends revealed in other oligotrophic sedimentary regimes? Are there significant differences in the ability for viruses and predators to attack between oligotrophic and carbon-rich sediments?

4.4.2 Evolution of life in the face of extreme events and other environmental forcings

Extreme environmental events and punctuated evolution can be defined as geologically rare intervals of rapid and transient environmental and/or biotic change that have a global significance. Discussions at INVEST focused on understanding the (paleo)ecosystems, the biotic response, and consequences of these events. Also considered was the correlation between marine and terrestrial ecosystems during these events.

Extreme events over Earth's history provide important reservoirs of information about ecosystem response to rapid environmental change. For example, the Cretaceous OAEs and LIPs, K/Pg boundary impact and Deccan Traps, Paleocene-Eocene hyperthermal events *(e.g.*, PETM), the North Atlantic volcanic province, the Eocene-Oligocene transition, and intervals of anomalous cosmic dust input (two spikes:E-O transition, Miocene). As not all biotic events (evolutionary events) are associated with extreme environmental conditions, some important evolutionary steps are thought to have occurred during intervals of environmental stability (Jr-K boundary, early Aptian OAE1a (OJP), Aptian-Albian).

How biota responds to episodic events, how ecosystems function during extreme conditions, how they recover, and how they survive transient conditional changes are open and important questions to address in the next scientific ocean drilling program. Why are recoveries different between different regimes and between different events? How do biotic systems recover from some events and adapt to the post-event environment, whereas other events lead to thresholds and a new equilibrium? Can the rate of change be too great for the system to adjust? Is there a role for genetic and/or functional records in the modern biota?

The role of environmental change in biotic evolution remains an important open question. Resolution of this question may yield insights relevant to understanding and anticipating biotic responses to current rapid climate change. For example, why do different organisms respond differently to rapid environmental change? For example, planktonic *vs.* benthic, carbonate *vs.* siliceous, and primary producers *vs.* zooplankton exhibited fundamental differences in response during the K/Pg boundary crisis. Moreover, some originations occur under stable conditions rather than extreme events. During OAEs organisms start to change well before the major record of environmental change (thresholds). What is the trigger for changes during stable environments?

Impact events should also be examined as a cause for significant biotic compositional change. Is there a kill curve for these events (*e.g.*, K/Pg *vs.* Eocene)? These studies should be compared with other large impact events in order to understand how the surface and subsurface biospheres responded. LIPs are also of major interest and need to be studied for any direct evidence for related environmental stress reflected in biota (*e.g.*, by CO_2 + SO_x release, warming or cooling, effects on ocean chemistry such as poisoning by trace metals). Are there thresholds leading to evolutionary response and what are the ecological-evolutionary feedbacks?

4.5 Science Strategies

4.5.1 Archiving samples for microbiological and biogeochemical analyses

Having a reservoir of archived samples for microbiological and biogeochemical studies, so called 'bio-archives', represents tremendous value to the scientific community, especially for global biomass and molecular surveys at various oceanographic conditions and depths, as intensively discussed during the INVEST meeting. During the more than half century of scientific ocean drilling, most core samples have been stored at room temperature or 4°C in an open storage room without regard to possible contamination and alteration. Long-term storage under these conditions causes significant contamination through growth of microbes and also damages the small amounts of fragile biomolecules in the cores. Over the years there has been a number of task forces formed to make recommendations to IODP concerning sampling and archival of microbiological material (D'Hondt *et al.,* 2007). Recently a technique using a diamond-tip band saw system was developed that enables sub-sampling of requested frozen core material without melting (Masui *et al.,* 2009). As a result of the rapid technological and analytical developments in the life sciences, the INVEST participants again reiterate the recommendations for taking bio-archive samples for this community. The implementation of task force recommendations has yet to be fully realized, although deep-frozen (<–80°C) storage of whole round core and/or sub-core samples taken by 30 cc tip-cut sterilized syringes now occurs. INVEST participants highly recommended that deep-frozen bio-archiving is not enough and that storage under multiple conditions for different analytical uses, such as paraformaldehyde-fixed slurries for microscopic molecular analyses (*e.g.*, FISH) and anaerobic fresh sediments stored at 4°C for activity analyses (*e.g.*, advanced tracer experiments, enzymatic activity), is necessary for the future scientific ocean drilling program. To implement collection of bio-archive samples it is recommended that at minimum a staff scientist with appropriate background and training be onboard all expeditions to take and preserve bio-archive samples under appropriate conditions. Furthermore, the core repositories should have the curatorial and storage capacity for these bio-archives.

4.5.2 Arrays of environments

Individual expeditions will contribute to the important deep biosphere objectives of the drilling program; however, nearly all major questions will require multiple expeditions to fully address. For example, does the deep biosphere have connectivity in terms of population, activity, diversity, and metabolic function? If there is a thermal limit to life, does it vary with other parameters such as depth (pressure) or energy constraints?

In general we need to cover a far more diverse range of deep subsurface environments that embody the wide range of temperature, pressure, geochemical, and geological conditions found at the ocean floor. Previous microbiology-dedicated (or – integrated) drilling expeditions have almost entirely focused on continental margins, with the Eastern Equatorial Pacific sites drilled during Leg 201 being the notable exception. We need more transects across oceanic provinces that cover the ranges of conditions to study the limits of life (*e.g.*, 'biocline').

To address habitability in igneous ocean crust and the overlying sediment as a function of temperature, crustal age, and hydrological regime requires transects be drilled on ridge flanks and accretionary wedges that span different ages and geological/hydrological regimes. Such systems would also enable us to answer questions regarding the connectivity or isolation of biomes along a transect.

Transects that further address the issue of energy availability will be important in the new drilling program. For example, examining the diversity and activity of microbial life across the shelf environment from estuaries to the deep sea would specifically address major changes in energy sources along such a transect. This would also add to the little knowledge we now have about the deep subseafloor biosphere. We need sufficient numbers of sites to be able to confidently determine 'average' rates of global biogeochemical processes. Transects or areas that should be drilled in the future ocean drilling program are:

⇒ Shelf-to-basin biodiversity and productivity transects; terrestrial-marine communities

⇒ High deposition rates (*e.g.*, ancient drifts, continental margins)

4.5.3 Model observations to extrapolate data

Estimation of microbial biomass and metabolic activity in sediments and the underlying basement and their role in global biogeochemical cycles will heavily rely on combining observations (*e.g.*, *in situ* rate measurements) and modeling. Geochemical thermodynamics calculations can provide estimates of the free energies available for a large range of metabolic reactions. These calculations can be used to look for specific metabolic pathways in different environments. Estimates of free energy for catabolism (energy-yielding metabolism) can also be used to estimate the amount of biomass that may be supported by different redox reactions known to proceed at exceedingly low rates unless they are enzymatically catalized. This can be achieved either by using a free-energy dissipation approach (*i.e.*, empirical relations between energy availability and carbon fixation, which is primarily a function of the nature of the carbon source and electron donor) or by tying it directly to the energy requirements for ATP production or overall biosynthesis (anabolism).

Further development of this modeling approach critically relies on the availability of *in situ* measurements of the activity of critical chemical species (*e.g.*, acetate, dihydrogen), rates of catabolic reactions, and rates of carbon fixation. Such combined measurements are most likely to be achieved in instrumented boreholes, which offer additional opportunities summarized in section 4.5.5.

4.5.4 High-resolution sampling and analyses for microbiology and biogeochemistry

Previous microbiological and biogeochemical studies demonstrate that subseafloor microbes proliferate in narrow niches at geological or geochemical interfaces such as volcanic ash layers (Inagaki *et al.,* 2003) or sulfate-methane transition zones (Parkes *et al.,* 2005; Sørensen and Teske 2006), suggesting that high-resolution sampling is necessary to capture potential active microbial habitats within small niches in the recovered core samples. During the INVEST meeting, it was intensively argued that ultrahigh-resolution analysis is essential to better understand past climate and sea-level change, as well as correlation among paleontological records. Paleo- and modern ecosystems within the subseafloor biosphere were also a major focus of discussion. During previous and current IODP expeditions, most microbiological samples were taken as whole round core (WRC) without splitting; therefore, the sedimentological, paleontological, and lithological characteristics of the samples have been largely dismissed. If subseafloor microbial communities are very sensitive to local paths of fluid-flow that transport available energy and nutrients, the nature of subseafloor microbial habitat and activity distribution may be complex. Hence, high-resolution sampling for microbiological and biogeochemical analyses of fine-scale microhabitats will be required in the future scientific ocean drilling program. Indeed, non-destructive X-ray CT-scans of sediment cores on *Chikyu* revealed that lithological and mineralogical features such as micro-faults and pyrite formation are more complicated than previously expected based on visual inspections or multi-sensor core logger (MSCL) data, suggesting that modern or past microbial communities may inhabit these microhabitats and contribute to mineral diagenesis and/or biogeochemical reactions. High-resolution microbiological sampling is also of great benefit for capturing subseafloor life within micro-fractures and veins in crustal rocks. Recent progress in molecular and isotopic technologies enables study of microbial diversity and function at single-cell levels (Biddle *et al.*, 2006; Behrens *et al.,* 2008; Musat *et al.,* 2008), for which only a small volume of sample is required. To analyze microhabitats through high-resolution sampling, technological improvements and effective onboard sampling strategies combined with non-destructive scanning tools are highly recommended for the future scientific ocean drilling program.

4.5.5 Drilling observatories

The use of CORK observatories for study of the deep biosphere represents a powerful and only recently exploited means of studying microorganisms *in situ* within the deep biosphere. Of fundamental importance to understanding the deep biosphere is studying microorganisms in their native state. Pioneered as part of Expedition 301 on the Juan de Fuca, the use and development of increasingly sophisticated technological for CORK observatories for study of hard rock hosted microbial communities in their native state is on the rise and is planned for many new drilling expeditions. This will continue in the future and provide transformative advances as part of the new drilling program. Importantly, CORK observatory technologies are constantly and rapidly changing, and have not yet come to realize their full potential – for example, as a tool for biogeochemical activity assays. The advancement of CORK and experimental technologies requires appropriate resources (including time and labor) allocated for hardware and instrumentation development. New methods also need significant time and investment to develop. For example, biogeochemical activity assays have not been conducted in hard-rock environments. CORK observatories could potentially fill this gap in our analytical abilities, but methods would need to be developed and would involve significant pre-cruise preparation for an expedition. The effective use of CORK observatories for accomplishing deep biosphere drilling goals involves significant lead time and preparation for method development, infrastructure and instrumentation development, and coordination between disparate disciplinary groups. This represents a departure from the normal mode of IODP post-cruise scientific analysis operations and should be a major effort in the new drilling program.

It was also noted that observatories are not yet fully used for study of microbiological communities in sedimentary environments. Active experimentation in sedimentary systems represents a major untapped area of exciting new research that could be used for studying biogeochemical processes *in-situ* in sedimentary environments similar to how they are now used for microbiological hard-rock studies. For example, a few CORK boreholes in sedimentary environments (*e.g.*, the south Chamorro serpentine seamount in the Mariana forearc, fault-associated borehole in the Nankai Trough accretionary prism) will enable more microbiological and biogeochemical studies. In addition, the riser-drilling system will permit drilling of high-pressure hydrocarbon sources beneath BSRs or evaporite-salt layers; these regions have been impossible to drill using a non-riser system because of safety issues. Boreholes in these high gas/fluid-flux environments will be highly useful for microbiological and biogeochemical studies. These should be developed as a new frontier within the next scientific drilling program.

4.5.6 Site characterization

Site characterization typically takes the form of mapping, seismic surveys, and perhaps heat-flow measurements. To study very deep environments using riser drilling by *Chikyu*, detailed three-dimensional seismic surveys are highly recommended. Furthermore, to deploy riser pipe and the blowout preventer (BOP), the drill site must be tested for strength and cleared of potential safety hazards. In microbiology-motivated programs, site surveys also need to include pre-drilling and/or seafloor surveys using remotely operated vehicles (ROVs) for initial characterization of the microbial community and hydrological regime (*e.g.*, seawater recharge and discharge zones) associated with the site of interest. This can be accomplished through geochemical and biological analyses of fluids and sediment cores obtained by gravity coring, push coring, or multi-coring. These data provide critical information about the sediment-water interface and microbial community, which enables interpretation of the biomes in a broader context.

Increasingly large, multidisciplinary groups are assembling to conduct site surveys in a truly comprehensive fashion, yet they face challenges in raising support due to the high program costs and the long lead time (pre-deep drilling) that make the justifications within national funding agencies challenging. The next drilling program needs to consider these challenges to investigators and consider alternate means of supporting site characterization expeditions.

5 Earth-Human-Earth Interactions

Mankind and civilizations have always been threatened by geological hazards. Some are invariably linked to the oceans and to physical processes that act on the ocean floor and within the oceanic lithosphere. These hazards, namely earthquakes and submarine slope failures, are natural and their incidence is based on self-organized criticality of mechanical systems and processes within the Earth. Earthquakes, submarine slope failures, and tsunamis pose a major threat to coastal communities that are home to over sixty percent of mankind and also the location of a large proportion of major industrial installations, increasingly including offshore installations. Economic and population growth will increase the vulnerability of societies to these natural hazards. It is thus imperative that geoscientists adopt integrated approaches in order to: (1) better understand earthquake generation as a deep-Earth process; (2) investigate the causes, mechanics, consequences, and future likelihood of submarine slope failure; and (3) elucidate the consequences of these dynamics for tsunamis and other continental margin geohazards.

With population growth and ever increasing need for raw materials and energy, humans have fundamentally changed the interaction a biological species can have with the Earth system. Greenhouse gas concentrations in the atmosphere are increasing at a rate that might be without precedent in geological history and are about to become a major driver of changes in a multitude of surface processes on land, in the oceanic water column, and in the oceanic subseafloor environment worldwide. Among the most dramatic consequences are ocean acidification, the global rise in sea level, changes in the hydrological cycle, and the imminent release of large quantities of methane currently bound in gas hydrates on land and below the ocean floor. Scientific ocean drilling will play a key role in elucidating ecosystem response to such changes by using newly developed proxies. The approach will be 4-D reconstructions of past and more recent global changes by investigating geo-spatial transects with ultrahigh-resolution age control at human timescales. It is thought that a limited number of strategically chosen drill hole datasets can be used to calibrate numerical models and the results from modeling are in turn capable of constraining the optimum sites for drilling.

5.1 Geohazards - Characterizing Hazards

5.1.1 Earthquakes

Based on discussions at INVEST, a top priority for the new drilling program should be an earthquake and tsunami hazards program; this program can be combined with other onshore and offshore earthquake projects to provide key knowledge for hazard assessment and mitigation of earthquakes and tsunamis that have the potential to directly impact the majority of the world’s population. To achieve this goal we need to understand the nature of seismogenic and tsunamigenic faults and their dynamic behavior. The past decade has shown the scientific community that old models of only two types of failure, stick-slip and creep, are incorrect. We now recognize slow-slip events, very low frequency earthquakes, and tsunami earthquakes that all are a part of the stress-strain cycle (Fig. 5.1) (Rogers and Dragert, 2003; Obara *et al*., 2004).

The breakout group on Earthquake geohazards identified five major themes and unanswered questions for hazard assessment and mitigation of earthquakes and tsunamis:

⇒ What is the nature of large-slip zones in earthquakes?

In order to study the nature of large-slip zones in earthquakes, drilling is required to contrast the physical properties of fault zones in slip versus non-slip regions. These need to be compared at the same pressure-temperature condition. Investigating slow-slip/tremor regions may provide key information for understanding fault properties that control slip.

Strategies for examining these societally relevant processes include sampling and *in situ* access to faults, geodetic instrumentation, and rapid-response drilling. Geodetic studies of fault zones should be a strategic combination of downhole monitoring and seafloor to land-based networks. Rapid-response drilling should target an earthquake-rupture zone within a few years of the event to examine temperature at the slip zone (if accessible) and transients such as seismic velocity, chemistry, and post-seismic deformation. These strategies require a mix of deep (at or close to a large slip zone) and

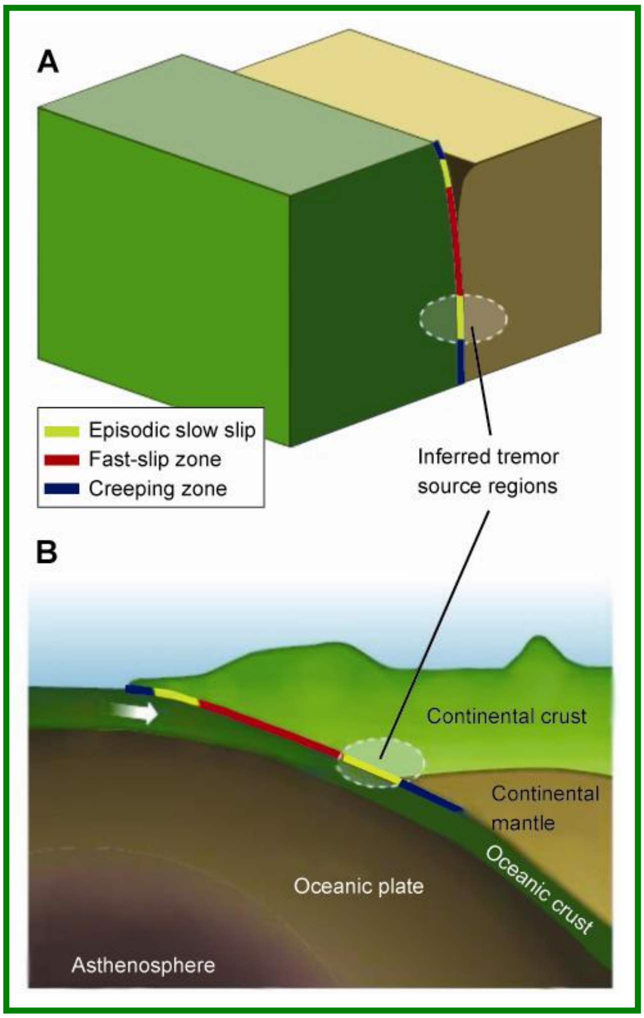

Figure 5.1 Locations of brittle fast-slip (seismogenic) and slow-slip zones: (A) Vertical strike-slip fault; (B) Subduction-zone. The new paradigm in earthquakes includes not only classically understood locked zones that break in fast slip producing earthquakes and adjacent creeping zones that nearly continuously deform without generating earthquakes, but also faults with episodic slow-slip zones that produce tremors. Additionally some subduction zones generate tsunami earthquakes that produce inordinately large tsunamis compared to the size of the earthquake (from Kanamori, 2008)

shallow boreholes and, to capture the range of deformation and the hazards implications, a major seafloor/land observatory program (Fig. 5.2). The breakout participants suggested the strategy of combining the new drilling program's geohazards and observatory efforts with other major programs and facilities such as EarthScope, the Dense Oceanfloor Network System for Earthquakes and Tsunamis (DONET), Neptune, and the European Seas Observatory Network (ESONET).

⇒ What controls the size of earthquakes? Are very large destructive earthquakes governed by the same processes as small earthquakes?

The related questions of what controls the size of an earthquake and whether large, destructive events are governed by the same processes as smaller events are vital to examine when considering human and financial risk. The breakout participants suggested that drilling is required to study these processes through three types of observatories/subseafloor experiments. The most provocative of these is to directly attempt to trigger a moment magnitude (M_w) 5-6 earthquake in an oceanic transform (which lies well away from any populations and would have a limited maximum size) using water injection. An allied strategy at the experiment site as well as at active earthquake zones is to assemble surface and subsurface geodetic experiments to monitor stress distribution and strain accumulation and release. These observatories and borehole seismometers and tiltmeters could aid in 4D monitoring of fault properties. These experiments require downhole pressure control from a riser or Riserless Mud Recovery (RMR) system, observatories in and around the borehole, and a strong link to the non-marine earthquake (geodetic and seismologic) community and ongoing experiments.

⇒ What are the characteristics of the earthquake repeat cycle?

Hazard assessment for earthquakes is governed by the likelihood of an event of damaging magnitude to happen in a given location. To consider this applied question, we must research the Earth processes that control the characteristics of the earthquake repeat cycle. This can be determined best by examining event stratigraphy of past earthquakes through turbidities, drowned marshes, corals, or slope/forearc basins. By diagnosing earthquake-driven events we can examine whether the cycle is regular or irregular, whether there are longer repeat cycle timescales for M_w 9+ events, and the role of segments. A suggested strategy is to span a wide area with shallow holes across a segment boundary of a major slip zone, which requires riserless drilling for multiple shallow cores.

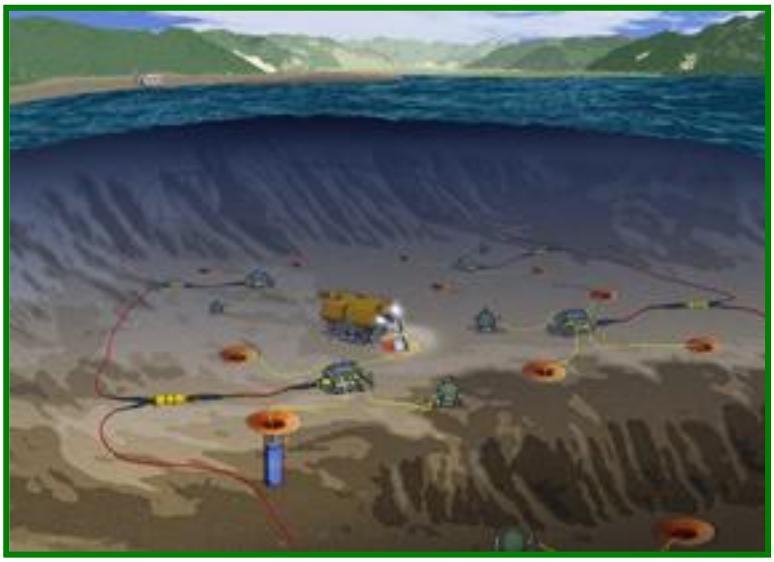

Figure 5.2 Artists rendition of a seafloor observatory to study plate deformation and geohazards (from Kaneda *et al.*, 2009)

- ⇒ What controls the range of tsunami efficiency generated by different earthquakes? What causes tsunami earthquakes?

Tsunamis are one of the most obvious and damaging effects of submarine earthquakes and have resulted in great loss of life from a natural hazard in modern history. Understanding controls on the range of tsunami efficiency generated by different earthquakes in different settings and the cause of so-called tsunami earthquakes is a first-rate science problem. To solve this we need to drill to: 1) study deformation characteristics of shallow, tsunamigenic fault zones; 2) determine rheologic properties of margin sediments overlying fault zone rupture areas; and 3) examine how fault zones and tsunamigenic-source regions behave during interseismic periods and whether elastic strain can accumulate in shallow regions. Strategies include sampling and logging tsunamigenic fault zones and the overlying and surrounding lithologies and borehole monitoring to examine deformation behavior in the interseismic (or post-seismic) period. These goals require mostly riserless drilling and multiple cored and logged holes of moderate depth; a strong link with the tsunami modeling community is vital.

- ⇒ Are earthquakes on different types of faults (*e.g.*, subduction megathrusts *vs.* plate-boundary strike-slip faults) fundamentally the same or different?

Damaging earthquakes are not limited to subduction zones alone. Therefore the breakout group suggested the new program should also target drilling in either strike-slip faults or normal faults that can be compared with the long history of ODP and IODP drilling into subduction thrusts as well as to onshore fault drilling studies. Strategies to study these include sampling, collecting *in situ* measurements, and geodetic and seismic monitoring. Drilling should span a wide area with shallow holes to study the stratigraphic record of seismic/tsunami events and long-term fault processes. This theme would benefit from a mix of deep and shallow boreholes and an integrated land-sea observatory program.

The breakout group concluded their discussion by highlighting the major research priorities for the first five years of scientific ocean drilling in the new program. These include: (1) tying deeper holes to offshore networks that are being developed as part of Themes 1 and 2; (2) capturing a range of slip events with observatory boreholes in keeping with Themes 1, 2, and 4; (3) drilling targeted deep hole(s) for understanding the nature of large-slip and non-slip zones (Theme 1); (4) drilling multiple shallow targets to reveal longer records of the earthquake cycle (Theme 3) and to elucidate tsunamigenic processes (Theme 4); (5) drilling different types of faults besides subduction thrusts (Theme 5); and (6) conducting a triggered earthquake experiment at an oceanic transform fault if feasible.

5.1.2 Submarine slides

Submarine landslides occur at a wide range of scales and settings. They often comprise distinctive mass transport deposits recognized on the seafloor or in seismic reflection profiles. Small-scale submarine landslides are relatively frequent. They have displaced oil rigs, damaged pipelines, broken deep-sea communication cables, and devastated segments of coastline. Both large and small slide events along coastal zones can create local, destructive tsunamis. In addition to documented past damage, future submarine landslides threaten vital parts of the highly connected and developed modern civilization by loss of communications (internet) and pollution from damaged offshore hydrocarbon production facilities.

