CHIKYU+10

INTERNATIONAL WORKSHOP

CHIKYU

REPORT

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CHIKYU+10 International Workshop Report

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CHIKYU+10 International Workshop Report

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EXECUTIVE SUMMARY

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

INTRODUCTION

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

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

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

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

> Dynamic Fault Behavior (termed Active Faults at the workshop): Seismogenic zones pose lethal hazards to humans and civilization through seismic shaking, deformation, and tsunamis. D/V *Chikyu* will help scientists understand the mechanisms that control fault behavior by sampling and monitoring conditions in the crustal earthquake zone.
>
> Ocean Crust and Earth's Mantle: The largest part of Earth's interior, the mantle, lies within reach of D/V *Chikyu*. Direct observations will fundamentally change

our understanding of early Earth, present-day mantle dynamics, and evolution of the ocean crust, with wider implications for our solar system.

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

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

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

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

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

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

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

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

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

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

Dynamic Fault Behavior

Introduction

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

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