A range of conditions and triggers has been implicated in the initiation of submarine landslides (Masson *et al.*, 2006). Earthquake-generated landslides are well known, resulting in a tsunami threat much larger than that predicted for the earthquake. In a recent example more than 1,600 people lost their lives in 1998 when the M_w 7.0 Sissano earthquake in Papua New Guinea triggered a massive submarine landslide, generating a tsunami that inundated the coastline (Heinrich *et al.*, 2000). The largest submarine landslides, however, have occurred on aseismic passive continental margins. The Storegga slide that occurred about 8,100 years ago on the Norwegian margin is probably the best-known example, with 90,000 km^2 of disrupted continental slope and evidence for tsunami inundations in Norway, Iceland, and the British Isles (Bugge *et al.*, 1987). The cause of this and other slides on passive margins is much debated. Hypothesized triggers include local fluid overpressures, groundwater seepage forces, and storm-induced wave action. Changes in sea level or seawater temperatures may also cause slope failure through gas-hydrate dissociation or dissolution, which can release free gas to the atmosphere. This process fits into the more general 'Clathrate Gun Hypothesis', relating the release of methane from gas hydrates to global climate change (Kennett *et al.*, 2000).

The major hypotheses and unanswered questions of global relevance in connection with submarine slides are:

⇒ How safe is the ocean floor?

⇒ What causes and triggers submarine landslides?

⇒ What are the frequencies and magnitudes of submarine landslides? Is there a size-frequency relationship to submarine landslides?

⇒ What is the relationship between climate change and submarine landslides?

⇒ What is the tsunamigenic potential of past and future slides?

To date, there are no known examples of medium- to large-sized submarine mass movements where the geometry, *in situ* stresses, and pressures have been characterized prior to, during, and after failure. Thus, it is still unclear how and why failures initiate where and when they do, and what governs their subsequent flow behaviors. While forensic work on past slides is essential, a ground-breaking strategy for drilling submarine slides would have to include drilling into sediment sequences in areas of known slide potential that are about to fail, especially to drill, sample, and monitor proto-slide planes. If drill holes and *in situ* measurements are collected inside and outside of the landslide body, along with surveys and seabed characterization, then geotechnical parameters, their lateral variability, and slope failure potential can be constrained. Maybe the most important variable is pore fluid pressure and its gradients, as lithostatic-level pore pressures can be reached locally by lateral fluid-flow and transfer of pore pressures in a regime of lithostatic load decreasing downslope on a continental margin. Regarding the importance of earthquakes as a trigger, there may be seismically induced increases in pore fluid pressure within slope sediments; these sediment masses are locally accelerated and tilted, and oversteepened surfaces ultimately drive failure. Although the mechanisms that relate earthquakes and slope failure are conceptually understood, drilling is necessary to measure sediment properties to understand how they will respond to strong ground motions.

The justification for drilling submarine slides is simple and compelling: study cannot occur without direct sampling. Initially also data obtained *in situ* are of prime importance, especially cone penetration tests, strength measurements, stress measurements, pore-pressure measurements, and high-resolution logging while drilling (LWD). Drilling proposals must address examples of mega-slides after high-resolution site characterization, but also small- to medium-sized slides, as it is small slides on steep slopes located nearshore that might carry the highest tsunami risk. At a later stage development of drilling programs into a borehole-based monitoring approach is necessary. Boreholes in slide-prone areas are to be instrumented with piezometers, inclinometers, sensors for fluid composition, temperature sensors, and acoustic sensors.

There are a multitude of potential interactions with other science programs and with industry including ICDP for the study of integrated shoreline-crossing structures, the European Multidisciplinary Seafloor Observatory (EMSO), Global Monitoring for Environment and Security (GMES), ESONET, or other cabled seabed observatory programs such as NEPTUNE or DONET. With increasing hydrocarbon exploration and exploitation of the lower parts of continental slopes, interaction with industry would be on issues regarding the safety of pipelines, seafloor cables for communication and power, and seafloor-based production installations. Understanding submarine slides is of very high societal relevance because of the impact of deep-sea processes on coastal areas. Most tsunami early warning systems do not work in the case of landslide-triggered tsunamis. A yet unexplored issue is the potential impact of methane from destabilized gas hydrates on the global climate after large submarine sliding events.

5.1.3 Gas-hydrate (clathrate) instability?

Gas hydrates occur in sediments on most continental margins. The formation processes, stability, distribution, and response to climate change of submarine gas hydrates all remain poorly understood and there is a pressing need for quantification. BSRs in seismic sections are commonly associated with gas hydrates and help with mapping of the regional extent of gas hydrates; however, such regional geophysical features cannot be confidently used to estimate gas-hydrate resources without associated drilling. Although the P-T phase diagram is well established by experimental data, the extent and stability of gas hydrates on continental slopes and their anticipated response to the documented warming of oceanic bottom waters is not understood. Irrespective of whether this relates to changes at the end of the recent glacial cycle or to even more recent changes, the possibility of destabilization of large regions of continental margin sediments with associated tsunami hazard is a serious concern.

The slow leakage of deep source methane-bearing fluids at mud volcanoes and cold vents supports microbial and macrofaunal communities, and rising fluids provide windows for the investigation of deep diagenetic and metamorphic processes at active and passive margins. Importantly, methane is a potent greenhouse gas and catastrophic release of very large quantities of methane due to the destabilization of gas hydrates on continental margins has greatly impacted past climate and would further exacerbate current warming trends associated with anthropogenic fossil-fuel consumption. In Arctic regions, where changing climate is particularly evident in the warming of deep and intermediate waters and in the melting of permafrost, natural methane-gas emissions are expected to increase dramatically as methane hydrates change phase both in the subseafloor and on the continent. Flooding of low-lying land as a consequence of sea-level rise would result in a very rapid and significant temperature change leading to the melting of permafrost and potentially the release of methane and other gases presently trapped beneath the impermeable permafrost. An integrated investigation of the stability of permafrost at the Arctic continental margin to the response of deepwater gas hydrates on the associated continental shelf would form an excellent opportunity to collaboratively link IODP and ICDP in a field of investigation of great societal relevance.

5.2 Exploring the Future: Anticipating the Transition to a High pCO_2 World

5.2.1 Climate sensitivity

The term 'equilibrium climate sensitivity' originates from the climate modeling community and is described in the IPCC 4th assessment report (Core Writing Team For the AR4 Synthesis Report, 2007) as a measure of the climate system response to sustained radiative forcing. It is defined as the equilibrium global average surface warming following a doubling of CO_2 and greenhouse gas equivalent concentrations. The AR4 provides an assessment that "*climate sensitivity is likely to be in the range of 2 to 4.5°C with a best estimate of about 3°C, and is very unlikely to be less than 1.5°C. Values substantially higher than 4.5°C cannot be excluded, but agreement of models with observations is not as good for those values*". In the current context, climate sensitivity is more extensive than this narrow definition and crucially includes feedback processes that may operate on a wide range of timescales, including phenomena such as carbon-cycle feedbacks, cloud cover, albedo, glacial processes, weathering, and acidification. Climate sensitivity may also be non-linear (feedbacks affected by feedbacks) and most likely depends on the state of the climate system (cold versus warm mean state). Climate sensitivity may also affect the characteristics of climate variability, for example the response to orbital forcing in a warm-climate compared to a cold-climate state.

> *"Recent modeling studies show that uncertainty in carbon cycle feedbacks are as significant as physical uncertainties in controlling the future increase of atmospheric CO_2."*
>
> Huntingford *et al.*, 2009

AR4 states that, "*Models differ considerably in their estimates of the strength of the different feedbacks in the climate system*" and that "*The magnitude of future carbon cycle feedbacks is still poorly determined*". The main uncertainties highlighted in AR4 include: (1) incomplete understanding of the impacts of changes in ocean circulation on ocean CO_2 uptake; (2) the response of marine biota to ocean acidification (see section 5.2.2); (3) the role and response time of terrestrial vegetation feedbacks; and (4) our knowledge of the global methane cycle. Recent modeling studies show that uncertainty in carbon-cycle feedbacks are as significant as physical uncertainties in controlling the future increase of atmospheric CO_2 (Huntingford *et al.,* 2009), thus allowing ocean drilling to make a major contribution to this debate.

Increasing atmospheric CO_2 is the main driving force for future projected climate change. The rate of this increase is dependent on the addition of carbon to the atmosphere, but also on a range of feedbacks within the carbon cycle. Such feedbacks play a significant role in regional climate change through their influence on ecosystems, albedo, and water budgets. Understanding these biogeochemical feedbacks in the carbon cycle is thus fundamental to the prediction of future climate change. Important aspects of this cycle operate on timescales that make paleoclimate a powerful tool for better quantification (Henderson *et al.,* 2009).

It is one of the major strengths of ocean drilling that it can deliver unique data necessary to quantify climate sensitivity in the past and contribute to understanding of the feedback processes that need to be included for successful modeling of this topic of great societal relevance. This is possible because paleo proxy data can deliver estimates of both temperature and ocean chemistry, including pCO_2, from a wide range of different past boundary conditions and over a whole range of timescales inaccessible by modern, historical, or ice-core records.

> *"The PETM either resulted from an enormous input of CO_2 that currently defies a mechanistic explanation, or climate sensitivity to CO_2 was extremely high."*
>
> Pagani, 2006

Ocean drilling has played a major role in framing the current focus on past atmospheric CO_2 concentrations and temperature, allowing modelers to complement the knowledge gained from ice cores. Continuous, high-fidelity records from times with higher pCO_2 levels are only obtainable through drilling ocean sediments deposited during warm intervals of the past. As such, ocean drilling provides the means to answer some of the key questions related to the quantification of climate sensitivity. Ocean drilling only recently provided some of the key records of atmospheric pCO_2 concentrations throughout the Cenozoic (Palmer and Pearson, 2000; Pagani *et al.,* 2005; Pearson *et al.,* 2009) and temperature estimates from the deep-sea record (Zachos *et al.,* 2001; 2008). Early Cenozoic climate has received considerable attention because the response of climate to a broad range of high atmospheric values of pCO_2 can be examined from time periods relevant for future climate in the next few hundred years (Figs 5.3 and 5.4). The major hypothesis to be addressed by ocean drilling is: Ocean drilling can provide otherwise inaccessible high-resolution paleoclimate records on a multitude of timescales that provide information on the coupling between global temperatures and greenhouse gas concentrations, and also provide insights into the feedback processes that will allow a reduction in uncertainty of climate sensitivity and climate feedbacks for future climate predictions.

Throughout the history of ocean drilling (and paleoceanography as a consequence) there has been a co-evolution of proxy methodologies, obtaining improved and extended records, and framing new fundamental research questions. Ocean drilling has allowed us to demonstrate that paleoclimate data from Cenozoic and older time slices provide records of the global carbon cycle and global temperatures.

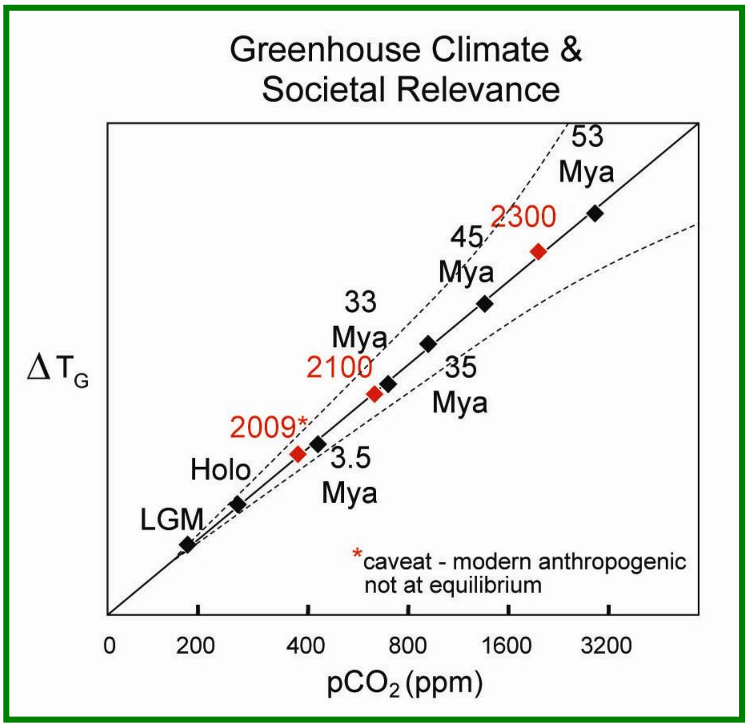

Figure 5.3 Schematic diagram showing the potential of the geological record to constrain climate sensitivity estimates across a range of pCO_2 values. Ocean drilling will provide observations of global temperature change as a function of atmospheric pCO_2 for past climates that can be compared to future predictions (Jim Zachos, INVEST meeting personal communication); red numbers indicate calendar years now and in the future, whereas the black indicates ages in the past. For progressively higher pCO_2, possible geological analogues are found further and further back in time.

These data can provide answers to a number of key questions necessary to make progress with modeling future climate change, including:

⇒ How have atmospheric CO_2 levels and temperatures varied through time? What is the relationship between atmospheric CO_2 levels, ocean chemistry (*e.g.*, pH), depth of the CCD, and temperatures in various oceans and climate states?

⇒ For past changes in the carbon cycle, what were the rates of pCO_2 increase, temperature increase, and Earth system recovery, as compared to present and future rates?

⇒ During past warming and cooling events, what was the partitioning between direct radiative forcing and feedback components to global temperature change (Zeebe *et al.*, 2009; Pagani *et al*., 2006)?

⇒ How has climate sensitivity changed in the past?

⇒ Are there pCO_2 thresholds in the climate system (cryosphere, ocean physical/chemical state)? What are the thresholds for different past time periods (deConto *et al.*, 2008)?

⇒ How does the meridional temperature gradient depend on pCO_2? What are the implications for poleward heat transport?

⇒ What are the properties of the hydrological cycle during warmer climate regimes? To what extent does it feedback on the climate state?

⇒ How are transient climate states affected by climate sensitivity?

⇒ Has Earth's system become more sensitive in the Neogene?

⇒ What is the temporal evolution of pCO_2 (with higher accuracy)?

⇒ How can we use orbital forcing to better understand climate feedbacks and variability? Why is there a change in response after 1 Ma?

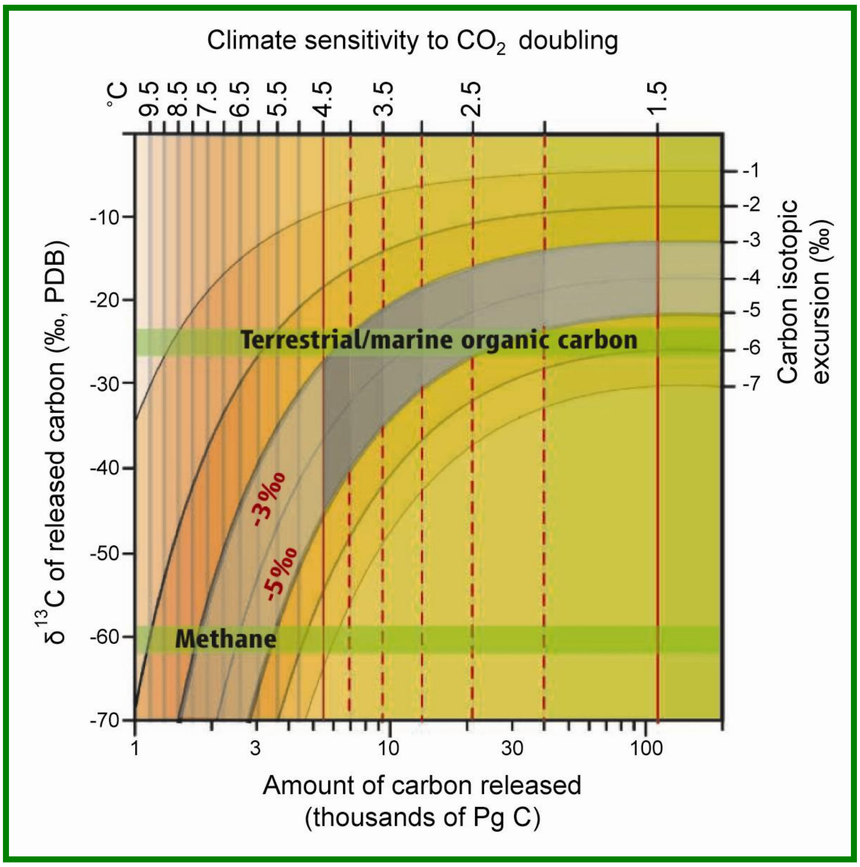

Figure 5.4 Estimate of climate sensitivity for PETM (from Pagani *et al.,* 2006). This figure demonstrates the approach to determining climate sensitivitiy from paleoclimate data. Note that it does not consider potential initial warming pre-dating the PETM.

⇒ What were past methane levels?

⇒ What role do boundary conditions play in determining Earth's climate (*e.g.*, paleogeography, topography)?

New ocean drilling is required because it is the only way to obtain past records of large-amplitude climatic events that are necessary to fully understand and constrain climate sensitivity. Specific aspects of these requirements are given here.

Proxy methods to determine past pCO_2, pH, and carbonate-ion concentration have dramatically developed or improved in the last few years, allowing a more strategic reconstruction of past conditions. One exciting prospect is our ability to fully reconstruct past ocean carbon chemistry based on a new carbonate-ion proxy (B/Ca) and the dramatic improvement of our ability to measure $\delta^{11}B$ as a pH proxy through new measurement techniques (see section 5.2).

In addition, very recently a new 'clumped isotope' proxy has been added to the paleoclimate toolbox that will allow direct determination of sea-water temperatures and thus complete the requirements for a detailed reconstruction of past climate sensitivities. Proportions of ^{13}C–^{18}O bonds in carbonate minerals are sensitive to their growth temperatures, independent of bulk isotopic composition. Thus, 'clumped isotope' analysis of ancient carbonates can be used as a quantitative paleothermometer that requires no assumptions about the $\delta^{18}O$ of waters from which carbonates grew (Eiler, 2007; Came *et al.,* 2007). This proxy complements existing temperature, ice-volume, and carbonate-ion proxies ($\delta^{18}O$, alkenones, Mg/Ca), but currently requires a very large quantity of carbonate for measurement, thus necessitating additional coring of high-quality and high-resolution cores. One further new temperature proxy developed during the past few years has been the TEX86 temperature proxy, based on the relative abundance of long-chain lipids from Crenarchaeota that appear to be ubiquitous in present and past oceans and have been shown to contain a paleotemperature signal (Kim *et al.,* 2008). Although this proxy is being refined, initial applications of it have provided challenges for the climate modeling community, for example through the suggestion that during the PETM Arctic temperatures exceeded 20°C (Sluijs *et al.,* 2006; Bijl *et al.,* 2009).

Previous drilling has demonstrated the need for more complete and global coverage to fully understand the coupled global carbon cycle, allowing us to more strategically select drill sites (Panchuk *et al.,* 2008). One important requirement for additional drilling is to constrain the Pacific CCD prior to the PETM (Zeebe *et al.,* 2009).

Existing cores provide only partial information necessary for climate sensitivity reconstructions, for many periods such as the early Pliocene. There is a need for latitudinal transects covering other warm climate intervals and continued funding is required to process existing cores for new proxies. In addition, there is an expressed need to obtain sediment cores from thermally immature, expanded sections that are stratigraphically complete. Ideally, these would be from clay-rich horizons with good carbonate, silica, and organic matter preservation (Pearson *et al.,* 2009).

For the Miocene time interval, a much higher temporal resolution is required to address this problem. Needs include new drill sites located along latitudinal and depth gradients, as well as continent-ocean transects. Such improved geographic and depth coverage is necessary to constrain the location and latitudinal variation of the CCD and deep circulation and overturning in various oceans in detail so these data can be used in carbon-cycle models.

New drilling is needed specifically in shelf and marginal-sea regions when there is a requirement for clay-rich sediments that contain better preserved carbonates, organic fossils, and biomarkers (Pearson *et al.,* 2009). These records will be complimentary to deep-ocean transects, as they are likely to be less complete, but will allow geochemical analyses that necessitate better preserved material.

The highest research priorities identified to address climate sensitivity and future predictions of climate are the use of chemical, isotope, and biotic proxies to reconstruct atmospheric pCO_2 levels and temperatures over the Cretaceous and Cenozoic, as well as the range, mechanism, and rates of past carbonate saturation states of the oceans.

The highest priority research objectives are then to:

⇒ narrow the uncertainty and improve temporal resolution of paleo–pCO_2 and paleotemperatures.

⇒ address how climate sensitivity and variability depend on the mean state and temporal variation of the climate system (Greenhouse *vs.* Warmhouse *vs.* Icehouse worlds).

⇒ establish the spatial response of the climate system, especially temperature and changes to the hydrological cycle, requiring latitudinal and land-ocean transects.

Once long-term proxy records have been obtained it becomes possible to determine feedback systems, processes, and times necessary to switch the climate system between states. These high-priority research questions will then allow the climate community to achieve the societally relevant goal to understand how climate feedback processes operate.

Scientific strategies required to determine and understand climate sensitivity include three main steps. As a first priority, the timescales of interest need to be identified and then continuous records need to be obtained across these timescales. Possible target intervals include times of rapid and large-amplitude climate-state reorganizations such as the EECO (Zachos *et al.,* 2001), the MECO (Bohaty *et al.,* 2009), the Eocene/Oligocene boundary (Coxall *et al.,* 2005; Liu *et al.,* 2009; Pearson *et al.,* 2009), the Oligocene/Miocene boundary (Pälike *et al.,* 2006), and the Neogene (Pagani *et al.,* 2009).

Identified target time slices should then determine drill site selection, with the requirement that the material to be cored allows the application of multiple proxies (both carbonate and organic-carbon based). This will probably require drilling near margins and in areas with high sedimentation rates. Over a ten-year period, it could be possible to conduct a latitudinal transect, following the GEOSECS approach ('PALEOSECS') identified in the CHART report (2009).

Platform needs are dictated by the desirability to determine long-term pole-to-equator thermal gradients for specific time slices. One important missing piece is to recover the missing time intervals from the ACEX (IODP Expedition 302, Moran *et al.,* 2006).

A new approach will also be required to fully exploit the opportunities offered by collaborating with international partner organizations. Interaction with ICDP is requested to connect continental processes with the oceans. Closer and more frequent interaction with the modeling community is required to develop synergies and expand observations globally. Interaction with the ice-modeling community is needed to fully appreciate glacial stream flows. More collaboration with physical oceanographers is required to comprehend the potential impact of ocean circulation pattern changes on climate sensitivity. Furthermore, ANDRILL and SHALDRIL expertise and data will form a natural link to fully exploit the breadth of data required to tackle this problem of extreme societal relevance.

5.2.2 Ocean acidification

Numerous efforts are currently underway to investigate the dramatic modern-day increase in atmospheric pCO_2 and to decipher its impact on global and local temperature, sea level, and the hydrological cycle. Yet, increasing atmospheric CO_2 levels will not only cause global warming but also ocean acidification through carbonate-ion concentration changes and decreasing pH (Caldeira and Wickett, 2003; Zeebe *et al.,* 2008). Known as "*the other* CO_2 *problem*" (Doney *et al.,* 2009), lower oceanic pH values (Fig. 5.5) will affect biocalcification and thus the productivity of oceanic biocalcifiers. It will also impact upon both oceanic carbon-cycle feedbacks and ecosystems. Indeed, the impacts of ocean acidification are additional to, and may exacerbate the effects of, climate change (Royal Society Policy Document, 2005; Anderson *et al.,* 2009).

> *"Ocean acidification is a predictable consequence of rising atmospheric pCO_2 and does not suffer from uncertainties associated with climate change forecasts."*
>
> Doney *et al.* (2009)

The basic principles of this process are clear, but we do not know how much CO_2 can be absorbed by the oceans, where and how it spreads, or how fast it is neutralized. Over a range of timescales, from hours to hundreds of thousands of years, these chemical changes influence the climate via the CO_2 that remains in the atmosphere and also affect the oceanic biota. In turn, there is the possibility of a direct feedback of ocean acidification on the carbon cycle. The main uncertainties highlighted in the IPCC 4th assessment report (Solomon *et al.,* 2007) include: (1) an incomplete understanding of organic carbon production; (2) the impacts of changes in ocean circulation on ocean CO_2 uptake; (3) the response of marine biota to ocean acidification; (4) the role and response time of terrestrial vegetation feedbacks; and (5) our knowledge of the global methane cycle. Recent modeling studies show that uncertainty in carbon-cycle feedbacks are as significant as physical uncertainties in controlling the future increase of atmospheric pCO_2 (Huntingford *et al.,* 2009).

Ocean drilling has played a major role in framing the current concern about ocean acidification. While ice-core records indicate that atmospheric pCO_2 changes have only varied within a very narrow range during the past ~800,000 years (Siegenthaler *et al.,* 2005; Zeebe and Caldeira, 2008), archives from times of much more elevated pCO_2,

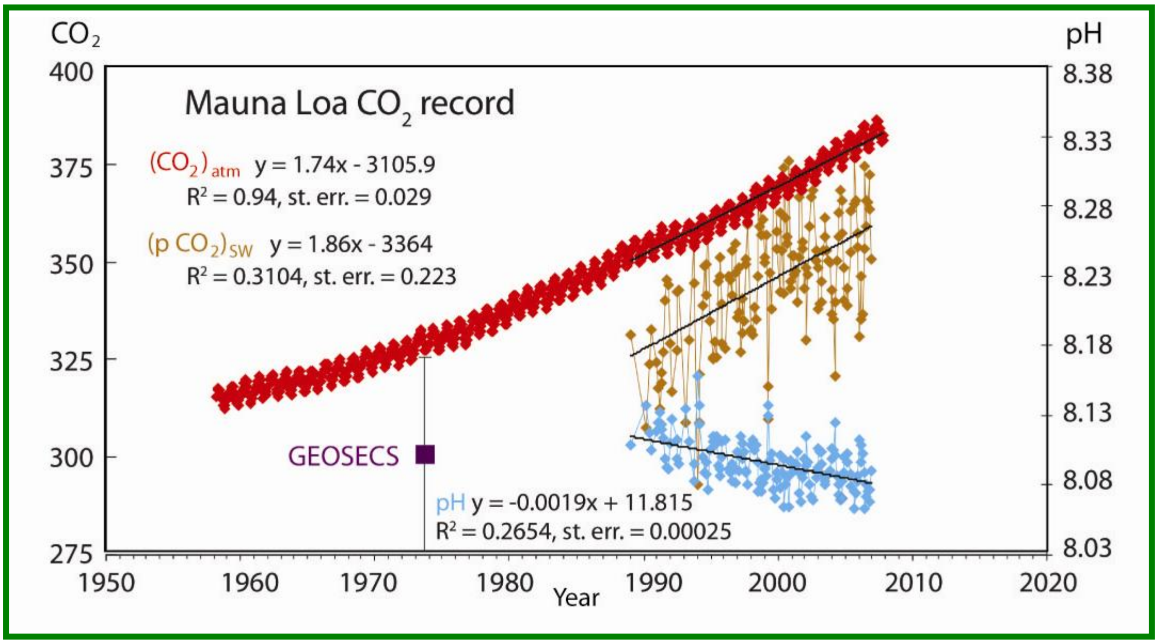

Figure 5.5 Time series of atmospheric CO_2 at Mauna Loa (in parts per million volume, ppmv) (red), surface ocean pH (cyan), and seawater pCO_2 (μatm) (tan) at Ocean Station ALOHA in the subtropical North Pacific Ocean (from Doney *et al.,* 2009). Note that the increase in oceanic CO_2 over the past 17 years is consistent with the atmospheric increase within the statistical limits of the measurements. Geochemical Ocean Section Study (GEOSECS) data are from a station near Station ALOHA collected in 1973 (data from Takahashi et al., 1980).

obtained through ocean drilling, provide the means to answer some of the key questions that relate to quantification of the acidification process.

> *"Reducing uncertainty of atmospheric pCO$_2$ predictions for 2300 is not an option for Ocean Drilling, it is a societal obligation."*
>
> James C. Zachos, INVEST 2009

Ocean drilling only very recently provided key records of lysocline shoaling (Fig. 5.6), atmospheric pCO$_2$ concentrations, and carbonate-ion concentrations from the PETM (Zachos *et al.,* 2005) and from a de-acidification event near the Eocene/Oligocene boundary (Merico *et al.,* 2008). Ocean drilling has also allowed the determination of how biota reacted to changes in carbonate-ion concentrations in the past (Gibbs *et al.,* 2006).

"*The other CO$_2$ problem*" was recognized only recently and thus featured only peripherally in the IODP Initial Science Plan. Ocean drilling can make a substantial and unique contribution to this field of immediate societal relevance and exploit some key new advances in recently developed proxies and our understanding of where to collect new records.

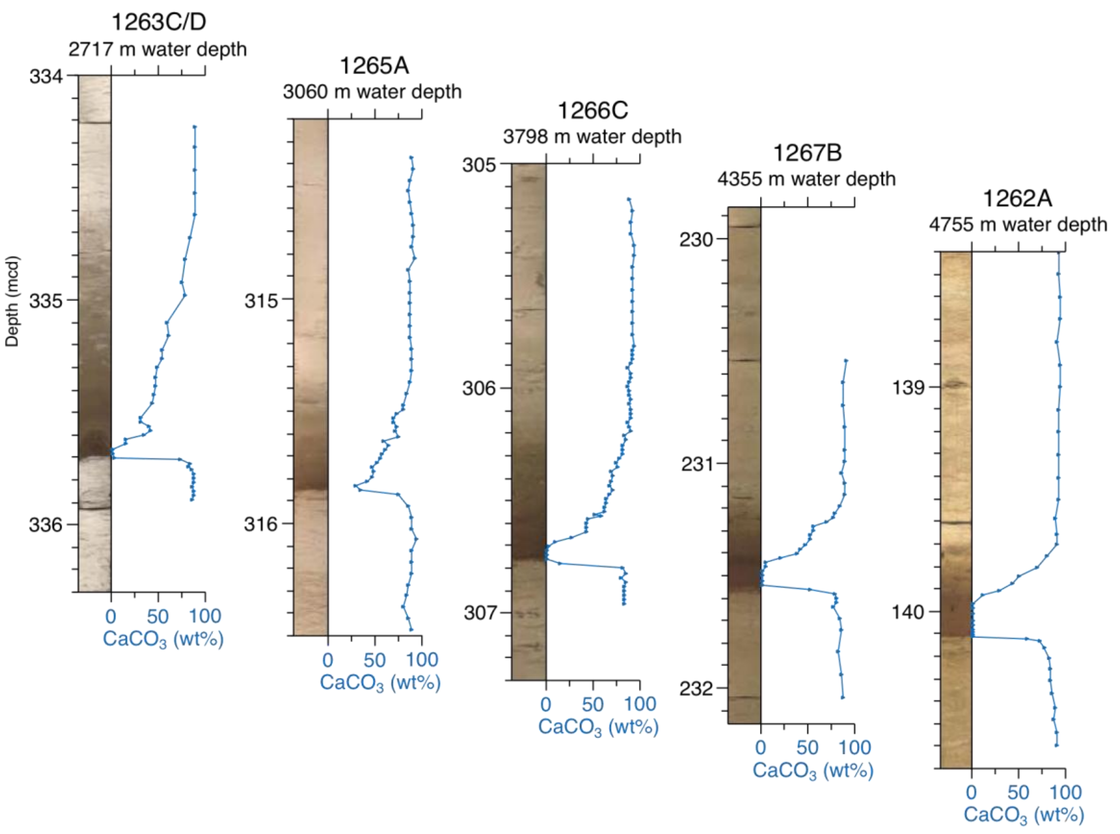

Figure 5.6 Example of a depth transect approach to constrain extreme changes of the CCD during the PETM (from Zachos *et al.,* 2005). Digital core photos and weight % CaCO$_3$ content plotted versus meters composite depth (mcd) across the PETM interval at ODP Holes 1262A, 1263C/D, 1265A, 1266C, and 1267B on Walvis Ridge. Records are plotted from left to right in order of increasing water depth.

The major hypothesis to be addressed by ocean drilling is: Increasing atmospheric CO_2 levels will not only cause global warming but also ocean acidification, *i.e.*, decreasing pH ("*The Other CO_2 Problem*"). Decreased oceanic pH values will affect biocalcification, thus productivity of oceanic biocalcifiers, and affect both the oceanic carbon cycle and ecosystems. The basic principles of this process are clear, but we do not know how much CO_2 can be absorbed by the oceans, where and how it spreads, and how fast is it neutralized. Over a range of timescales (from hours to hundreds of thousands of years) these chemical changes will influence the climate via the CO_2 that remains in the atmosphere and also affect the oceanic biota.

Ocean drilling has allowed us to demonstrate that records of ocean-acidification state can provide key answers to questions such as: How fast is fossil fuel (or added carbonic acid) neutralized? What is the effect of $CaCO_3$ buffering on oceanic carbonate-ion saturation and in turn atmospheric pCO_2 (Walker and Kasting, 1992; Millero, 2007)? The large number of feedback components that connect the global carbon cycle, atmospheric pCO_2, temperature, dissolved oceanic $[CO_3^{2-}]$, and pH need to be constrained by present-day measurements and data from the geological archive in order to advance prediction of the timing and amplitude of future changes. Records of past large-scale and rapid ocean acidification events are only obtainable through ocean drilling and link directly to other high priority research themes (see section 5.2.1).

Specific questions to be answered by strategically planned ocean drilling initiatives include:

⇒ How have atmospheric CO_2 levels varied through time?

⇒ What is the relationship between atmospheric CO_2 levels, ocean chemistry (*e.g.*, surface ocean pH), depth of the CCD in various oceans, overturning and circulation, and climate?

⇒ What has the biotic response (including evolution/extinction and changes in physiology/ecology, biocalcification, and dominant phytoplankton group) and feedback been during acidification events throughout the Cretaceous and Cenozoic?

⇒ For past ocean acidification events, what were the rates of pCO_2 increase, pH change, and Earth system recovery, as compared to present and future rates?

⇒ What are the atmospheric chemistry feedbacks and how might gas emissions of N_2O, CH_4, and DMS to the atmosphere change as ocean pH decreases?

⇒ What are the impacts of high pCO_2 and rates of change in pCO_2 levels on calcification, respiration, primary production, settlement of particulate organic and carbonate matter, and remineralization in the water column?

New ocean drilling is required because it is the only way to obtain past records of large amplitude ocean acidification events that are necessary to fully understand and model this problem. Specific aspects of these requirements are given here.

Proxy methods to determine past pCO_2, pH, and carbonate-ion concentration have dramatically developed or improved in the last few years, allowing a more strategic reconstruction of past conditions. B/Ca ratios have been established as a proxy for carbonate-ion concentrations (Yu *et al.,* 2008), whereas a new measurement protocol using multi-collector inductively coupled plasma mass spectrometry (MC-ICPMS) overcomes many of the problems that plague traditional $\delta^{11}B$ measurement approaches for the $\delta^{11}B$ pH proxy. Combining these two proxies allows a complete reconstruction of the carbonate system (including pCO_2) without recourse to further assumptions. These techniques can now be applied to existing and new ocean drilling records of past ocean-acidification and de-acidification events and complement existing proxy records for atmospheric pCO_2 (Pagani *et al.,* 2005).

Paleo-records generated from material uniquely recovered by ocean drilling have resulted in a more complete interaction with the modeling community, which allows us to select drill sites of the highest priority and directly incorporate carbon-cycle data into new advanced models (Panchuk *et al.,* 2008). One important requirement for additional drilling is to constrain the Pacific CCD prior to the PETM (Zeebe *et al.,* 2009).

Previous drilling has demonstrated the need for more complete and global coverage to fully understand the coupled global carbon cycle, allowing us to more strategically select drill sites (Zeebe *et al.,* 2009). A requirement to address this problem includes new drill sites located along latitudinal and depth gradients as well as continent-ocean transects. Such improved geographic and depth coverage is necessary to constrain the location and latitudinal variation of the CCD and deep circulation and overturning in various oceans in detail so that these data can be used in carbon cycle models.

New drilling is needed specifically in shelf and marginal sea regions where we may obtain clay-rich sediments that contain better preserved carbonates, organic fossils, and biomarkers (Pearson *et al.,* 2009). These records will be complimentary to deep-ocean transects, as they are likely to be less complete, but will allow geochemical analyses that require better preserved material.

Ocean acidification research has only developed in the past few years. Our new understanding of the magnitude and timescales of changes that are involved in understanding and modeling this problem allow us to target specific areas of research related to ocean acidification. For instance, how ocean acidification leads to biotic changes and adaptations might be studied by drilling the high-latitude oceans. This line of research may also locate areas of past deep-water formation, which is directly influenced by surface changes in carbonate-ion concentration. One of the areas where ocean drilling is the only means to establish past variations in ocean acidification is by providing the material needed to reconstruct short- and long-term regional variations of the lysocline and CCD. In order to achieve this, a geographically distributed database of carbonate measurements from sediment cores is required, covering time slices of known and yet to be found major events of carbonate ion variations.

Ocean drilling is thus in a unique position to address several aspects of ocean acidification that are of direct societal relevance. It will assist in understanding past episodes of high atmospheric pCO_2 levels, document the reliability of climate models in reconstructing global environments, and provide policy makers with reconstructions of past ecosystem responses and feedback. Ocean drilling will increase our current understanding of the global carbon cycle and specifically how reduced pH will change the amount of atmospheric CO_2 absorbed by the oceans. This research will be able to address the reduction and possible regional cessation of calcification by organisms in acidified oceans, which would strongly affect ecosystem regulation and the flow of organic material to the seafloor. Ocean acidification can decrease the diversity of marine organisms; this might include the disappearance of planktonic calcifying organisms such as coccolithophores from the high-latitude oceans, It will also have a strong impact on reef-building organisms. Understanding this process has extreme relevance for worldwide fishing and tourist industries. In addition, a reduction of coccolithophore blooms has the potential to change global albedo, enhance global warming, and decrease long-term carbon sequestration.

The highest research priorities identified to address ocean acidification and future predictions of this process are: (1) the use of chemical, isotope, and biotic proxies to reconstruct atmospheric pCO_2 levels over the Cretaceous and Cenozoic and (2) ascertain the range, mechanisms, and rates of past acidification and carbonate-saturation states of the oceans.

In order to achieve these priorities, the required core material needs to be obtained through ocean drilling in strategic locations. When this is accomplished, the development of new and improvement of existing seawater chemistry proxies can be applied. These include:

⇒ The stable isotope ratio of boron ($\delta^{11}B$) incorporated into carbonate and aragonite skeletons, including corals, planktonic foraminifers, and benthic foraminifers is sensitive to seawater pH.

⇒ The stable carbon isotope ratio of biologically produced particulate organic carbon is influenced by the concentration of dissolved carbon dioxide $[CO_2]_{aq}$. This proxy is useful in surface environments and is further constrained by the measurement of compound-specific fractions of organic carbon such as alkenones.

⇒ The incorporation of various trace metals (including Cd, Zn, B, U, Mg) into skeletal calcite and aragonite has been associated with the carbonate-ion concentration $[CO_3^{2-}]$ and/or saturation state at the seafloor.

⇒ Calcium isotopes as a proxy for the oceanic carbonate cycle.

⇒ Various biotic proxies for acidification: the morphology of skeletons of biocalcifying organisms may be affected by acidification (*e.g.*, dwarfism, deformed specimens, mass of shells). Other proxies may include accumulation rates or species composition of assemblages. To develop and calibrate biotic proxies we need to: (1) cooperate or participate in studies aimed at determining the calcification response to elevated CO_2 in benthic and planktonic calcifying groups; (2) determine mechanisms of calcification within different calcifying groups; (3) evaluate the interactive effects of multiple variables that affect calcification and dissolution; and (4) interpret the results of laboratory experiments in terms of the natural environment, including understanding of diurnal and seasonal cycles of the carbonate system on coral reefs.

Once long-term proxy records have been obtained it becomes possible to determine the feedback systems, processes, and lengths of time necessary to restore the system to 'normal' conditions after ocean acidification (*e.g.*, terrestrial weathering). We can define variability in the long-term records (millions of years) and compare that variability with superimposed 'transient events' on timescales of thousands to hundreds of thousands of years. It is of prime importance to cooperate with climate and Earth-system modelers who can help in defining key locations (paleogeography, depth) for drilling. These might include equatorial upwelling regions, the Southern Ocean, the high-latitude Arctic, and shelf regions.

Scientific strategies required to achieve a leap in our understanding of ocean acidification necessitate a number of different approaches and target areas for drilling. In general, much improved global coverage, depth, and age distributions are required to provide meaningful constraints for the carbon cycle and climate-modeling community. Specific suggestions for target areas include: (1) depth transects, including continental shelves and margins to obtain clay-rich sequences with excellent carbonate preservation, organic microfossils, and biomarkers, as demonstrated by shore-based coring in Tanzania (Pearson *et al.,* 2009); (2) end-member environments for an initial evaluation of biotic and chemical changes, including cold oceans at high latitudes, warm oceans in the tropics, shallow water (corals), and upwelling areas; and (3) Pacific Ocean Cretaceous records from guyots, providing the ability to obtain carbonate sediments and acidification indicators from different paleo water depths, even on very old crust that would otherwise be in too deep water or too deeply buried.

Target projects in order of geological age include the Cretaceous OAEs as acidification events. The Cretaceous Period experienced intervals of increased organic carbon burial that must be linked to extreme changes in ocean carbon chemistry during these times. These large-amplitude events could be of similar amplitude to the PETM events (Jenkyns, 2003) and provide data points for acidification in an extreme Greenhouse world. The Paleocene-Eocene transition and multiple hyperthermal acidification events of the Paleogene have recently come to the focus of research (Lourens *et al.,* 2005) and require further drilling to build a global database of regional oceanic changes:

⇒ The Cenozoic trend of declining pCO_2-levels and cooling.

⇒ Plio-Pleistocene glacial/interglacial dissolution cycles (*e.g.*, MIS 11).

⇒ Late Quaternary to Recent, with pCO_2 fluctuations over a smaller range (coral drilling, specifically coral reef drilling).

Research topics on carbonate dissolution and other issues related to ocean acidification require global-scale datasets for each time slice in order to analyze the degree of undersaturation of carbonate, deep-ocean circulation, and evolution of the biosphere. Single coring expeditions would be insufficient; therefore, one or more workshops may be needed to evaluate how to coordinate a series of expeditions (latitudinal, land-sea, depth transects) and also target sites of opportunity. Such workshop(s) would serve a combination of paleoceanographic purposes (*e.g.*, greenhouse climate, Greenhouse-Icehouse transition, rapid and extreme events). Ocean drilling will be able to draw on significant interactions with dedicated ocean acidification research efforts, including the Ocean Acidification Network, the European Project on Ocean Acidification (EPOCA), the International Ocean Carbon Coordination Project (IOCCP), the Integrated Marine Biogeochemistry and Ecosystem Research (IMBER), the US Ocean Carbon and Biogeochemistry Program (OCB) ocean acidification subcommittee, the International Geosphere-Biosphere Programme (IGBP), as well as directed national ocean acidification research efforts in the US, EU, and Japan.

5.2.3 Rapid sea-level change

The impact of future dramatic sea-level rise related to global warming is likely to be experienced directly or indirectly by a large part of the world's population, over one-third of which live within 100 km of a coastline. One-tenth of the global population and

13% of the world's urban population live in the low elevation coastal zone (≤10 m above sea level), which covers only 2% of the world's land area (McGranahan *et al.,* 2007). Predictions regarding the stability and habitability of the shoreline, where sea level intersects dry land, and on the changes affecting coastal ecosystems, groundwater resources, and nutrient cycling from land to sea therefore have enormous societal importance in the coming decades; however, predictions of future sea-level rise are poorly constrained.

The flooding record is not a direct measure of eustatic change because variations in subsidence and sediment supply and the mantle response to altered sediment and water loads during sea-level change also influence shoreline location. Reconstruction of global mean sea level since 1870 based on tide gauge records indicates a 20th century rate of sea-level rise of 1.7 ± 0.3 mm yr^{-1} and a significant acceleration of sea-level rise of 0.013 ± 0.006 mm yr^{-1} (Church and White, 2006), in part due to anthropogenic influences. Satellite measurements are limited to the past ten years and have demonstrated that rates of sea-level rise have increased since 1993 to 3.3 ± 0.4 mm yr^{-1} (Cazenave and Nerem, 2004). In some of the most heavily populated areas (*e.g.*, the US Atlantic seaboard) relative sea-level rise exceeds 4 mm yr^{-1} (Psuty and Collins, 1996) due to combined effects of eustasy and subsidence; large deltas are especially vulnerable to relative sea-level rise, often with large population densities. Remote-sensing data suggest that ice sheets currently contribute little to sea-level rise, which is mostly due to thermal expansion of the oceans (Church *et al.,* 2001) and the melting of land-locked ice. How much and when this rate will change during the next century is not well constrained due to the poor knowledge of ice-sheet dynamics and behavior of the climate system during steadily warming conditions. Best estimates given by the most recent IPCC Report are that sea level could rise by as much as 50 cm in the next 100 years (IPCC, 2007); however, the uncertainties in these sea-level projections are large as ice-sheet dynamics are poorly understood and have not been included explicitly in the IPCC reports. Accordingly, dynamical instabilities in response to climate warming may cause faster ice-mass loss (Cazenave, 2006) involving either or both of the Greenland and Antarctic ice sheets (Gregory *et al.,* 2004; Hu *et al.,* 2009), but it is not known whether this has happened previously within the warmest intervals of the late Quaternary. In particular, the WAIS, which is currently held in place by grounded ice, may be disrupted due to increased buoyancy as sea level rises from the melting of northern hemisphere ice sheets. The current estimates of future sea-level rise are within the high end of the IPCC estimates, with a sea-level rise of 80 cm, and perhaps >1 m, by 2100 (Rahmstorf *et al.,* 2007). While the predicted rates are gradual on a human timescale, the geological record shows that they can increase dramatically (*e.g.*, >2 m in a century; Fairbanks, 1989; Bard *et al.,* 1990); in addition, the retreat of shorelines can be erratic and rapid even under conditions of moderate global sea-level rise.

Because the instrumental record of sea-level change extends back only about 150 years (Revelle, *et al.*, 1990), the refinement of predictions for sea-level rise over the coming decades and centuries and the assessment of anthropogenic influence, clearly rely on past high- to ultrahigh-resolution records of rates and magnitudes of rapid sea-level change. There is a clear need to improve our knowledge of the Earth's response to rapid sea-level rise over short timescales and to provide expectations for the locations and impact of changes for the rest of the 21st century. Central to this aim is understanding how the Earth system has operated on short timescales during past abrupt climate changes and under past conditions of extreme climate forcing, especially when atmospheric CO_2 levels and global temperatures were comparable with those projected for 2100. The clearest, most direct records of sea-level change over the time intervals required are found in shallow water. Existing drill cores in this setting are too limited in geologic time, tectonic history, and proximity to the shoreline to be useful and new drilling is necessary. Coral reefs can be considered accurate recorders of high-resolution sea-level change as corals live in a sufficiently narrow or specific depth range to be useful as absolute sea-level indicators and can be precisely dated by radiometric methods. High sedimentation rate siliciclastic margins provide another appropriate system for gauging shoreline response to rising sea level, with drill site locations adapted to the style of sediment distribution of that particular margin, *i.e.*, with respect to tide-, river-, or storm-dominated delta systems. New shallow-water records will provide the opportunity to document the impact of rapid sea-level rise and coeval abrupt environmental changes on the architecture of sedimentary sequences, sedimentary processes, and groundwater flows in the coastal zone during a time of shoreline transgression, as well as the response of the relevant coastal ecosystems at various timescales. The resilience of ecosystems to sea-level and climate changes at timescales relevant to humans is of critical importance in the face of projected warming.

During the glacial-interglacial transitions known as terminations, ice volume decreased and sea level (magnitude > 100 m), temperatures, and greenhouse gas concentrations increased abruptly (Petit *et al.,* 1999; Lambeck *et al.,* 2002a). Terminations are therefore regarded as potential analogues for future rapid sea-level rise and coeval abrupt climatic and environmental changes. Central to this aim is the evaluation of relative contributions of Northern and Southern Hemisphere ice to past and future sea-level changes in terms of rate and magnitude. Since key parameters such as ice volume, sea level, and temperature changes are closely related to each other, the precise reconstruction of sea level is critical to understanding ice-sheet dynamics and suborbital climate variability during terminations and determining the timing and volume of meltwater release under varying thermal regimes during deglaciations.

The reconstruction of rates and magnitudes of sea-level rise during several terminations may help in modeling ice-sheet dynamics and in understanding the role of high-latitude summer insolation in the Northern or Southern Hemisphere as a trigger for deglaciation processes. Moreover, it is of prime importance to constrain the dramatic changes in freshwater fluxes to the oceans brought by meltwater pulses, which disturb general thermohaline circulation and hence global climate, during the abrupt melting phases of glacial ice sheets. The termination of the last glacial period, designated Termination I (TI), is thought to have been characterized by two episodes of accelerated sea-level rise known as meltwater pulses (MWPs) 1A and 1B (dated to 13.8 and 11.3 ka respectively), amounting to as much as 20 m of sea-level rise in less than a century (Fairbanks, 1989; Bard *et al.,* 1990) (Fig. 5.7). Such events are thought to coincide with catastrophic ice sheet collapses whose mechanisms and sources are still poorly constrained. The proposed involvement of the Antarctic ice sheet as a key trigger for climatic events that led the Earth system out of the previous glacial period (Weaver *et al.,* 2003) still needs to be confirmed (Bassett *et al.,* 2005). The far-field sea-level record is a powerful constraint for testing a range of plausible ice sources responsible for the MWPs and the relationship of those pulses to global climate. This raises the question of the influence of different mean climatic states on the probability of catastrophic collapse and the rates and amplitudes of associated eustatic rise; however, the timing and amplitude of the MWP events are still debated.

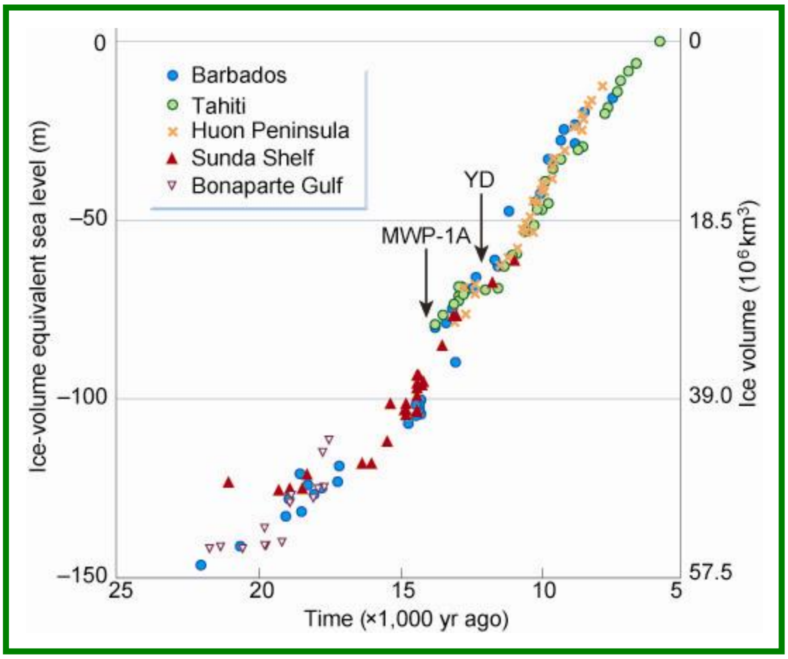

Figure 5.7 Changes in global ice volume from the time of the LGM to present. The figure shows ice-volume equivalent sea level for the past 20 kyr based on isostatically adjusted sea-level data from different localities (Yokoyama *et al*., 2000; Fairbanks, 1989; Bard *et al*., 1990;1996; Hanebuth *et al*., 2000). Because of spatial variability of the sea-level response to the glacial and water loading, sea-level observations from different localities should not be combined into a single sea-level curve unless the isostatic effects can be shown to be similar. The ice-volume equivalent sea-level function used here corresponds to the observed sea levels corrected for these effects (Lambeck *et al*., 2002b). It relates to the change in total ice volume with respect to the present, of continent-based ice and any ice grounded on the shelves. With one exception, the results indicate an ice volume at the LGM that was ~55x10^6 km^3 greater than at present (Milne *et al*., 2002; Lambeck *et al*., 2002b). The error bars (not shown) are typically 0.1–0.15 kyr in calendar years and 5 m or less in position. MWP-1A refers to the timing of the meltwater pulse at ~14 kyr ago. At the YD (~12 kyr ago), sea-level rise may have momentarily halted (from Lambeck *et al*., 2002a).

Furthermore, the existence of the MWP-1B has remained controversial (Bard *et al.,* 1996; Bassett *et al.,* 2005). This is especially due to the limited availability of coral reef sequences encompassing terminations, most of which are eroded or were deposited below present sea level; new drilling is therefore necessary. Coral reef-based sea-level records from sites distant from former ice sheets ('far-field' sites) that are less affected by isostatic deformation are crucially needed to verify the occurrence of those events and to constrain the timing and amplitude of the glacial meltwater signal. Outcomes from empirical sea-level evidence can indeed constrain global-climate models and a sophisticated computational climate model; a coupled general atmosphere-ocean GCM can, in principle, predict Greenland and Antarctic ice sheet behavior in a globally warming climate.

The course, timing, and magnitude of sea-level changes during older terminations have yet to be reconstructed in detail and can be resolved only by drilling. In particular, the period leading out of the penultimate glacial maximum and into the last interglacial (Termination II; TII) remains poorly constrained. U-series dates recovered from Pleistocene coral reef sequences from Tahiti have demonstrated that the timing of the start of the relevant deglaciation processes is shown to be near coincident with a minimum in Northern Hemisphere insolation (Thomas *et al.,* 2009) (Fig. 5.8).

Sea level during this maximum is thought to have been about the same as during the LGM, but the timing has not been established quantitatively. Several studies have suggested that, despite the apparent similarities in climate records between the last two terminations, TII may not have consisted of a monotonic sea-level rise. This termination might have included an interlude of significant sea-level fall (Esat *et al.,* 1999; Siddall *et al.,* 2006; Thomas *et al.,* 2009) that occurred during the transition from glacial to interglacial conditions, at a time when there was a seemingly monotonous rise in temperature and CO_2 as recorded by ice cores. This event may have thus consisted of a YD-like climate oscillation, although there is a contradiction between different records whether this was larger or smaller in magnitude than the YD itself (Cannariato and Kennett, 2005); furthermore, the YD event was apparently not associated with a sea-level drop. It remains to be answered if this phenomenon was unique to TII or if it occurred in older terminations. Additionally, causes of sea-level reversal events during TII and older terminations, if they exist, are yet to be determined.

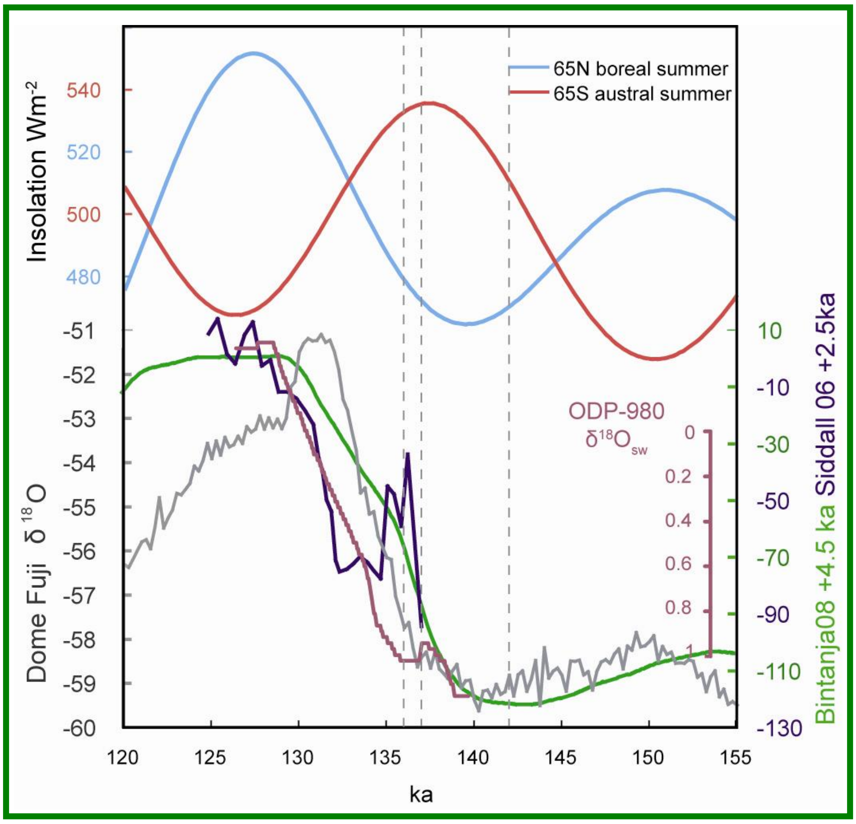

Figure 5.8 The timing of the penultimate deglaciation, illustrated with the data of Bintanja *et al.*, 2005 (in green) with the chronology adjusted (+4500 years) and the Red Sea record of Siddall *et al.*, 2006 (in dark blue), adjusted by +2500 years. The Dome Fuji ice core $\delta^{18}O$ (Kawamura *et al.*, 2007) and North Atlantic bottom water $\delta^{18}O$ (Cheng *et al.*, 2006) records are shown for comparison in gray and purple, respectively. Local summer insolation is shown for 65°N (light blue) and 65°S (red) (Laskar *et al.*, 2004). The gray dashed vertical lines are the timing constraints of the deglaciation. Note that deglaciation must start when Northern Hemisphere insolation is at or close to a minimum. Figure from Thomas *et al.*, 2009.

6 Cross-Disciplinary Research Frontiers

6.1 Extreme Events

Earth history, both on the human timescale and on the geologic timescale, is punctuated by extreme events. Increasingly, we have discovered these intermittent, abrupt departures from stable, steady-state conditions can have major impacts on the Earth's environment, the evolution of life, and global biogeochemical cycles. The rock record of these extreme Earth events can be read through ocean drilling. As inhabitants of the Earth we care about these extreme events both for setting the stage that we now live on as well as for the potential of future paradigm changing events that may either benefit or limit us as a species. Two types of extreme events with the potential to change societies or even eliminate species are impacts by comets or asteroids and volcanic eruptions.

6.1.1 Impact events

Comets and asteroids have regularly hit the Earth throughout its history and have been invoked as mechanisms for bringing water and life to Earth, forming the Moon, and causing extinction events, including the K/Pg mass extinction (Fig. 6.1). Despite their importance, our understanding of impact processes and their effects remains relatively poorly constrained. Scientific ocean drilling has played a significant role in improving our understanding of these events (*e.g.*, the K/Pg boundary impact and its global effects).

Future drilling can play a vital role in improving our understanding of impacts and their role in Earth's history. One key objective is to study the only example of an impact-caused mass extinction event known so far; specifically why the Chicxulub impact had such a catastrophic effect on life, whereas other large impacts, such as the 35 Ma Chesapeake Bay impact, caused only a minor lasting record. Are the critical factors for global environmental devastation the energy of impact, the chemistry of the target rocks, multiple environmental stresses, and/or the vulnerability of life at the time of impact? Chicxulub is the largest known impact since the Cambrian explosion; the only other impacts of similar size are approximately two billion years old. The Chicxulub impact occurred on a continental shelf and the release of gases from the carbonate-evaporite sediments may have been particularly lethal. In addition, some biologists suggest that mass extinctions occur when life is particularly vulnerable to environmental/ecological change and unable to adapt. To further examine these issues, the new phase of scientific ocean drilling should target Chicxulub and other specific impact craters and also sample sites known to be expanded sections across key global events, such as the Permian/Triassic boundary. Where impact is a potential cause of extinctions, increased use of key isotopic tracers (*e.g.*, Os) may help to support or refute a large impact origin for an event.

Future drilling can also play a role in understanding how impacts affected microbial life on Earth. Insofar as microorganisms ultimately depend upon elements released from rocks as a result of geochemical cycles in suitable habitats, then these energetic and perturbing events would be expected to play a significant role in the emergence of microbial life (Cockell *et al.,* 2002). Most of the microbiota on Earth resides in the subsurface; thus, a complete understanding of the effects of impacts on life means that different impact craters must be drilled and the effects of impact on the microbiota examined.

Even the impact of relatively small asteroids or comets can have disastrous consequences for our civilization. There is a one in 10,000 chance that a large asteroid or comet two km in diameter (corresponding to a crater of about 25-50 km in diameter) may collide with the Earth during the next century, severely disrupting the ecosphere and annihilating a large percentage of the Earth's population. Understanding of impact structures, their formation processes, and their consequences should be of interest not only to Earth and planetary scientists, but also to society in general. Hazardous impact effects are dependent on the energy and site of impact. A large-sized impact will have a global effect as material is ejected at high velocity. These ejecta then spread around the world temporarily blocking out sunlight and causing rapid cooling. The environmental effects will be more severe if the target rocks are volatile-rich and large volumes of climatically active gases are released on impact – as is postulated for the Chicxulub impact (Pierazzo *et al*., 2003).

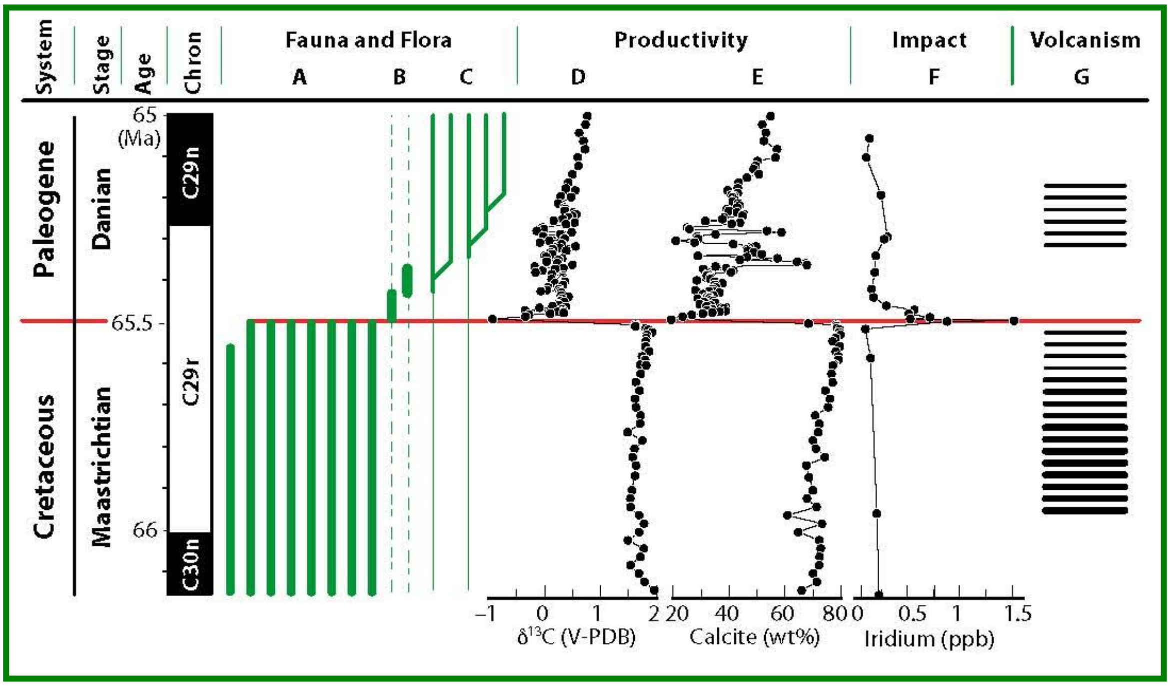

Figure 6.1 K/Pg boundary mass extinction event and its clear correlation to the Chicxulub impact. Many (>60%) Cretaceous species experienced mass extinction at the boundary (A), whereas successive blooms of opportunistic species (B) and radiation of new species (C) occurred in the Early Paleogene. V-PDB - Vienna Pee Dee Belemnite; wt % - weight %; ppb - parts per billion. The mass extinction coincides with a major perturbation of the global carbon cycle as indicated by a negative $\delta^{13}C$ anomaly (D), a major drop of carbonate sedimentation in the marine realm (E), and the enrichment of PGEs in Chicxulub ejecta deposits (F). Composite stratigraphic column of the formations of the main Deccan Trap flood basalt province showing their cumulative thickness and estimated basalt volumes (G). Figure from Schulte *et al.,* 2010.

Impacts in the ocean will cause tsunamis, whereas impacts on the continents and continental shelves will cause landslides (which can trigger tsunamis) during crater formation. They may also generate earthquakes that induce landslides and gravity flows, as occurred around the Gulf of Mexico and Atlantic margins following the Chicxulub impact. Even much smaller events are a severe local hazard; for example, the Tunguska explosion ~100 years ago in Siberia caused high-speed winds, which would have been catastrophic if the impact site had been near a populous city. In general, the hazardous effects will be greatest close to the impact (Collins *et al.*, 2005). Impacts arrive at velocities of >11 km s^{-1}, which generate shock waves in the atmosphere that cause high-velocity winds. On impact, rapid compression and heating cause the target rocks to be vaporized and melted and material is ejected at high velocity in a vapor plume, which can cause fires.

Almost 70% of the Earth is covered by ocean. Impacts into the water generate intensive surface waves, which transform into tsunamis in shallow water (Ward and Asphaug, 2003; Wünnemann *et al.,* 2007). The number of people affected by a tsunami depends upon how far the beaching wave rises in elevation (the run-up) and how far the waves surge inland (the run-in). Both values are defined by initial conditions (*i.e.*, projectile size and oceanic depth), but also by the sea-bottom and coastline topography. On average, one near-Earth asteroid (Fig. 6.2) will survive atmospheric transit and strike somewhere into Earth's oceans every 5,880 years. In a mean generic scenario, the tsunami from the impact would affect 1.1 million people and destroy $110B of infrastructure. A generic impact of a 400-m diameter asteroid like 2004MN4 would destroy $400B of infrastructure. For comparison, the estimated infrastructure loss due to the December 2004 Sumatra tsunami was $10B (Chesley and Ward, 2006).

Key questions that can be answered by drilling include: What are the size, frequency, and geographic distribution of bolide impacts and any associated tsunamis? What are the short- and long-term effects on global climate and ecosystems from impacts of various sizes and into various target rocks (*e.g.*, impact-induced 'winter' and 'summer', changes to atmospheric chemistry)? Why do some large impacts cause extinctions, whereas others do not? Can the resulting climate record in the wake of an impact be detected in the stratigraphic record? This line of inquiry has clear ties to paleoceanographic studies. How do regional ecosystems respond to major events? What is the time frame for recovery after an impact? What magnitude of event causes irrevocable change and why? What is the production and distribution of impact material during the cratering process, from the proximal to distal setting (and worldwide)? What are the physical-chemical processes resulting in excavation and dispersal (*e.g.*, role and type of lithology, presence/absence of water)?

Obtaining the data necessary to answer these questions can be accomplished by drilling transects across craters and through basin-wide to global-scale examinations of key time intervals. Goals would be to obtain basin-wide to global event stratigraphy; identify the source, timing, and geographic distribution of deposits; and document biosphere and stratigraphic changes in the marine record. Ocean drilling is uniquely suited due to the better-preserved sediment record in submarine environments, which are unaffected by subaerial erosion. Examination of proxies in the paleo-record for significant changes in climatically active gases and aerosols that induce climate change and potentially mass extinctions, evidence of impact-induced winter and summer, and potential suggestions for destruction of the ozone layer are all important targets for drilling with clear synergies in terms of proxy development with paleoclimate studies. Determining impact recurrence history and the effect of the target rock can lead to improved event prediction and hazard mitigation.

Impact craters also are known economic resources, serving as reservoir rocks for petroleum and also hosting economic metal deposits (*e.g.*, Sudbury crater in Canada with its enormous reserves of tin and copper sulfide). Impacts, cataclysms, and key events such as the extinction of the dinosaurs are also of major interest in geosciences education and public relations, as these events garner intense public excitement.

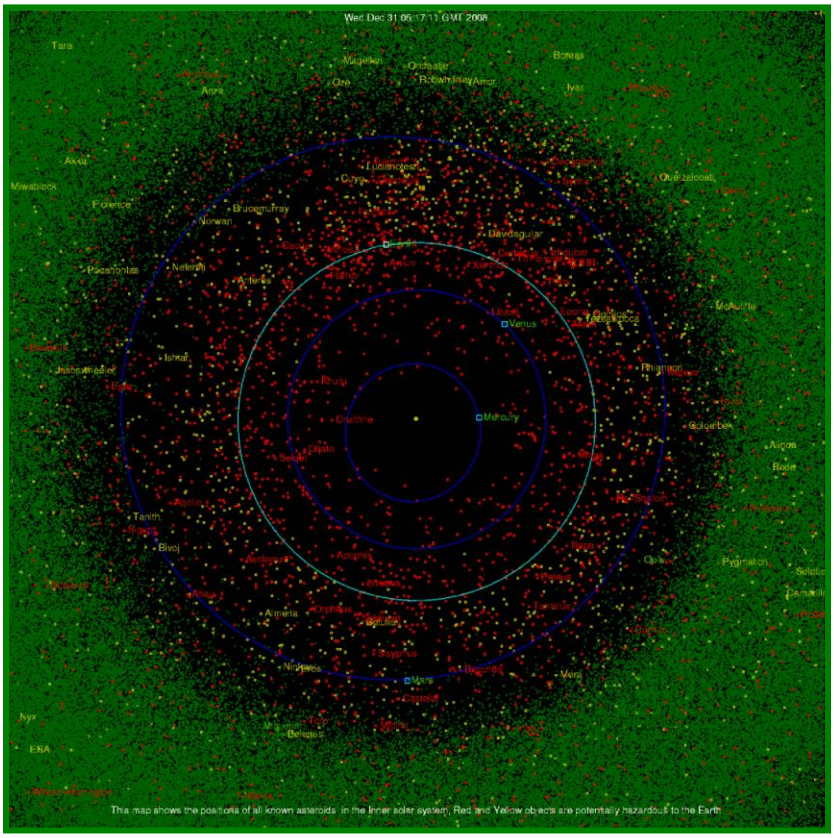

Figure 6.2 Map of the Solar System with all known near Earth asteroids in 2008 (from Armagh Observatory http://szyzyg.arm.ac.uk/~spm/neo_map.html); reds and yellows could potentially impact Earth whose orbit is shown in light blue.

6.1.2 Catastrophic volcanism

Mass movement in the solid Earth, from deep mantle to the surface of the planet and back again, occurs in two fundamental modes driven by the energy of radioactive decay. In the first mode, steady-state convection of primarily the upper mantle results in the plate tectonic cycle of ocean basin opening, aging, and closing. In the second mode, intermittent, whole-mantle overturn results in periods of eruption of LIPs, faster than usual seafloor spreading and arc collisions, and sea-level highstands (Fig. 6.3). Strong evidence is accumulating that the second mode, last prominent in the Cretaceous to early Tertiary Periods (135-55 Ma), produced rapidly constructed igneous systems on

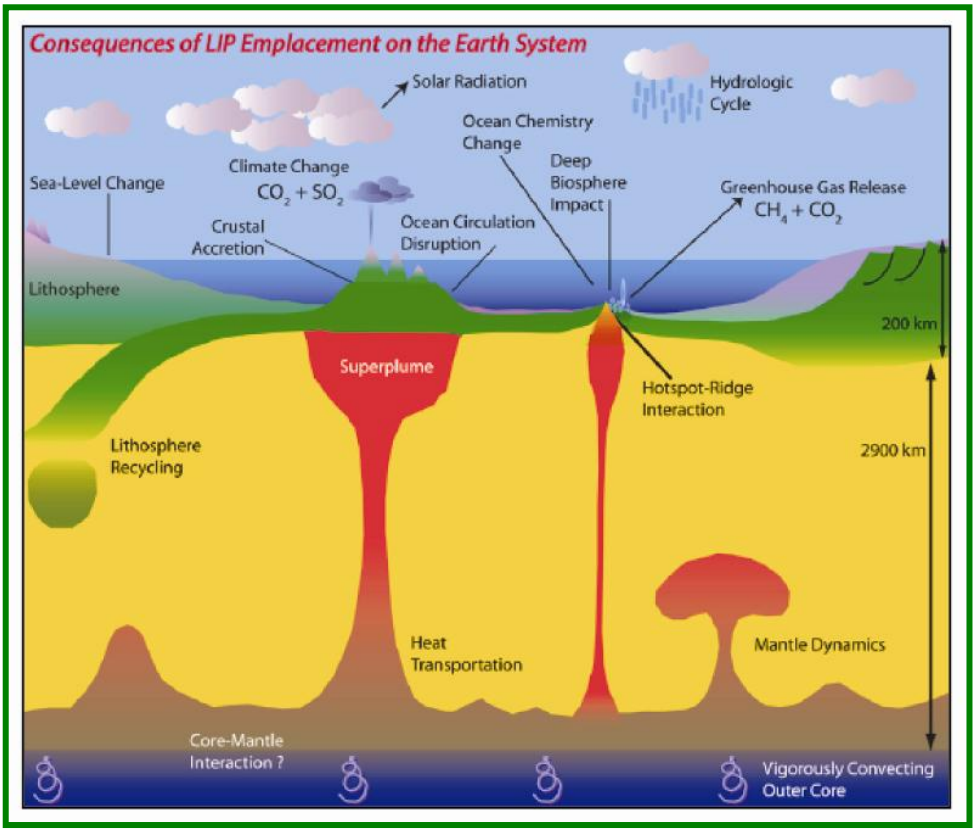

Figure 6.3 Cartoon view of whole-mantle convection, with emphasis on the intermittent, mantle-overturn style of mass and energy transfer from the deep mantle to the surface. The apparently extreme rates of magma production and eruption of Mg-rich lava compositions during LIP events (continental flood basalts, volcanic rifted margins, ocean plateaus) require delivery of enormous volumes of super-hot mantle to the base of the lithosphere, pictured here as a 'superplume'. Source components are possibly primitive deep mantle plus recycled slab material (ocean crust and sediments) from ancient subduction zones. Heat from the core may be partially responsible for the generation of a warm, buoyant layer at the base of the mantle (D") from which superplumes rise. Models suggest that this layer thickens gradually until buoyancy overcomes viscosity, spawning a period of superplume activity, such as during the Cretaceous-early Tertiary Periods. Rapid upper mantle melting and eruption through the lithosphere produces a LIP that releases volatiles into the atmosphere (continental) or degasses and exchanges hydrothermally with seawater (oceanic), leading to rapid environmental change (from Neal et al., 2008).

both continents and in ocean basins at extraordinary eruption rates. How rapid? What volumes? What total duration? What chemical exchange? These are critical questions that have huge implications for geodynamic mechanisms for their origin and for their potential environmental impacts, such as mass extinctions, rapid global warming, ocean acidification, and OAEs.

Continental LIPs (*e.g.*, Deccan, Karoo, Siberia) are generally more accessible than submarine plateaus and volcanic rifted margins, but original volumes are difficult to estimate due to erosion and environmental effects are often conjectural given incomplete records. However, volumes of individual eruptions as large as 10^3 to 10^4 km^3 can be calculated from the mapped distribution of lava flows. Modern improvements in radiometric dating (^{40}Ar-^{39}Ar and U-Pb zircon) have shown generally short durations of peak volcanic activity (<1 m.y.) that correlate with periods of rapid environmental change and biodiversity turnover (mass extinctions; Fig. 6.4). Recent measurement of paleo-secular variation in Deccan lava flows implies that single, large eruptions may have occurred over as little as decades (Chenet *et al.*, 2009). Such enormous rates of magma production and volcanism are unknown in steady-state, plate boundary sites of magmagenesis and require geodynamic models that produce rapid mantle melting over large regions. The consequences for atmosphere, ocean, and biosphere impacts increase directly with eruption rates.

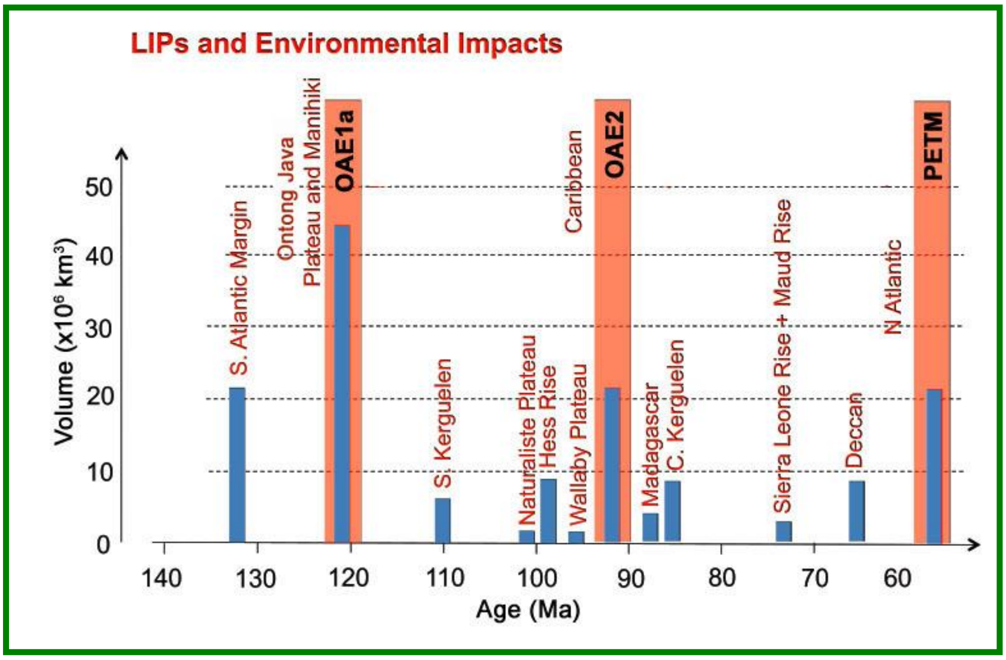

Figure 6.4 Estimated LIP volumes and their ages within the Cretaceous-early Tertiary interval of superplume generation. Individual LIPs are believed to have erupted rapidly, although timescales of peak activity and total duration are largely unknown. Three of the most extreme global environmental changes in the oceans occurred during OAEs 1a and 2 and the PETM, contemporaneous with three of the largest volume LIPs (N. Ohkouchi INVEST presentation modified from Eldholm and Coffin (2000)).

We know much less about the timing and physical characteristics of oceanic LIPs, but it is clear from estimated volumes that these are easily the largest igneous events in Earth history. Several ocean plateaus (*e.g.*, Ontong Java, Manihiki, and Hikurangi (Fig. 6.5) and Caribbean) are 20-40 million km^3. Emplacement of these plateaus appears to correlate with abrupt periods of global changes in ocean chemistry (OAEs 1a and 2 and the PETM). Evidence linking the submarine volcanic eruptions with these major changes in ocean chemistry and biology includes large accumulations of trace metals (Snow *et al.*, 2005) and isotopic excursions (Kuroda *et al.*, 2007; MacLeod *et al.*, 2008; Turgeon and Creaser, 2008) that are consistent with an ocean plateau source (Fig. 6.6).

Discovering the full eruptive history of such enormous features presents several major challenges. The ocean crustal sections of lava flows and sills that make up the plateaus are 15-30 km thick, which is too much to penetrate by drilling. Portions of a complete volcanic history might be accessed in a condensed section at the 'feather-edge' of the plateau margin, but it is more likely that initial eruptive products are buried beneath the center of each plateau and only the very largest flows reach the edges.

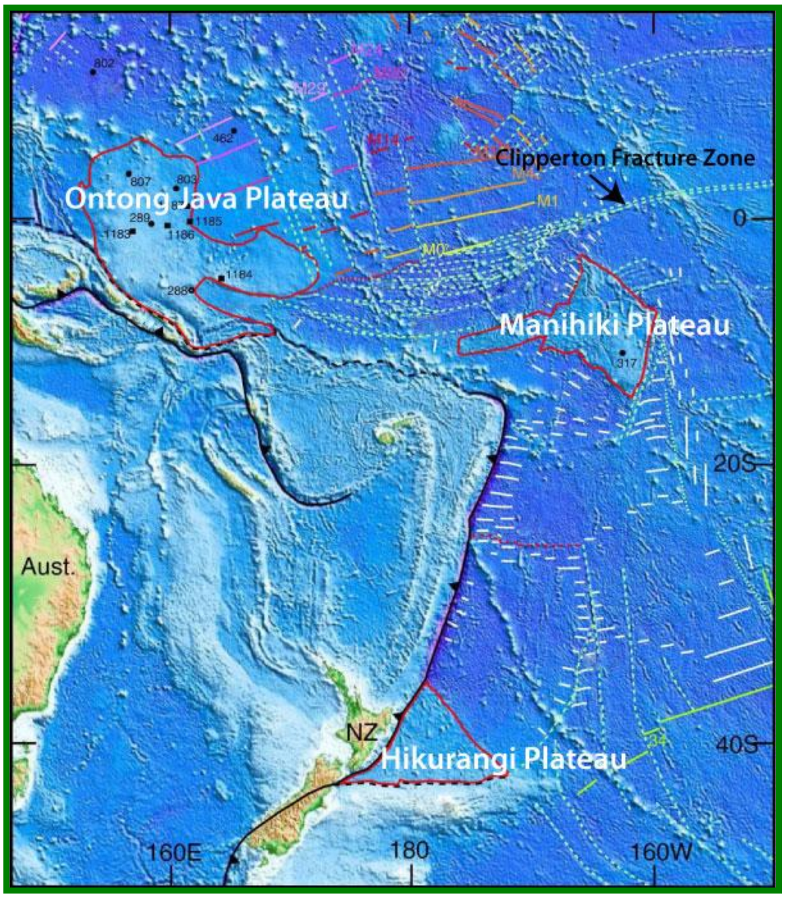

Figure 6.5 The largest known LIP now lies in the SW Pacific, as the Ontong Java, Manihiki, and Hikurangi Plateaus (outlined in red) that were separated by spreading ridges active in the Late Cretaceous. The southern margin of the Manihiki Plateau is faulted and may offer access to the inner architecture of the plateau through offset drilling (K, Hoernle, personal communication). Abyssal hill seafloor fabric (white lines), fracture zones (coarse dashed green lines), triple junction traces (fine dashed green lines), zigzag rift boundary (fine dashed red line), trenches (black lines with barbs on the upper plate), and sutures (dashed black lines) are shown. Black numbers label drill sites (DSDP, ODP). Magnetic lineations are color-coded and labeled 34 and M0-M29. Figure from Taylor, 2006.

An alternate approach to determining the full eruptive history of oceanic LIPs and the resulting environmental responses is to drill and recover marine sediments in an array of proximal and distal sites (Fig. 6.7). High-resolution, orbitally tuned sections can provide the time frame for recording volcanic activity using isotopic 'fingerprints' for degassing and hydrothermal activity (Fig. 6.6). Trace metal abundances can indicate periods of peak activity and distance from the source. Drilling at the LIP itself is still needed to: (1) use lava flow compositions to constrain geodynamic models of mantle melting (source, depth, temperature, degree of partial melting, interaction with pre-existing lithosphere) and (2) confirm that degassing and hydrothermal activity were responsible for the signals measured in contemporaneous sedimentary sections.

A cross-cutting initiative

An extreme-events initiative links many high priority science goals across several broad themes (Fig. 6.8) and would answer fundamental questions about evolutionary processes, ecosystem responses to global change, and tipping points, including: How have ecosystems and biota responded to critical events in Earth history? What do past ocean acidification events imply for response to future global change? What ecosystem assembly rules are revealed by recovery from mass extinctions and hyperthermals? What are the processes that generate and destroy biodiversity? What are the oceanographic and climatic drivers of ecological assembly, speciation, and extinction?

One of the highest priorities of this theme is an improved understanding of the effects of a perturbation (impacts, LIPs, global anoxia, thermal extremes) on biota.

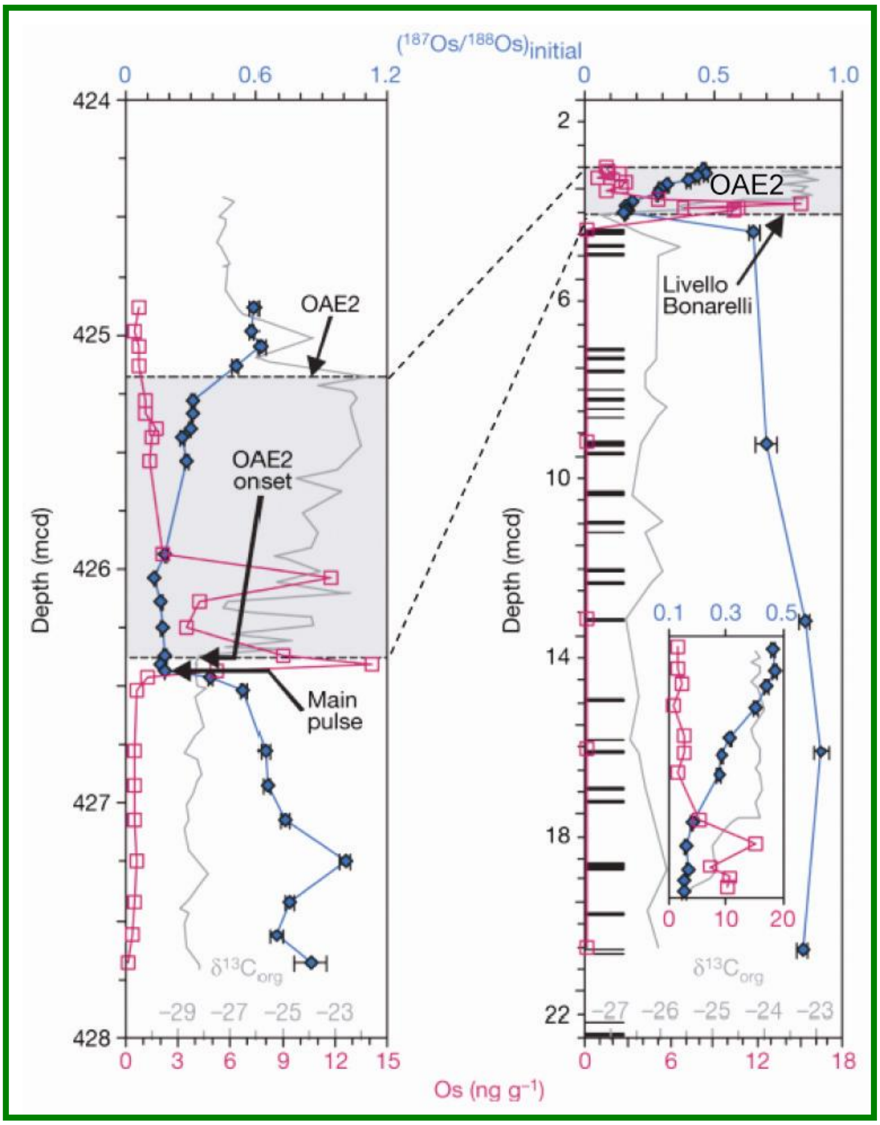

Figure 6.6 Seawater ^{187}Os/^{188}Os isotopic excursion for bulk marine sediment from two sites that record OAE2 (Demerara Rise, ODP Site 1260 (left) and Furlo, N Italy (right)). The long-term seawater Os-isotopic composition (^{187}Os/^{188}Os = 0.6) is determined by a balance between continental input (^{187}Os/^{188}Os = 1.4) and mantle input (^{187}Os/^{188}Os = 0.12). Both locations show an abrupt drop from the long-term average composition to mantle values just before OAE2 commencement, continuing through and rising toward the end of OAE2. This indicates a large additional mantle input to the oceans, coincident with OAE2, and consistent with the Caribbean LIP construction (from Turgeon and Creaser, 2008).

LIPs can be studied as extreme mantle melting and volcanic events to answer questions about geodynamic models whose critical distinctions are magma flux through time, geochemical variability, and internal architecture, all of which are best answered by drilling to obtain direct samples and far-field, high-resolution marine sedimentary sections. LIPs are also relevant to understanding Earth's resources since many of the most productive petroleum-bearing sedimentary formations were deposited during OAEs when large volumes of marine organic matter were buried (*e.g.*, La Luna Formation (Colombia/Venezuela) during OAE2).

Finally, LIPs need to be studied as potential causes of extreme events and rapid climate change. Examples are the study of abrupt warming (PETM) and cooling events, changes in ocean chemistry (OAEs) and ecosystem response, and integration with improved climate models to gain better understanding of likely futures as we head into a high pCO_2 world.

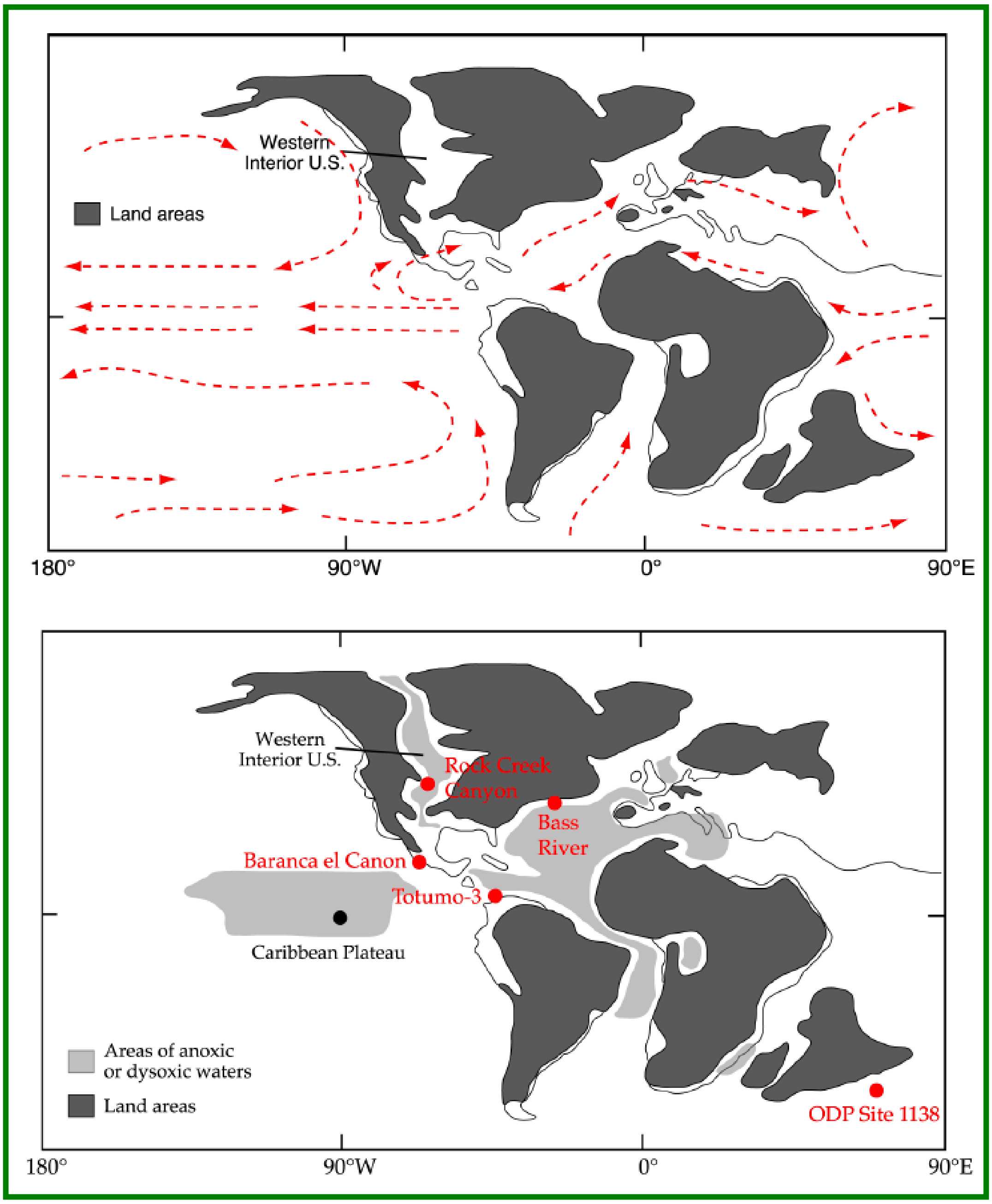

Figure 6.7 Plate reconstruction for the Late Cretaceous, showing generalized surface ocean circulation (above) and the location of five marine sedimentary sections (below) that record anomalously high abundances of trace metals at OAE2 (Cenomanian/Turonian boundary, 93 Ma), contemporaneous with initial volcanic activity that constructed the Caribbean Plateau (from Snow, 2003). New drilling sites to the west of the Caribbean Plateau, in the central Pacific, should provide the best record of total duration and peak production of volcanic activity through isotopic excursions (Nd, Pb, and Os) and trace metals released during submarine eruptions.

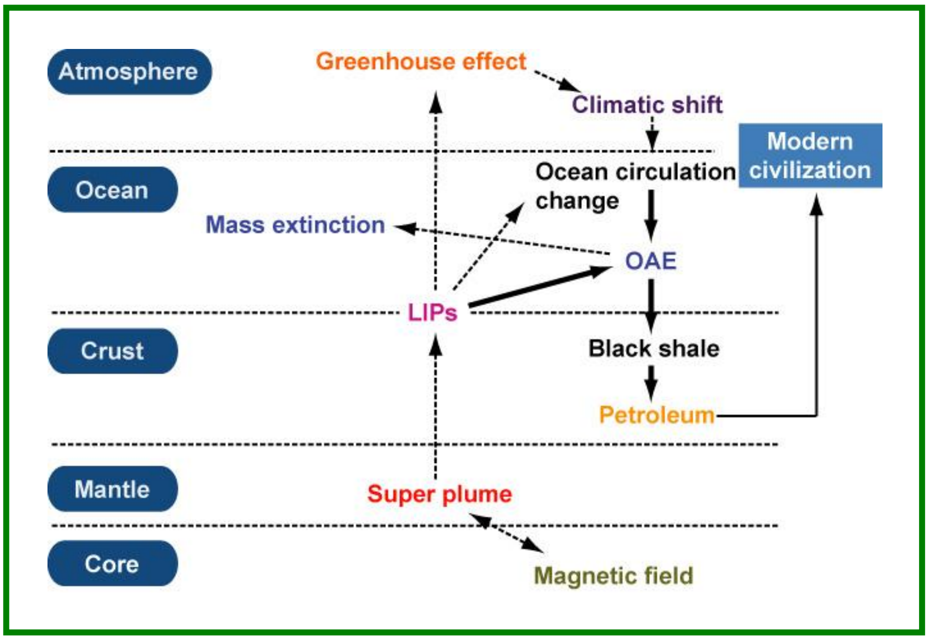

Figure 6.8 Proposed interconnections between reservoirs and fluxes within the Earth system during extreme volcanic events (from N. Ohkouchi, INVEST meeting personal communication). The emplacement of LIPs, an expression of the Earth's interior behavior, could explain episodes of enhanced greenhouse gas input to the atmosphere and subsequent climatic and ocean circulation changes that led to OAEs. OAEs are extreme oceanic events that resulted in biological impacts and markedly enhanced organic carbon burial.

6.2 Hominin Evolution

Scientific ocean drilling can transform our understanding of the role of past African climate changes on early human evolution. Current hypotheses of human origins suggest that late Neogene changes in northeast African climate influenced the evolution of human ancestral lineages, leading to the emergence of traits that are uniquely human: bipedality, exceptionally large brains, and the construction of increasingly sophisticated stone tools.

The basic premise of these hypotheses is that large-scale shifts in climate alter the ecological composition of a landscape which, in turn, presents specific faunal adaptation or speciation pressures leading to genetic selection and innovation. Emerging fossil faunal and paleoclimate data broadly support this idea but fundamental questions remain concerning the timing, nature, and causes of African climate variability and for defining the imprint of climate change on the fossil record of faunal evolution. "*The field of paleoanthropology is on the brink of novel ideas and datasets concerning the* how *and* why *of hominin evolution. Tremendous advances in the environmental sciences are forcing these developments to occur*" (Potts, 1998).

The rationale supporting a major drilling initiative to understand the role of past climate change in human evolution is compelling. There are presently very few ocean drilling sites off East Africa, where the majority of hominin fossils are found, and none of these are suitable for comprehensive paleoclimate research. While some DSDP sites drilled over thirty years ago in the Gulf of Aden have been useful for low-resolution paleoclimate records (Feakins, 2006), these were rotary drilled and have significant recovery gaps and disturbed intervals. No shallow (carbonate-bearing) sites exist along the entire east coast of Africa, nor are any sites available near the mouths of major river systems draining the East African interior. Most of our current understanding of East African paleoclimate changes comes from marine records of aeolian dust export from sites off subtropical west and northeast Africa (deMenocal, 2004) and it can be reasonably argued that these records are distal from the fossil localities themselves.

Ocean drilling has a unique opportunity to contribute observations to test the hypothesized role of past climate changes in shaping the course of human evolution. Terrestrial paleoclimate records from East African fossil localities or from lake basin drilling programs are either too short or stratigraphically incomplete. Ocean drilling of specific, previously-undrilled sedimentary packages described below provides the best opportunities for constraining the timing, nature, and causes of paleoclimatic change in this geographic region where our ancestors evolved.

6.2.1 Key events and environmental hypotheses of human origins

Bursts of evolutionary activity and behavioral changes punctuate the fossil record of early human evolution (Fig. 6.9). Although the fossil record is still incomplete, two time windows encompass key evolutionary events near 3.0–2.5 Ma and 2.0–1.5 Ma that effectively shaped the characteristics that define us as human (see summary in Potts, 2006). Impressively, these same time windows also include dramatic changes in other African mammalian taxa such as bovids and rodents (Vrba, 1995).

Between 3.0–2.5 Ma at least two new hominin lineages emerged (*Paranthropus* and early *Homo* genera) from an ancestral lineage that itself became extinct at this time (*Australopithecus afarensis*); this interval also marks the first appearance of stone tools (Semaw *et al.,* 2003) (Fig. 6.9). Members of the *Paranthropus* lineage are distinctive for their robust, massive frames, large and broad post-canine (molar) dentition, specialized chewing adaptations (sagittal crest), and intermediate cranial volumes. The *Paranthropus* lineage first appeared at ~2.7 Ma (Fig. 6.9). The fossil record of African bovids (antelope family) indicates evidence for exceptional faunal first and last appearances near this time, roughly synchronous with the appearance of specialized arid-adapted grazers (Vrba, 1995; Bobe and Behrensmeyer, 2004; Bobe *et al.*, 2002). The earliest record of stone tools, at ~2.6 Ma, is from Gona, Ethiopia (Oldowan industry) (Semaw *et al.,* 2003).

By 1.8–1.6 Ma, *Homo habilis* became extinct and its immediate successor and our more direct ancestor, *H. erectus*, first occurs in the fossil record near 1.8 Ma (Kimbel, 1995). *Homo erectus* may have migrated to southeast Asia as early as 1.9–1.8 Ma (Swisher *et al.,* 1994). Near 1.7 Ma, South African (Reed, 1997) and East African bovid assemblages shifted toward further absolute increases in the abundance of arid-adapted species (Vrba, 1995). Earliest occurrences of the more sophisticated Acheulean tool kit (bifacial blades and hand axes) occurred near 1.7–1.6 Ma (Ambrose, 2001; Clark *et al.,* 1994) (Fig. 6.9).

Environmental hypotheses of early human evolution share the view that changing African environmental conditions over the late Neogene selected for the morphological and behavioral characteristics that make us human. Where hypotheses differ is in the proposed role of climate change in natural selection. The Savannah Hypothesis is perhaps the best known of the habitat-specific hypotheses of African faunal evolution

(Bartholomew and Birdsell, 1953; Dart, 1925; Klein, 1989; Wolpoff, 1980). Current interpretations of the Savannah Hypothesis state that the evolution of African mammalian fauna, including early hominins, was primarily linked to the progressive expansion of more open grassland conditions. The Turnover Pulse Hypothesis is a recent variant of this idea and posits that focused bursts of biotic change (quantified in terms of first and/or last appearance datum clustering) were initiated by progressive shifts toward greater African aridity that occurred roughly near 2.8 Ma and 1.8 Ma (Vrba, 1985, 1995). The Variability Selection hypothesis accommodates one of the more obvious yet also curious features of the fossil record (Potts, 1998). Fossil hominin and other mammal lineages typically persisted over long durations (10^5 to 10^6 year) yet they are preserved within sediment sequences recording rapid, orbital scale (10^3 to 10^4 year) climate oscillations (deMenocal, 1995; Dupont and Leroy, 1995; Feibel *et al.*, 1989). This view suggests that changes in the amplitudes of orbital African climate variability, linked to the eccentricity modulation of precessional monsoonal cycles, may have been an important genetic selection criterion. A fundamental limitation to testing these hypotheses has been the lack of suitably detailed, well-dated, and multi-proxy reconstructions of African climate variability to constrain the basic paleoclimate history of the region. How and why did African climate change?

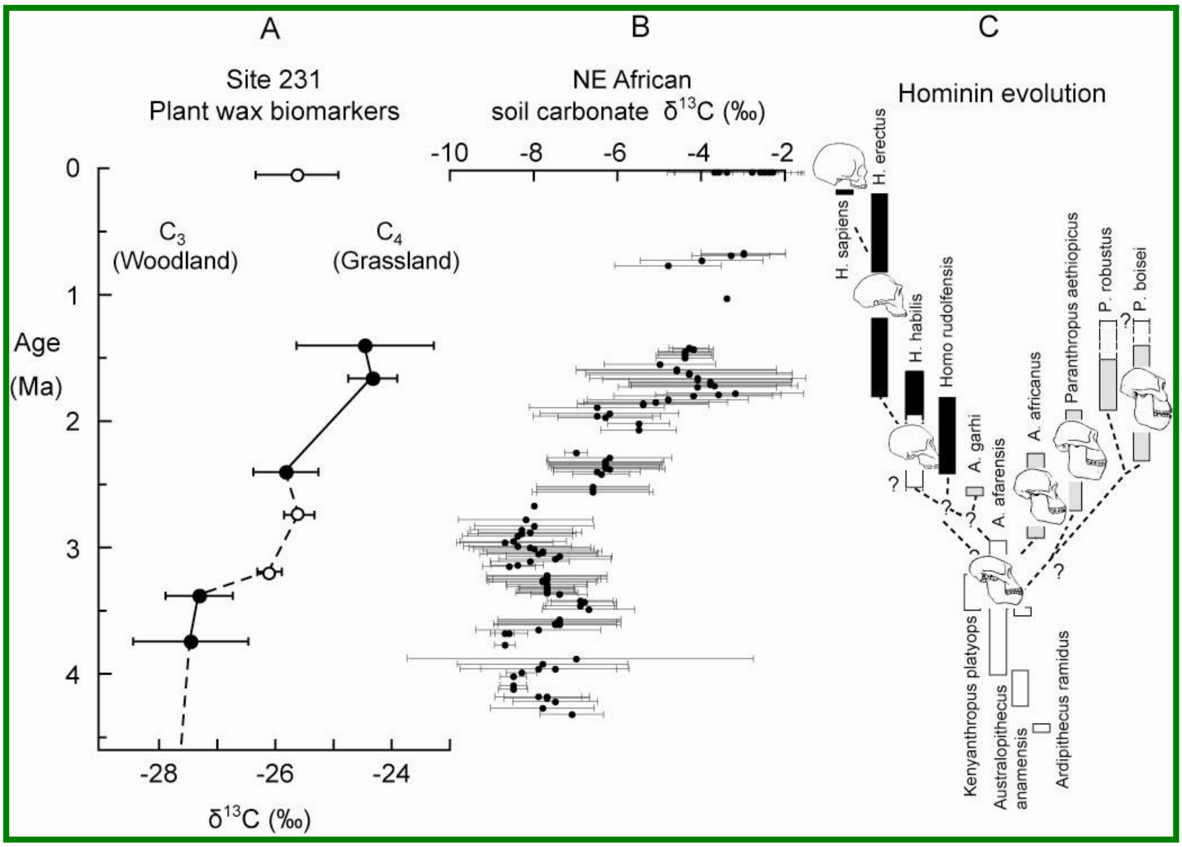

Figure 6.9 Summary figure from Feakins *et al.* (2005). A) Interval means and (1σ) standard deviation of C_{30} *n*-alkanoic acid $\delta^{13}C$ for intervals >40 k.y. in duration (filled circles) and for intervals <40 k.y. induration (open circles, dashed lines). B) Soil carbonate $\delta^{13}C$ from Turkana Basin (northern Kenya); means and (1σ) standard deviations from individual stratigraphic layers (from sources in Feakins et al., 2005). C) Phylogeny of major hominin lineages throughout Pliocene-Pleistocene (from sources in deMenocal, 2004).

6.2.2 African paleoclimate history

Over the late Neogene, North Africa and equatorial East Africa experienced a long-term drying trend that commenced near 3 Ma, culminating in the driest, most open conditions around 1.8 Ma. Superimposed upon this aridification trend are rapid, orbitally paced wet-dry cycles that persisted throughout the Neogene (see summary in deMenocal, 2004). Evidence documenting this pronounced shift to more open conditions has been found in carbon isotope analyses of East African soil carbonate nodules, indicating a dramatic increase in the proportion of C4 (grassland) vegetation that commenced near 3 Ma and reach maximum development near 1.8 Ma (Fig. 6.9) (Cerling, 1992; Cerling *et al.*, 1994; Wynn, 2004). At Gulf of Aden DSDP Site 231, a comparable record of C4 grassland expansion was established using carbon isotope analyses of plant wax biomarker compounds (Feakins, 2006) (Fig. 6.9). At Site 231 there is a 40% increase in C4 representation over the last 4 Ma from a nearly pure C3 baseline in the early Pliocene. Higher resolution analyses at Site 231 also resolved orbital-scale (precessional) vegetation cycles and, surprisingly, these were found to have peak-to-peak amplitudes that were as large as the overall late Neogene trend.

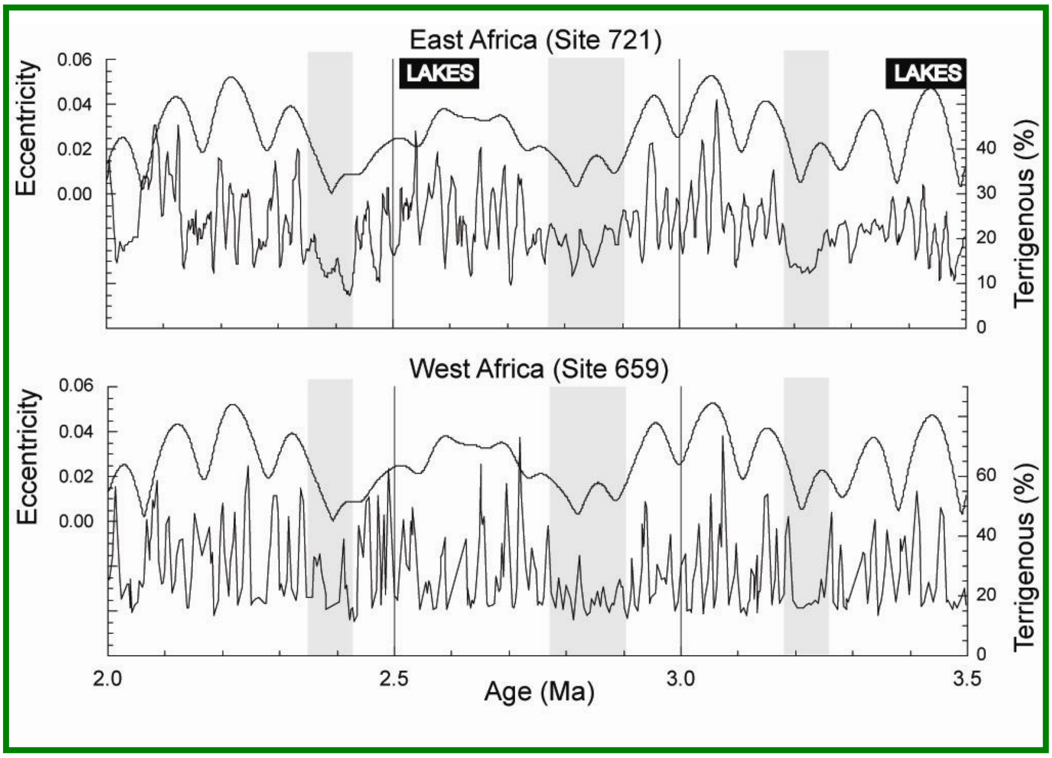

Figure 6.10 Evidence for high- and low-amplitude African climate variability 'packets' from West and East African Sites 659 and 721/722 (deMenocal, 1995; Tiedemann *et al.*, 1994). African paleoclimate variability over this interval was strongly regulated by orbital precession, which is modulated by orbital eccentricity (shown). Prolonged (10^4-10^5 year) intervals of exceptionally high- or low-amplitude paleoclimate variability are apparent off both margins of subtropical Africa. Highest variability occurs during periods of maximum orbital eccentricity *(e)* when modulation of the precession index ($\Pi = e*\sin(\omega)$) and the seasonality of low-latitude insolation receipt is greatest (Berger, 1978; Prell and Kutzbach, 1987). Low variability intervals are shaded. The filled black rectangles denote lactustrine depositional phases between 2.51–2.66 Ma recorded at several NE African terrestrial localities (Trauth *et al.*, 2005). Figure modified from deMenocal, 2004.

African paleoclimate history also includes persistent orbitally paced wet-dry climate cycles throughout the Neogene linked to orbital precession regulation of African monsoonal rainfall intensity. The Mediterranean sapropel record is one of the most compelling examples of orbital climate control. Ocean drilling in the eastern Mediterranean and careful fieldwork on older, uplifted sediments in southern Italy have documented the strong eccentricity and precessional response of sapropel deposition related to episodes of enhanced Nile River outflow linked to orbital monsoon forcing. These same precessional climate cycles are also detected in aeolian dust records from ODP sites off East and West Africa (Clemens *et al.,* 1996; deMenocal, 1995; Tiedemann *et al.,* 1994). These eccentricity-modulated variability 'packets' represent 10^4-10^5-year intervals of exceptionally high- or low-amplitude paleoclimatic variability. Some of the largest amplitude packets are associated with widespread deposition of deep lake diatomite facies in East African Rift basins (Trauth *et al.,* 2005) (Fig. 6.10).

Ocean drilling can significantly contribute to dating the fossil record of human evolution. Dates for most fossil material are obtained by either direct radiometric dating

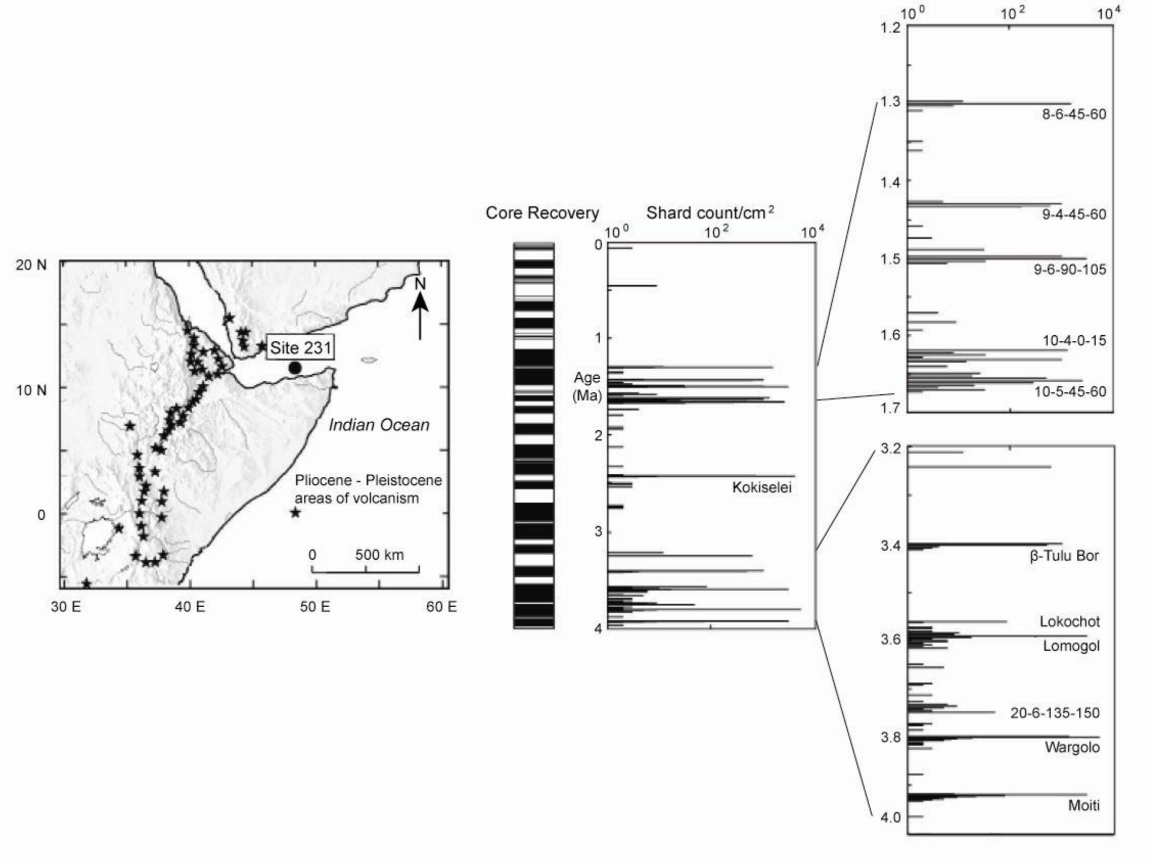

Figure 6.11 Volcanic ash shard abundances at DSDP Site 231 (modified from Feakins *et al.*, 2007). Areas of known volcanic activity during the Pliocene and Pleistocene are identified with asterisks. Approximately 15-20 tephra layers are identified for the Pliocene-Pleistocene interval. Continuous scrape-sampling provides a complete downcore sedimentary record throughout the last 4Ma where sediments were available (solid); gaps in the sediment recovery indicate areas where no data on tephrostratigraphy are available (recovery was about 70%), so many tephra layers were probably not sampled.

or indirect stratigraphic dating of fossil material intercalated between datable volcanic tuff deposits. Since the East African Rift region has been volcanically active for much of the late Neogene, the rift basins have been periodically blanketed with tephra from hundreds of discrete volcanic eruptions. A relatively small number of these tuffs have sufficiently large/abundant phenocrysts for direct ($^{40/30}$Ar) dating and the majority of ash layers serve as marker beds with approximate (interpolated) ages. These same ash layers are found and indentified geochemically in marine sediments offshore of East Africa (Fig. 6.11). Here they can be dated directly using the orbitally tuned oxygen isotope stratigraphy. This has been demonstrated for some ash layers preserved in Arabian Sea and Gulf of Aden sediments (deMenocal and Brown, 1999; Feakins *et al.*, 2007), but a larger, all-Africa integration of tephra stratigraphy with the marine oxygen isotope stratigraphy awaits new core material.

6.2.3 East African river systems as archives of regional climate variability

To constrain African paleoenvironmental changes during the late Neogene will require the recovery of sediments that specifically address the timing and signatures of African climate change over the subtropical African geographic domain where hominin fossils are found, including South Africa, Tanzania, Kenya, and Ethiopia. Ocean drilling targets would need to be prioritized by their anticipated scientific contribution to the primary question of whether climate change impacted African faunal evolution. This section addresses the most valuable drilling targets – sites that, if drilled, would reshape our understanding of the timing and causes of African climate changes over the period of major African faunal evolutionary changes.

Jubba, Rufiji, Limpopo, Orange, and Zambezi distal fan drilling

Among the most promising new opportunities for reconstructing past changes in African climate are sediment packages accumulating near the mouths of rivers draining large sectors of subtropical and tropical Africa (Fig. 6.12). Hemipelagic sediments accumulating near the mouths of rivers draining interior East and South Africa (Jubba, Rufiji, Limpopo, Zambezi, and Orange Rivers) would provide promising opportunities for understanding both terrestrial paleoclimate and regional paleoceanographic variability over the Neogene. Smaller river systems in Kenya (Galana and Tana) and Tanzania (Rufiji) were likely much larger and more active systems in the past when African monsoonal rainfall was stronger, based on lithologic evidence of much larger and deeper East African lake systems (Garcin *et al.*, 2009; Trauth *et al.*, 2005).

The largest of these East African drainage basins are, from north to south (Fig. 6.12), the Jubba (800,000 km^2), Rufiji (175,000 km^2), Limpopo (415,000 km^2), and Zambezi Rivers (1,400,000 km^2). The Jubba drainage basin spans roughly one-third of the national area of Kenya, Somalia, and Ethiopia and captures summer monsoonal rainfall, principally off the Ethiopian highlands. The Rufiji drainage basin is the smallest of the three and is confined to eastern Tanzania. The Zambezi drainage basin is the largest of the three (the fourth largest river in Africa) and the drainage basin includes much of Zambia, Malawi, and Zimbabwe. Significantly, the Zambezi drainage basin also includes Lake Malawi, so lacustrine sequences drilled there may be directly compared to offshore drilled sequences of the Zambezi distal fan.

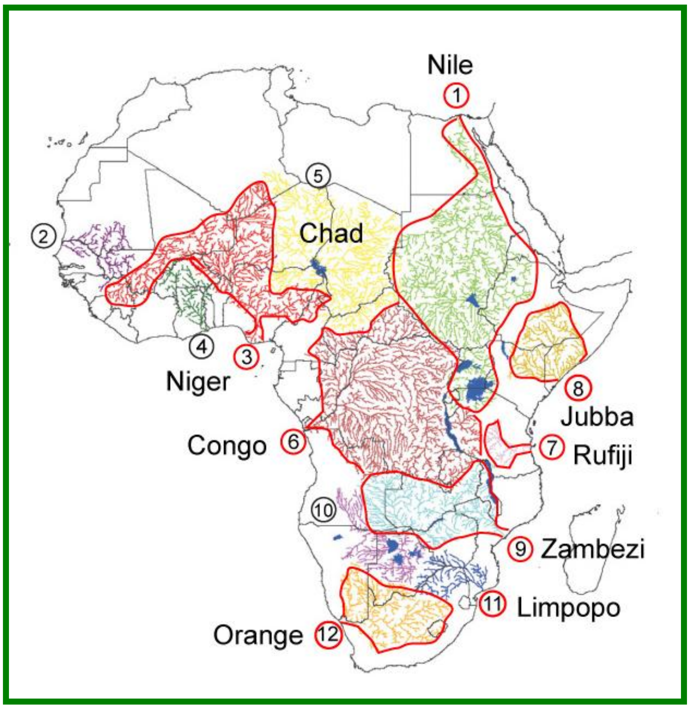

Figure 6.12 African drainage basins (modified from Africa Earth Observatory Network Database http://www.aeon.uct.ac.za).

Africa's largest drainage basins, such as the Nile, Niger, and Congo, each drain several millions of square kilometers and thus represent large areal integrators of regional climate change. Smaller drainage basins of East Africa, such as the Ganane, Rufiji, Zambezi, and Orange rivers, drain terrains containing known hominin fossil localities.

The sediments accumulating in the modest deltaic systems formed by these rivers are comprised of proximal and distal fan deposits. Proximal fan sediments are commonly complicated by turbidites and intermittent sedimentation, whereas distal fans provide more continuous, high accumulation rate, hemipelagic depositional environments. Distal fan sediments are comprised of marine biogenic components (microfossils and marine organic carbon) as well as terrestrial lithogenic (riverine clays and silts) and organic (terrestrial organic matter and biomarkers) sediments. Oxygen isotope analyses of marine foraminifera can be used to constrain an orbital (10^4 year) chronology. The terrestrial organic fraction can be exploited to yield an impressive diversity of proxies that monitor the paleoclimatic, paleohydrological, and paleovegetational history of the specific drainage basin.

Analyses of the terrestrial organic fractions in distal fan environments have presented new opportunities for reconstructing African vegetation and hydrologic changes. River-borne terrestrial organic matter is comprised of a broad spectrum of compounds, or biomarkers, which can be used to record basin-scale changes in regional climate, vegetation, and hydrological balance. For example, a recent study of a sediment core off the Congo fan documented large changes in Congo Basin mean annual temperature using terrestrial biomarkers that record river runoff (Branched and Isoprenoid Tetraether (BIT) index) and soil temperatures (Methylation of Branched Tetraethers (MBT) index), as well as the δD composition of plant wax biomarker to document changes in regional humidity changes (Weijers *et al.*, 2007). Another related study from this same area used δ^{13}C analyses of plant wax biomarkers (*n*-alkanes) to document glacial-interglacial changes in the relative proportion of C3-C4 vegetation in the Congo Basin. These are examples of the approaches that could be applied to East African nearshore sediments recovered under this drilling mission.

Gulf of Aden drilling

The Gulf of Aden is the most proximal ocean basin to hominin fossil localities in Ethiopia, Kenya, and Tanzania and several previous studies on older DSDP material have demonstrated the utility of these sediments for addressing this problem. Several cruises lead by French, Japanese, and American scientists have acquired single- and multichannel seismic lines for the region to identify drill sites. Piston cores obtained at these drill sites indicate high accumulation rates (5-10 cm k.y.$^{-1}$) at these localities. Unfortunately drilling in this region is likely to be challenging given the geopolitical tensions of the Gulf of Aden region.

Together, drilling these regions (the Gulf of Aden and the distal fan deposits from the Jubba, Rufiji, and Zambezi Rivers) would fundamentally reshape our understanding of the timing and causes of African climate changes over the period of major African faunal evolutionary changes.

6.3 Climate-Tectonics Linkages and Feedbacks

Tectonics-climate linkages and feedbacks is a long-standing research theme that has attracted geoscientists' attention, especially those interested in Earth system dynamics. Traditional hypotheses on tectonics-climate interactions generally consider tectonic impacts on climate either through topographic and/or bathymetric changes or through chemical and/or biological processes that control the concentration of atmospheric CO_2. Bathymetric change such as opening of oceanic gateways can fundamentally alter global ocean circulation and therefore climate (Smith and Pickering, 2003). Uplift of mountain ranges can in turn perturb atmospheric circulation and also affect climate (Zhiseng *et al*., 2001). General circulation models can evaluate the effects of changing topography/bathymetry on climate through changes in atmospheric and ocean circulation, the hydrological cycle, and the radiation budget if appropriate boundary conditions are provided. Today, significant research programs in continental dynamics are instead focusing on how climate, through focused erosion, can directly affect tectonics (Berger *et al*., 2008; Huntington *et al*., 2006; Tomkin and Roe, 2007). Within the theme of how tectonics influences climate, the timing and extent of topographic and/or bathymetric changes in key areas are still poorly constrained because of insufficient data; large uncertainty still exists around the important boundary condition of atmospheric CO_2 concentration and how it changes through time. Within the climate influencing tectonics theme, breakthroughs have been made by correlating exhumation rate changes in mountain ranges onshore with known changes in climate. The missing elements are examining the erosional products of these climate-controlled tectonic events in the offshore and equivalent dating resolution.

One way in which tectonics impacts the climate system is through control of atmospheric CO_2 concentrations by silicate chemical weathering and burial of organic carbon. It is well known that silicate weathering, especially weathering of Mg and Ca silicates, is considered an important process to draw down atmospheric CO_2 (Kump *et al*., 2000). Temperature and precipitation are considered two major parameters that control the rate of chemical weathering. Both temperature and precipitation are considered strongly dependent on atmospheric CO_2 concentration; their control on chemical weathering rates has been regarded as a strong negative feedback to stabilize atmospheric CO_2 (Walker feedback) (Walker *et al*., 1981); however, the effect of tectonic uplift on atmospheric CO_2 through enhancement of physical weathering and erosion is not well evaluated. The other process through which tectonics affects atmospheric CO_2 is the burial of organic carbon. Tectonics influences organic carbon burial through two mechanisms: (1) enhancing delivery of nutrients such as P and Si through accelerated chemical weathering and (2) enhancing burial efficiency of organic carbon by increasing sedimentation rates on continental margins (Raymo and Ruddiman, 1992; France-Lanord and Derry, 1997). The influence of tectonics on organic carbon burial and its impact on atmospheric CO_2 have never been fully evaluated because of insufficient data coverage of sediment composition (including P and organic carbon contents) and land-ocean sediment-flux budgets. As a result, the impact on regional and global climate of tectonically driven changes of continent-ocean configuration, increases or reductions in topography/bathymetry, and drawdown of atmospheric CO_2 caused by silicate weathering and organic carbon burial has not been evaluated quantitatively. What is the relative importance of these processes and how does this importance change through geologic time as the Earth enters different climate states?

Ways in which climate can impact tectonics is gathering increasing attention and has become the primary focus for tectonics-climate interplay research. Erosion can be enhanced in key areas, such as on the windward side of orogens, either through focused precipitation increasing river discharge or through development/intensification of temperate glaciers (Tomkin and Roe, 2007). Focused precipitation caused by intensified monsoon or mountain glacier development or intensification caused by global cooling can enhance erosion and preferentially unroof an orogen on the windward side (Huntington *et al*., 2006; Berger *et al*., 2008). Rocks underneath the locus of erosion will be exhumed in these compressional settings and the uplifted rock will be subjected to further erosion, which will induce further uplift. These systems can develop a positive feedback loop governed by strain rate resulting in crustal aneurysms and significant development of relief; many of the highest mountain zones on Earth appear to be the result of these positive feedback loops. Thus, focused precipitation and/or glacial activity and consequent erosion will cause focused exhumation and uplift. Focused exhumation may further induce deformation and erosion/deposition in the surrounding area resulting in significant mass flux from the orogen source to depositional sinks. Additionally, there is evidence that both zones of high exhumation as well as regions with significant sediment burial can result in changes to deformation rate and even fault locations (Berger *et al*., 2008). Quantitative evaluation of this process is still insufficient and the significance of this positive feedback is poorly understood primarily due to a need to match the depositional history with exhumation history at sufficient resolution.

6.3.1 Major hypotheses and questions

Climatic Super Cycle

It is conceptually well established that the Earth experienced warm greenhouse climate and cool icehouse climate alternately over 100 m.y. timescales (Veevers, 1990) and that such long-term climate cycles (the Climatic Super Cycle) are probably related to the so-called Wilson Cycle at least during the Phanerozoic (but more likely since the Proterozoic). However, the relative roles of changing plate configuration and topography/bathymetry of the continents and oceans versus changing concentrations of greenhouse gases, especially CO_2, are poorly understood. Also underconstrained is the relative importance of degassing, chemical erosion, and organic carbon burial on controlling atmospheric CO_2 and whether their relative importance changes during the course of a Wilson Cycle. A fundamental problem in Earth system science is to understand what the role of changing configuration and relief of the continents and oceans is on global climate. Can tectonic reconfigurations drive climate in predictable directions, such as cooling the planet during the assembly stage of supercontinents and heating the planet during subsequent breakup? How important is the role of tectonics on atmospheric CO_2 concentration through geologic time?

Climate-driven erosion and tectonics

Recent hypotheses regarding mechanisms for how climate influences tectonics are erosion-based; thus, the new drilling program is in a unique position to test the prevailing hypotheses through drilling eroded products in offshore depocenters. In the southeast Asian Himalayas, increased precipitation on the windward side of the orogen due to monsoon intensification has been proposed to have enhanced exhumation, especially where major river systems drain the orogen. The unroofed sediments are ultimately deposited in the Indus and Bengal Fans in the northern Indian Ocean. In the St. Elias Mountains in Alaska, the mid-Pleistocene Transition (where glacial-interglacial cyclicity changed from 40 kyr to 100 kyr) is proposed to have intensified erosion associated with glacial advance-retreat cycles, resulting in an order of magnitude increase in exhumation and a shifting locus of fault activity onshore and offshore. In contrast, the onset of Northern Hemisphere glaciation did not appear to have produced a significant change in mountain building. These are examples of cases where there are climate drivers proposed for tectonic responses and where testing these hypotheses requires dating the eroded products deposited offshore. Other orogens such as the Andes, Alps, Zagros, and New Zealand all have been the focus of modeling efforts examining these processes but with few studies of the depositional record.

In order to test both the ideas of the Climatic Super Cycle and climate-driven erosion building mountains we require ground-truth to test key mechanisms, which should be a top-priority theme of the new program. Fundamental questions regarding these tectonics-climate linkages include:

⇒ How does changing configuration and topography/bathymetry of the continents and oceans influence ocean and atmospheric circulations and biogeochemical cycles?

⇒ How do orogens respond to significant climate shifts such as the onset of Northern Hemisphere glaciation, the mid-Pleistocene Transition, and the development of the Indian monsoon?

⇒ How do freshwater, nutrient, and sediment discharge from continents to oceans influence biota and biogeochemical cycles in continental margins and marginal seas?

⇒ How does tectonics affect physical and chemical weathering and delivery of nutrients to the ocean (through enhancement of erosion)?

⇒ How has freshwater, nutrient, and sediment delivery to the ocean changed through time and space (spatial pattern and budget changes with time)?

⇒ How large are the roles of small rivers, groundwater, and aeolian transport on global freshwater, nutrient, and sediment budgets?

⇒ How do continental-margin strata record the history of continents such as exhumation, erosion, climate, vegetation, and topography?

6.3.2 Need for new drilling

In order to test hypotheses and answer the questions described above, global coverage (in time and space) of sedimentary basins, especially in continental margins and terrestrial depocenters, is necessary. Thus far global coverage of key sedimentary basins (especially in Arctic and Antarctic areas) is insufficient and focused studies in depocenters (often deep-sea fans) associated with key mountain ranges do not exist. In this regard, new drilling is strongly desired on continental margins, in marginal seas, and in deep-sea fans. Continental drilling of key intra-continental basins and coordination and integration with continental margin drilling are also highly important. Recent advances in drilling technology make it possible to recover sandy continental-margin strata, which will allow us to constrain sediment, nutrient, and carbon budgets much better than previously, and advances in biogeochemistry allow us to better estimate temporal changes in terrestrial climate and vegetation. For the next drilling program, capturing a complementary array of continental margin and fan records of exhumation and terrestrial climate/vegetation history, sediment, nutrient, and carbon budgets, and freshwater discharges for the highest flux areas will make great strides towards understanding the feedbacks between tectonics and climate.

6.3.3 Implementation strategies and platform needs

In order to achieve the scientific goals related to this theme, the following strategies and technological developments are desired:

⇒ Obtain seismic images for understanding sediment architecture development in continental margins and adjacent fans and good spatial site coverage for sediment, nutrient, and carbon budget calculations.

⇒ Attain high and continuous recovery of unconsolidated sediments such as terrigenous records contained in submarine fan deposits.

⇒ Invent new proxies for evaluation of weathering intensity, exhumation rate, provenance, continental climate, and vegetation.

⇒ Further develop non-destructive and rapid core-scanning techniques for organic geochemistry and cyclostratigraphy.

⇒ Coordinate and integrate with continental drilling.

⇒ Integrate with modeling studies on landscape development, sediment budgets and fluxes, and climate to develop and test hypotheses.

⇒ Organize drilling arrays to evaluate paleo-bathymetry and its changes through time.

To effectively conduct the above listed strategies, coordination of all kinds of platforms such as non-riser, riser, mission-specific platform (MSP), and continental drilling will be important. A long-term comprehensive project aiming to capture a complementary array of continental basin/fan records of exhumation and terrestrial climate/vegetation history, sediment, nutrient, and carbon budgets, and freshwater discharge is strongly desired through coordination of individual expeditions. These expeditions will likely each be focused on specific climate-tectonics linkages but together can build this array of data on continent-ocean fluxes and tectonics-climate feedbacks over geologic time.

6.3.4 Integration with other scientific programs and industries

Involvement and cooperation with terrestrial research projects and integration with ICDP and ANDRILL are necessary to obtain proximal sedimentary records of tectonic and climatic events and complete sediment, nutrient, and carbon budgets, and also to understand fluvial and glacial reorganization. Also important are involvement and cooperation with commercial industries (especially the oil industry) and local governments to obtain seismic data, core and cuttings, and other information from continental margins of scientific interest. Involvement and cooperation with biologists and biogeochemists are also desirable to investigate ecological interactions in marginal areas and the potentially unique deep biosphere in organic-rich fans and across the terrestrial/marine boundary. Cooperation with geodynamic and climate modelers is also critical for testing mechanisms for interactions. Dating onshore sediments needs to be mated with offshore dating, which will require involvement of thermochronologists, paleomagnetists, paleooceanographers, and biostratigraphers.

6.3.5 Social relevance and outreach

Because drilling for tectonics-climate interactions focuses on continental margins, marginal seas, deep-sea fans, and integration with continental drilling, the results are expected to hold information highly relevant to the society in many respects. For example, in some cases the recovered sedimentary strata will preserve high-resolution geohazard records of earthquakes and tsunamis in seismogenically active margins and floods and droughts in monsoon areas. Additionally, public interest is peaked when convincing cases can be made for systems interacting in surprising ways, such as the concept of ‘climate moving mountains’. Information on sediment input and its relation to the migration of coastlines will be useful for maintaining the location of the shore in highly populated areas, whereas information on the ecosystem response to nutrient input will be useful for protection of coastal marine ecosystems. The high sedimentation rates in these regions also provide records of paleoclimate and human impact useful for a number of the goals of the new program. Knowledge about factors controlling chemical weathering and organic carbon burial will be useful for developing methods for CO_2 sequestration. All of these topics can be used for outreach and raising the public’s interest.

7 Technological Needs and Development

To study the least-explored subseafloor realms, technological development of platforms and drilling is essential. As discussed during the INVEST meeting, some future drilling explorations to meet new scientific objectives depend on improved drilling capabilities such as enhancing depth penetration, improving core recovery and quality, coring in high-temperature and high-pressure environments, coring in shallow-water margins, coral reefs, and sea-ice covered regions (*e.g.*, such as with the planned the Research Icebreaker *Aurora Borealis*), and preventing magnetic, chemical, and microbiological contaminations. Overall, the next phase of the scientific drilling program will require a significant and even more coordinated engineering effort.

7.1 Analytical Capabilities

Vast efforts in technological developments during previous scientific drilling programs have successfully enabled tremendous scientific discoveries in the frontier research field of subseafloor environments. During the INVEST meeting, a number of new scientific concepts and ideas were proposed for future scientific drilling. To achieve these fundamentally important and unsolved scientific objectives, analytical capabilities should be continuously improved or developed in the future drilling program. One of the most significant technological requirements discussed is how we can measure the intrinsic and/or ephemeral properties inherent to core materials. The *in situ* analysis tools involve redox states, chemical compositions, physical parameters, pH, and microbial populations and their activities. For example, newly developed (or improved) logging sensor tools, *in situ* sampling/monitor devices, and *in situ* microbial colonization systems will be highly valued for multidisciplinary scientific objectives through borehole observatories and experiments. A real-time hydrocarbon gas monitoring system including stable isotope measurements should also be deployed in platform laboratories. Using fresh cores, novel and/or improved analytical technologies for quick and high-resolution measurements of temperature- and redox-/oxygen-sensitive chemical and microbiological components must be developed for the new scientific drilling program, since explorations of high-temperature hydrothermal systems and the deep, hot biosphere have great potential for understanding co-evolution of life and the planet. Onboard measurements of interface properties related to physical, chemical, and biological events are extremely useful for rapid decisions necessary for subsequent onboard core-flow and additional drilling. Some strategies for multiple analytical measurements on the same core should be developed, with the advantages of intimate association of core properties.

7.2 Sampling Improvements

To analyze *in situ* characteristics of subseafloor environments, the development of a pressure- (and temperature-) keeping coring system is required by many research communities within scientific ocean drilling. There was consensus among INVEST participants that *in situ* pressure and temperature are significant controlling factors for various geochemical and biological reactions. The pressure limit of currently available high-pressure-coring systems (*e.g.*, PCATS or FPC by GeoTek Ltd.) is up to 25 MPa, which is not enough for high-pressure gaseous fields or deep coring at a target depth greater than 2500 m below the sea surface; hence, the system must be improved for more high-pressure environments and be adaptable to all platform drilling facilities. In addition, it is important to construct an onboard high-pressure core transfer system equipped with an X-ray computed tomography (X-CT) scan device, multiple (micro-) sensors, gas and fluid extraction ports, biogeochemical and microbiological tracer injection systems, and a mini-core sub-sampling system like the DeepIsoBUG system (Parkes *et al.,* 2009) (Fig. 7.1). This will allow cross-disciplinary *in situ* measurements and active experiments for the new scientific drilling program.

Quality assurance and quality control (QA/QC) are necessary to accurately characterize physical, geochemical, and biological properties in the recovered cores. For example, a non-magnetic core barrel (and the oriented cores) will allow deeper coring and collection of reliable magnetic data. To define the extent of subseafloor microbial populations, activity, and metabolic functions, uncontaminated 'clean' coring and sub-sampling technology is required.

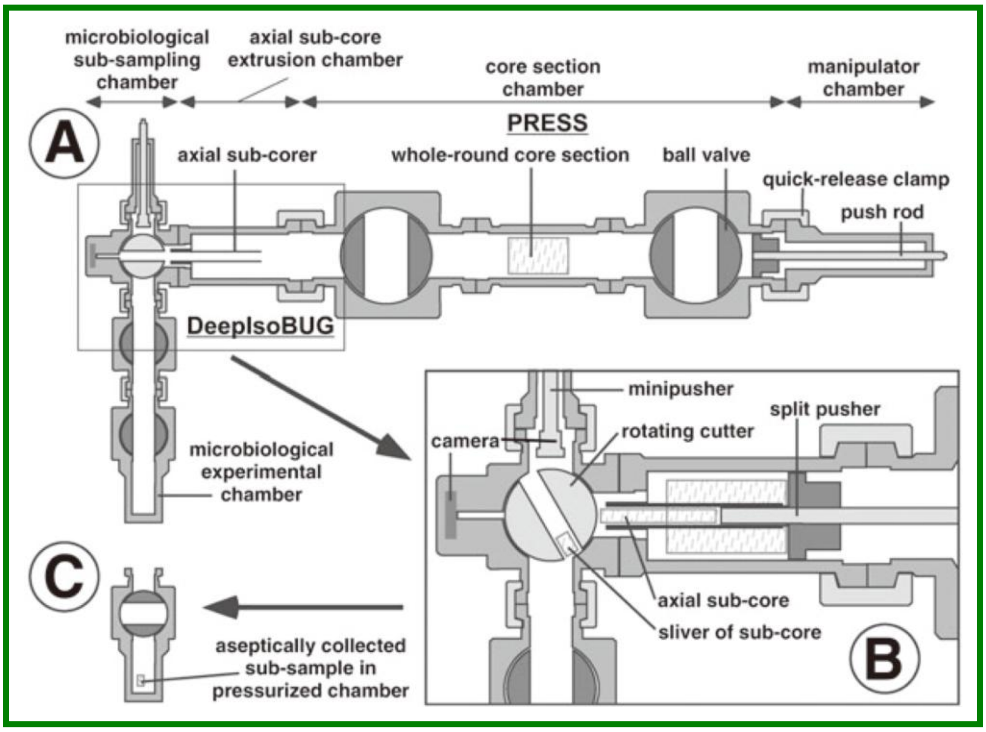

Figure 7.1 Schematic figure of a microbiological high-pressure core transfer system, designated as the DeepIsoBUG system (Parkes *et al.*, 2009).

The circulation ‘mud’ for riser drilling should be simultaneously analyzed with core samples as the experimental control, because some microbes may grow in the stored ‘mud’ and contaminate the core samples (Masui *et al.,* 2008). Additional ways to clean and monitor and minimize contamination of sub-sampling equipment should be considered.Previous microbiological and biogeochemical studies have demonstrated that subseafloor microbes proliferate in narrow niches at geologic or geochemical interfaces such as volcanic ash layers (Inagaki *et al.,* 2003) and sulfate-methane transition zones (Parkes *et al.,* 2005; Sørensen and Teske 2006). If subseafloor microbial communities are very sensitive to local paths of fluid-flow that transport available energy and nutrients, the population and activity distribution may be more complicated; hence, high-resolution sampling is necessary to capture the small niches for subseafloor life. During the INVEST meeting, it was intensively discussed that ultrahigh-resolution analysis is very important especially for better understanding of past climate and sea-level records. Describing the paleo- and modern ecosystems within the subseafloor biosphere is also recognized as a significant scientific objective in the future drilling program. During ODP and IODP expeditions, most microbiological samples were taken as 5- to 10-cm length WRC; therefore, the sedimentological, paleontological, and lithological characteristics of WRC samples have been largely dismissed and co-relations remain elusive. To analyze microhabitats with high-resolution depth sampling, shore-based technological improvements and effective onboard sub-sampling strategies for quick locus identification must be developed.

7.3 Shipboard Facilities

Current shipboard computational and dissemination capabilities should be more effectively integrated between software programs, database mining, and accessibility. Ideally, it should be interfaced with multiple drilling platforms and databases in core repositories.

Previous IODP expeditions (Expeditions 314, 315, 316, and 322) demonstrated that X-CT scanning is highly valuable as it provides a complete three-dimensional core image non-destructively. Examining the CT-image reveals important geological and sedimentological information prior to core splitting and sub-sampling for geochemical and microbiological analyses. The CT-scanned image analysis also provides three-dimensional elemental distribution (*e.g.*, pyrite accumulation in non-visible microfractures) and structural characteristics (*e.g.*, vain/fracture angle). The non-destructive identification of core quality and structures will be highly valuable to future microbiology/biogeochemistry-dedicated drilling expeditions because lithological and mineralogical characteristics are highly co-related to microbial habitat and activity. Given those discussions, INVEST participants highly recommended that an X-CT scanning device be deployed on all platforms. To study large numbers of high-resolution images, high-speed computational capabilities must be available. For high-pressure cores, CT-scannable core liners made of materials such as carbon glass fiber or aluminum are recommended.

To achieve high throughput and high-resolution analyses onboard, INVEST participants recommended use of computer-driven automated systems. For example, an auto-extractor should be deployed onboard for organic geochemistry analyses with efficient measurement and analytical tools. Recently, an automated cell-counting microscope system using fluorescent image analysis was developed (Morono *et al.*, 2009) (Fig. 7.2). The new computer-based cell-counting system should be equipped with an automated slide-loader system, which will reduce the working time of shipboard participants and produce objective and high-resolution microbial population data.

To share scientific information as quickly and efficiently as possible, a computational high throughput and high-resolution analytical scheme is essential and multiple measurement strategies and techniques should be developed in the future scientific drilling program.

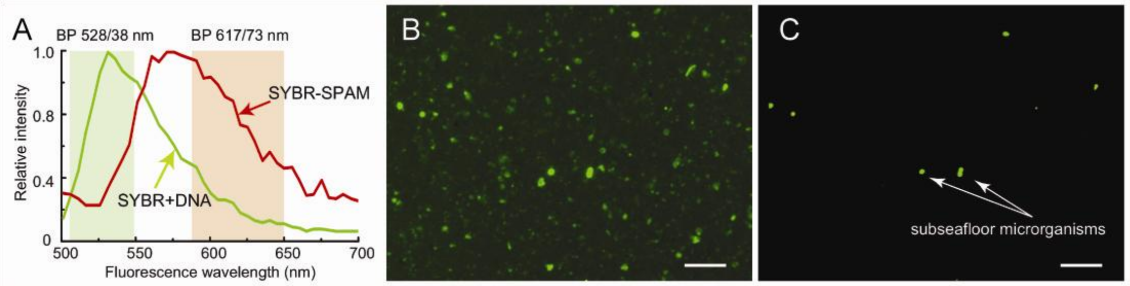

Figure 7.2 Computer image-based cell detection and enumeration. Using SYBR Green I fluorescent dye, non-biological backgrounds (*i.e.*, SYBR-SPAM: SYBR Green I-stainable particulate matter) produce longer fluorescent wavelengths than the cellular DNA. (A) Cell-derived fluorescent signals can be retrieved from the forest of backgrounds by processing fluorescent microscopic images obtained with green (528nm) and orange (617nm) binary filters. (B) Green fluorescent microscopic image of a sediment sample from Site C0006 (IODP Exp. 316). (C) The processed image provides signals derived only from subseafloor microorganisms. Bars represent 10 µm. Figures modified from Morono *et al.*, 2009.

7.4 Platform and Drilling Capabilities

During over a half-century of scientific drilling one of the important, enthusiasm-inspiring, but yet-to-be accomplished scientific objectives is the deep drilling of Earth's interior, as proposed as the project 'Mohole'. Currently, deep drilling targeting the asperity zone is proposed. Today, these deep-drilling projects involve more interdisciplinary scientific objectives than when originally proposed (*e.g.*, water-rock interactions at different depths/conditions may produce some nutrient and energy substrates for subseafloor life within the upper lithosphere). To achieve these cross-disciplinary deep-drilling explorations in the future scientific drilling program, technological development is essential. Necessary drilling capabilities include (but are not limited to): (1) deep-water riser drilling capability down to 4000 m or more; (2) deep-penetration depth beneath the basement; and (3) borehole and drill bit cooling technology for high temperature (>250°C) environments. To solve these technological issues for deep drilling, improvement of riser-pipe quality, casing strings, the BOP, and the mud-circulation/recovery system are particularly important. The newly developed RMR system has great potential for various purposes in future drilling, especially for borehole controls (*i.e.* stability and cooling) and lowering cost. Combining the dual gradient technology with RMR, the drilling system enables environmentally friendly (*i.e.*, clean without mud pollutants to seawater) access to deeper environments and other areas previously not drillable by riser-less drilling. The RMR technology is directly applicable to all IODP platforms for the suitable target depth range (Fig. 7.3).

Improving core recovery and quality (*e.g.*, fewer disturbances) is a fundamental technological challenge. The degree of core recovery and quality depends on various factors such as depth, lithology, physical properties, and coring tools. During previous drilling explorations, low or no core recovery has been observed in: (1) chert and/or shales, (2) sand and gravel layers, (3) hydrothermal deposits, (4) rubble basalts and sheeted dyke complexes, and (5) fault and fracture zones; unfortunately most of these environments were scientifically important to the expeditions. To solve this problem, more accurate compensation for drill bit motion, torque, and type of cutting shoe is required and use of a feedback system for real-time drilling parameters should be considered. The improvement of coring systems and other drilling and/or sampling systems (*e.g.*, cuttings and side-wall coring) will increase core recovery rates and improve scientific information obtained from coring gaps. These and other options should be considered for specific scientific requirements, such as drilling at sediment-thick ice-sheet interfaces. Borehole management, particularly in terms of stability, is also very important. Cuttings removal and compensation of lithostatic and pumping pressures

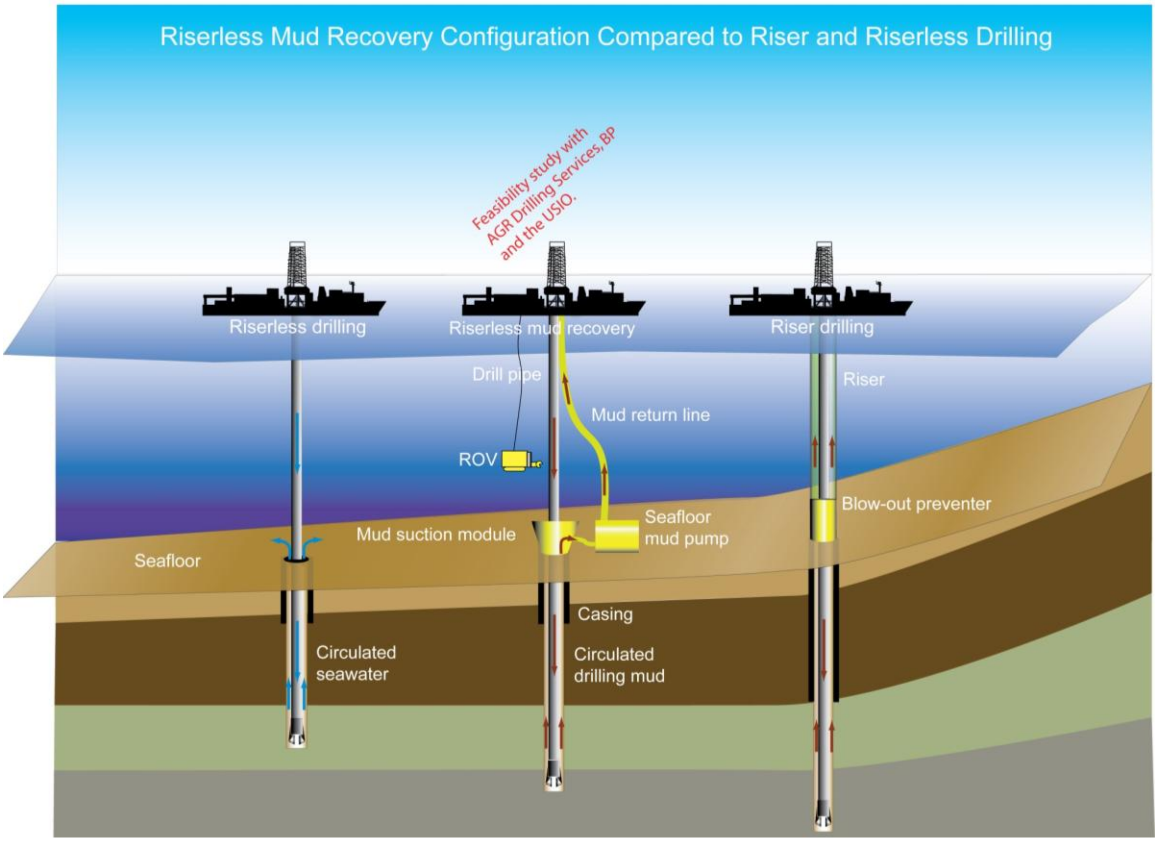

Figure 7.3 Diagrammatic figure of platform properties equipped with riserless-, RMR, and riser-drilling systems (from Greg Myers, IODP-MI)

should be improved in both riser and riser-less drilling. In addition, large-diameter pipes may provide opportunities to conduct various geophysical analyses (*e.g.*, pore pressures and resistivity) and reduce the probability of microbial and geochemical contamination of the core from drilling fluids.

Monitoring while drilling (MWD) using downhole logging tools (*e.g.*, Davis-Villinger Temperature-Pressure Probe (DVTPP)) has greatly expanded our understanding of *in situ* pressure and stress conditions in the borehole. The use of logging tools during drilling or in CORK boreholes is highly applicable for various new drilling opportunities as well as in previously-drilled boreholes. During the INVEST meeting, large-scale logging programs within multiple holes are recommended for the future scientific drilling program, including technological developments related to injection tests, slug tests, and cross-borehole pressure studies, as proposed by the International Ocean Network (ION) (see section 6.4). Broadband and high-sensitivity sensors such as fiber-optical seismo-sensors combined with the continuous data recovery system should be developed and installed in active subseafloor environments (*e.g.*, basement crust near the ridge). To study *in situ* conditions of high-temperature and/or high-pressure environments, the durability of logging systems regarding temperature and pressure must be improved. Development of new slim-line multi-logging tools and borehole equipment (*e.g.*, wide range of environmental parameters, three-dimensional seismo-sensors and networks, microbiological/biogeochemical experimental kits) is highly recommended for application to all platforms and drilling opportunities in the future scientific drilling program.

8 Outreach, Education, and Branding

8.1 Background

8.1.1 Outreach *vs.* education/educational outreach

INVEST participants agreed upon definitions for outreach and education to facilitate discussion. Outreach refers to activities that target the general public and funding agencies. Education and educational outreach are aimed at school children, university students, and graduate students. Formal education programs involve some type of assessment designed to measure the impact of the education program on the target audience. Educational outreach activities do not typically have a rigorous evaluation component designed to measure the impact on the target audience.

8.1.2 Review of education and outreach during IODP

In February 2003, IODP-MI convened an international workshop to provide guidance on approaches to education and outreach for the new program. The workshop report contained many recommendations, all of which were implemented by IODP-MI. Key among these were the recommendations that: (1) IODP-MI would oversee branding by establishing a web presence, logo, templates for IODP correspondence and media releases, and uniform protocols for interaction with the public and funding agencies; (2) IODP-MI and the Implementing Organizations (IOs) would collaborate on media relations with IODP-MI taking the lead in issuing news releases; and (3) IODP-MI would support the IOs and/or partner advisory consortia (*e.g.*, JAMSTEC, Japan Drilling Earth Science Consortium (J-DESC), US Advisory Committee for Scientific Ocean Drilling (USAC)) in conducting public outreach by coordinating activities such as exhibit booths at scientific meetings, town hall meetings, port calls, *etc*. The workshop report also recommended that IODP-MI hire a high-level individual with media relations experience to oversee public outreach and branding and that a task force comprising IO and partner advisory consortia staff tasked with outreach be established in order to facilitate collaboration on public outreach. The workshop report further recommended that education activities be handled in a different way than media relations and public outreach, with each IO and/or partner advisory consortia (*e.g.*, JAMSTEC, J-DESC, USAC) responsible for funding and overseeing its own educational activities in support of ocean drilling. This recommendation was based on concerns that difficulties with language, customs, education standards, differing needs, *etc*. would make it difficult and expensive to implement uniform education programs in all partner countries.

IODP-MI hired a director of media relations and public outreach and created an Outreach Task Force at the start of the program in 2003 in response to recommendations contained in the February 2003 IODP Education and Outreach Workshop Report. The Task Force comprises those individuals at the IOs and partner consortia who are responsible for public outreach, especially media relations. IODP-MI coordinated the IODP Outreach Task Force from 2003 through August 2009. During this period, the Outreach Task Force communicated monthly via telephone conference calls and an internal newsletter. Their activities focused on media relations, websites, videos, exhibit booths, town hall meetings, and port-call activities. With time, as successful education and educational outreach activities carried out by the IOs and/or partner consortia emerged and gained recognition, limited collaboration across IODP occurred and some education staff were integrated into the Outreach Task Force.

Recent highlights from the Outreach Task Force:

⇒ Media coverage of New Jersey Shallow Shelf MSP expedition.

⇒ ABC news special/National Geographic.

⇒ European Consortium for Ocean Research Drilling (ECORD) Bremen Summer School, J-DESC core schools, Urbino Summer School for Paleoclimatology.

⇒ School of Rock (SOR) (limited collaboration).

⇒ Sand for students.

⇒ IODP exhibit at Japanese National Museum of Natural Science and weekly ship-to-shore video conference from *JOIDES Resolution* (*JR*) to museum audience with museum educator (collaboration between Japanese and US Implementing Organization (USIO)).

⇒ National Science Foundation (NSF) Course Curriculum and Laboratory Improvement (CCLI) program "Building Core Knowledge – Reconstructing Earth History" (individual US Principal Investigators, Leckie and St. John).

⇒ Education berth on the *JR* established.

Members of the IODP Outreach Task Force feel strongly that continued coordination through IODP-MI is essential to achieve the best results in the arena of public outreach. They point to the vital role that IODP-MI has played in prioritizing and guiding the Outreach Task Force on public outreach activities to pursue.

IODP education activities have been carried out by the IOs and/or partner advisory consortia (*e.g.*, JAMSTEC, J-DESC, USAC) without support form IODP-MI. In order to accommodate countries/regions with different languages, customs, and education standards, these education efforts have been customized for specific target audiences. The most successful education programs worthy of mention in this document are: (1) the ECORD Summer School with thirty PhD students (2 weeks), Urbino Summer School, and J-DESC Core School, all of which serve graduate, undergraduate, and young career scientists; (2) Deep Earth Academy SOR carried out by USAC for US science teachers (there is limited collaboration among IODP partners); and (3) JAMSTEC's Sand for Students program for secondary school students and their teachers.

Currently, IODP-related education efforts are mainly informal (*i.e.*, without rigorous assessment); formal education efforts with a strong assessment attached to measure outcomes and impact are lacking. Individual researchers have sought and received outside funding for high-impact education projects based on IODP science, but the outcomes of these projects are not captured by the program and thus do not become part of the IODP legacy.

8.2 Developing a Broad Vision

8.2.1 Branding

As the IODP competes with other geoscience programs for renewal, a successful branding campaign will be vital to ensure ongoing public recognition of its scientific discoveries and the technological achievements of scientific ocean drilling.

Public awareness of scientific ocean drilling is not very high. Participants identified several strategies to improve branding including the use of a simple and colorful tag line[1] that captures the imagination of the public and which will take precedence over the changing name of the program. "IODP" and "Integrated Ocean Drilling Program" do not resonate with the public. Visual impression is key for branding. Participants felt that websites across the program must have a common layout (look and feel) to promote the impression of a truly integrated program to the scientific community and the public and to facilitate access to information. Diverse types of materials should be used to convey an understanding of scientific ocean drilling, how it is done, and the key questions that are being investigated. The science and accomplishments of IODP and its successor program should be linked to broader objectives (themes) and not necessarily solely to expeditions. One idea that emerged was that of a traveling interactive exhibition that would move around to different partner countries. The idea of offering workshops to the media in an effort to engage them and educate them about scientific ocean drilling science was also discussed.

A series of bold, clear key messages should be an important element in any branding campaign. Many of these key messages are contained in this report as answers to the questions addressed by each working group. In addition, the interesting science associated with each expedition provides opportunities to promote key messages. Once the main science goals have been articulated in a planning document, IODP outreach professionals can help craft these public messages, making sure that they are customized for specific target audiences and delivered in formats appropriate for different audiences. Two examples to illustrate this point are: (1) providing a printed quarterly report to people who appreciate printed literature and (2) offering workshops to disseminate best practices for education and outreach.

Participants provided examples of kernels of main messages:

⇒ The program investigates a dynamic earth. That Earth is changing – not a static planet.

⇒ Be like the National Aeronautics and Space Administration (NASA)! Relevant to society; convey the notion that basic science is always valuable to society.

⇒ Scientific ocean drilling is relevant to society, providing knowledge about geohazards and climate change.

⇒ Scientific ocean drilling is on the edge of the science frontier. We are exploring the Earth thorough scientific ocean drilling, which shows us things we haven't seen before.

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[1] The catchy tag line '*Crossing the Shoreline*' was suggested at a recent MARGINS planning meeting.

8.2.2 Raising the profile of the IODP successor program

Outreach and education are important endeavors that will help to raise the profile of the IODP successor program. Although the two are treated separately in the current program, this need not be the case as education and outreach are highly complementary endeavors; however, additional funds are required for outreach and education to truly make an impact on public awareness. At present, only a few percent of IODP-MI's and the USIO's total budget is allocated for education and public outreach. The USIO allocates about ~1-2% of their budget for education and educational outreach. Participants suggested that funding for education and outreach should be where the science is implemented, but emphasized that is was also important to maintain and education and outreach budget for centrally based funding.

Participants felt that assessment of the program and education and outreach activities should be ongoing. Measuring and publicizing the return on investment made in education and outreach (*e.g.*, numbers of participants in summer schools, workshop attendees, web-based catalogue of important news stories, *etc*.) would help raise the profile of the new program, as would documents and products that synthesize IODP accomplishments (*e.g.*, Greatest Hits). An IODP coffee table book of the history of scientific ocean drilling (40+ years of DSDP, ODP, IODP) would also help raise the profile of scientific ocean drilling.

Participants recommended the creation of a full-time position for a science 'translator' (scientist or scientist educator with requisite skills) in the IODP-MI office with the goal of translating science for non-scientists. Among his/her responsibilities, this person would write short summaries for the general public after the completion of each drilling expedition.

8.2.3 Education and educational outreach

IODP scientists' personal involvement in education and outreach is tied most closely to education because many scientists are also educators. During the breakout session, a clear call for IODP to become more involved in education emerged. This is in contrast to the call for outreach (with minimal education) during the beginning stages of the program. Participants acknowledged the success of the SOR, ECORD Summer School, J-DESC Core School, and JAMSTEC's Sand for Students. Consideration should be given to expanding successful programs to include all IODP partners and adapting the SOR to serve other audiences (*e.g.*, undergraduates, faculty, young scientists) in addition to science teachers. Participants agreed that the ECORD Summer School, which has run three times to cover *Climate, Biosphere,* and *Geodynamics of Ocean Ridges*, would be a good candidate to pilot as an IODP-wide education program at the international level. Scientists and PhD students who have participated in the ECORD summer school have expressed that it has been a very rewarding experience. The implementation or expansion of formal education programs, such as the ECORD Summer School, would need increased funding. The importance of incorporating assessment that would be modeled after successful strategies and best practices in other education and outreach programs was discussed. Assessment is required in any NSF-funded education proposal.

Participants also discussed ways in which scientists could engage in collaboration with IODP outreach specialists. Many suggestions were put forward, including: (1) the development of an archive of basic images documenting the history of IODP that scientists could use when giving talks on their science; (2) sailing scientist educators, in addition to K-12 educators, on expeditions; (3) providing communications training for younger scientists who sail; (4) offering early career workshops sponsored by IODP and modeled after the successful US Marine Geophysics Workshop for Early Career Scientists; and (5) developing a mentoring plan for young career scientists who sail on expeditions and site survey cruises.

The success of the education program calls for more emphasis on education in the IODP structure in a formal (and informal) way. An education and outreach representative should be included on panels within the science advisory structure to ensure that education and outreach receive appropriate consideration in the science planning.

8.2.4 The role of NEW tools/media in education and outreach

Opportunities exist to publicize IODP and its successor program by taking advantage of the new ways in which people communicate (*e.g.*, Twitter) and by using social networking websites such as Facebook, as well as posting regularly to credible science blogs. Twitter streams from ships provide easy access and connection with undergraduate audiences. YouTube offers the opportunity to post video clips with light/catchy, simple messages. Unfortunately, none of these online resources (Facebook, Youtube) or approaches will be successful without branding, as name recognition is necessary for the public to know where to find online scientific ocean drilling information and resources.

There are also opportunities for IODP scientists to make targeted entries to online resources such as new *Encyclopedia of the Earth* (http://www.eoearth.org/) and Wikipedia about the program and its scientific achievements. IODP could also make greater use of Google Ocean and GeoMapApp to provide the public with images and video for education and outreach.

Webcasts and video from the ships are a powerful and effective way of reaching out to museum and school audiences and can result in media coverage by local TV and radio stations. A limited number of ship-to-shore events have occurred from the *JOIDES Resolution*, but continuation would require a full-time position.

8.3 Dedicated Education and Outreach Workshop for IODP Successor Program

Finally, participants recommended a workshop dedicated to planning education and outreach for the IODP successor program. In the short term, IODP could jumpstart education and outreach planning for a new program by convening a small workshop that would be held in conjunction with the upcoming March 2010 IODP Task Force meeting. In addition to the current education and outreach staff, external experts on best practices and scientists would be invited. This workshop would also offer the opportunity to showcase best practices in IODP education and outreach from the US, Europe, and Japan. In the longer term, IODP could host a workshop dedicated to planning education and outreach for the IODP successor program; however, questions about who should attend, how many, where, and when (coincident with science planning or immediately after science plan is developed) were not resolved.

9 Recommendations for the New Program

9.1 Program Architecture - Guiding Principles

9.1.1 The role of scientists

Scientific planning and execution in the new ocean drilling program, as in ODP and IODP, should be driven from the 'bottom up', with scientists playing key roles in proposing specific expeditions and drilling targets, in defining short- and long-term goals, and in advising and working directly with management and ship operators to execute the drilling program. The direct involvement of world-class students and scientists is what will keep the international ocean drilling program fresh and focused on emerging transformative topics that define the frontier of biogeosciences.

The drilling program should rely on scientists to infuse new scientific ideas into the program, work closely with engineering development, provide critical review and assessment of proposed and completed scientific objectives, and train, mentor, and inspire the next generation of scientists. Transformative science is often born from cross-disciplinary perspectives and the drilling program must have multiple mechanisms to proactively engage scientists and students from other disciplines outside of the traditional drilling community, including observationalists, theorists, and those in academia and industry.

9.1.2 The role of management

The program needs effective management who will provide visionary leadership to foster stronger international partnerships, well-integrated collaborations with other large geosciences programs, effective fundraising, and creative and efficient coordination amongst the national offices and implementation/ship operators. Management, as the face of the ocean drilling organization, should have expertise in communication, fundraising, and development. They should be charged with working with the science advisory committees to ensure that milestones are met and that the program can nimbly adjust to changes in resource availability and respond to opportunities to advance the development and implementation of new technologies.

INVEST meeting participants did not reach a consensus on how management should be structured, or even how strong it should be relative to the ship operators or national programs, but they emphasized the need for inventive and forward-thinking leaders who would seek and solidify ties with other programs and funding sources and work effectively with science advisory groups and ship operators.

9.1.3 Missions versus smaller projects

There was general support for 'mission-like' multi-expedition, long-term projects to achieve the ambitious goals of the new drilling program. Many of the grand challenges that were defined, as described in this report, cannot be achieved by single two-month expeditions. For the new program to tackle several of these grand challenges will require a commitment of resources and INVEST participants were supportive of the idea that the new ocean drilling program provide the leadership, planning, and resources required to achieve ‘big science’.

At the same time, it was recognized that many of the highest impact ocean drilling projects in the past were unanticipated and/or concise and focused ideas. Thus, there MUST be mechanisms by which the new ocean drilling program can quickly respond to, nurture, and execute any brilliant new ideas that require ocean drilling.

For all projects, regardless of size or scope, INVEST participants wholeheartedly emphasized the need for a rigorous peer-review system that could select amongst the best ideas presented by individual or groups of scientists. Once the best scientific projects are selected, the program needs to be committed, proactive, and efficient about executing the project. This will require savvy management that can work well with the science advisory structure and the ship operators.

9.1.4 The need for flexibility and long-term planning

To meet the scientific goals of the drilling program will require flexibility. Expeditions will vary from traditional two-month legs to multi-leg ‘missions’ focused on achieving long-term objectives. In addition, the program needs to be structured in a way that allows global arrays of sites to be drilled over time. For example, a north-south array of sites could be drilled a few at a time during transits between expeditions. Operations and expedition scheduling must be flexible in order to maximize the efficient use of resources to achieve the diverse objectives of the program.

Many of the transformative scientific discoveries of the ocean drilling program in the past have been through application of cutting-edge technology and this is sure to be the case in the future. Complex operations that employ innovative technology absolutely require long lead time to raise funds, to perform necessary engineering development, and, in some cases, to coordinate with third-party providers and other science programs. This can only happen if there is a long-term commitment of resources and support to these types of complex, and often expensive, projects.

In summary, INVEST participants emphasized that to implement the drilling projects necessary to achieve transformative science will require a new ocean drilling program architecture that, by design, will have the flexibility to react quickly to new opportunities, but also to make decisive commitments to long-term complex projects.

9.2 Science Advisory Structure

9.2.1 Guiding principles

There was not extensive discussion about the details of the design of a new science advisory structure, but there was consensus that there should be serious consideration given to designing a new science advisory structure that would optimally support the important characteristics of a new program. The science advisory structure should provide:

- ⇒ Flexibility to nurture both small and large projects with efficiency. This may involve a complex system of science evaluation committees with more focused tasks, a more proactive role of science advisory committees working directly with drilling proposal proponents, and better defined criteria for determining highest priority projects.
- ⇒ Ability to make decisions with enough lead time to plan and execute complex and/or expensive projects.
- ⇒ Ability to react to a changing funding climate and to capitalize on opportunities to work with industry or other science programs.
- ⇒ Ingenuity to promote the continued infusion of innovative scientific ideas and technological advances into the ocean drilling program.

9.2.2 Site Survey Panel in a new ocean drilling program

Specific discussion regarding geophysical site characterization lead to some recommendations that apply directly to the design of a site survey panel in the new ocean drilling program. Geophysical site characterization is an integral part of scientific ocean drilling. Geophysical images show the drilling target, place the cores/logs/observatories within a 2-D to 3-D geologic context, and allow assessment of environmental and safety issues. Integration of seismic data with drilling data allows scientific analyses and interpretation to be expanded beyond the borehole and between boreholes, thus often providing fundamental contributions to the scientific goals of the drilling expedition. At INVEST, the importance of site surveys and geologic/geophysical site characterization was raised in many of the thematic sessions. In addition, issues of site survey evaluation within the science advisory structure and tools that would enhance integration of site survey and borehole data were discussed in a breakout session.

Two primary results arose from the site survey breakout session. The first was that direct interaction between proponents and site survey panel watchdogs from the initial proposal stage through full site characterization would be beneficial in two important ways: (1) it would allow proponents to adequately plan for additional site surveys and (2) it would highlight ways to optimize science goals of a given drilling project. The breakout participants suggested that at some point in the review process this interaction could involve proponents presenting site survey packages to the site survey panel, similar to how proponents in the current program present to the environmental protection and safety panel. The second result of the breakout group was the agreement that site survey data should be integrated into the science program of an expedition as fully as possible. In order to achieve this goal suggestions included: (1) seeking ways to foster more direct linkages between proposals for site surveys and proposals for drilling; (2) sailing shipboard science party members with experience in seismic data routinely on drilling expeditions (through geophysicist or logging positions); (3) expanded use of technologies designed to allow integration with seismic data; and (4) potentially considering programmatic funding for major site survey endeavors such as 3-D acquisition in order to maximize the scientific results from drilling. Specific downhole, shipboard, and logging tools thought important for seismic integration include: (1) a formation micro-scanner for mapping of bedding planes, fractures, faults, foliations, and other formation structures and dip determination; (2) whole-core X-CT scans (rapid acquisition of X-ray images without destruction of samples); (3) logging-while-drilling, wireline logging, and checkshots/vertical seismic profiles (VSPs) to be able to correlate travel time in the seismic data directly with depth in the borehole; (4) hyperspectral logging (infrared radiation spectra of the core) to complement the X-CT scan; (5) velocity measurements at *in situ* pressures; (6) downhole magnetic logging on hard rock legs to aid in cases of poor recovery; (7) oriented cores; and (8) using cuttings for physical property studies in riser or RMR legs where possible. The breakout group also agreed in certain instances where drilling targets are shallow and uncomplicated geologically that it may be suitable for extremely limited use of the *JOIDES Resolution* for seismic surveys, such as acquiring single-channel/low-fold profiles in a remote geographic region.

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Acronyms and Abbreviations

ACEX	Arctic Coring Expedition
ACR	Antarctic cold reversal
ANDRILL	Antarctic Geological Drilling
ANTSTRAT	Antarctic Stratigraphy
AODC	Acridine orange direct count
AR4	Fourth Assessment Report (of the IPCC)
BIT	Branched and Isoprenoid Tetraether
BOP	Blowout preventer
BSR	Bottom-simulating seismic reflector
CCD	Carbonate compensation depth
CCLI	Course Curriculum and Laboratory Improvement
CNRS	
CORK	Circulation Obviation Retrofit Kit
CT	Conference theme
DFG	Deutsche Forschungsgemeinshaft
DIC	Dissolved inorganic carbon
D-O	Dansgaard-Oeschger
DONET	Dense Oceanfloor Network System for Earthquakes and Tsunamis
DSDP	Deep Sea Drilling Project
DVTPP	Davis-Villinger Temperature-Pressure Probe
EAIS	East Antarctic ice sheet
ECORD	European Consortium for Ocean Research Drilling
EECO	Early Eocene climatic optimum
EMSO	European Multidisciplinary Seafloor Observatory
ENSO	El-Niño Southern Oscillation
EPOCA	European Project on Ocean Acidification
ESONET	European Seas Observatory Network
FPC	Fugro Pressure Core
GCM	General circulation model
GEOSECS	Geochemical Ocean Sections Study
GMES	Global Monitoring for Environment and Security
Gt C	Gigaton carbon
HRRS	Hard rock reentry system
ICDP	International Continental Scientific Drilling Program
IfM/GEOMAR	Leibniz-Institut für Meereswissenschaften, University of Kiel
IGBP	International Geosphere-Biosphere Programme
IMAGES	International Marine Past Global Change Study
IMBER	Integrated Marine Biogeochemistry and Ecosystem Research
INVEST	IODP New Ventures in Exploring Scientific Targets
IO	Implementing Organization
IOCCP	International Ocean Carbon Coordination Project
IODP	Integrated Ocean Drilling Program
IODP-MI	Integrated Ocean Drilling Program-Management International, Inc.
ION	International Ocean Network
IPCC	Intergovernmental Panel on Climate Change
IRD	Ice-rafted debris
ITCZ	Intertropical Convergence Zone

JAMSTEC	Japan Agency for Marine-Earth Science and Technology
J-DESC	Japan Drilling Earth Science Consortium
JR	*JOIDES Resolution*
Jr/K	Jurassic/Cretaceous
K/Pg	Cretaceous/Paleogene (formerly K/T - Cretaceous/Tertiary)
KTB	Cretaceous/Tertiary boundary
LGM	Last Glacial Maximum
LIP	Large igneous province
LO	Late Oligocene (warming)
LWD	Logging while drilling
MBT	Methylation of Branched Tetraethers
mcd	meters composite depth
MC-ICPMS	Multi-collector inductively coupled plasma mass spectrometry
MeBo	Meeresboden-Bohrgerät (German for "seafloor drill rig")
MIS	Marine Isotope Stage
MMCO	Middle Miocene climatic optimum
Moho	Mohorovičić discontinuity
MPT	Mid-Pleistocene transition
MSCL	Multi-sensor core logger
MSP	Mission-specific platform
M_w	Moment magnitude
MWD	Monitoring while drilling
MWP	Meltwater pulse
NASA	National Aeronautics and Space Administration
NSF	National Science Foundation
OAE	Oceanic anoxic event
OCB	US Ocean Carbon and Biogeochemistry Program
ODP	Ocean Drilling Program
OJP	Ontong Java Plateau
PCATS	Pressure Core Analysis and Transfer System
PCR	Polymerase-chain reaction
PETM	Paleocene/Eocene Thermal Maximum
Pg C	Petagrams (10^{15}) of Carbon
QA/QC	Quality assurance and quality control
ROV	Remotely operated vehicle
RMR	Riserless Mud Recovery
rRNA	Ribosomal ribonucleic acid
SHALDRIL	Shallow Drilling on the Antarctic Continental Margin
SOR	School of Rock
SST	sea-surface temperature
T	Termination
USAC	United States Advisory Committee for Scientific Ocean Drilling
USIO	United States Implementing Organization
VMS	Volcanogenic-hosted massive sulfide
VSP	Vertical seismic profile
WAIS	West Antarctic ice sheet
WG	Working group
WRC	Whole round core
X-ray CT	X-ray computed tomography
YD	Younger Dryas

D/V *JOIDES Resolution*

D/V *Chikyu*

Mission Specific Platforms
e.g. Icebreaker *Vidar Viking*

INVEST Scientific Planning Conference

K-IODP
Korea Integrated Ocean Drilling Program

IODP India

IODP-CHINA

Australian and New Zealand Integrated Ocean Drilling Program Consortium

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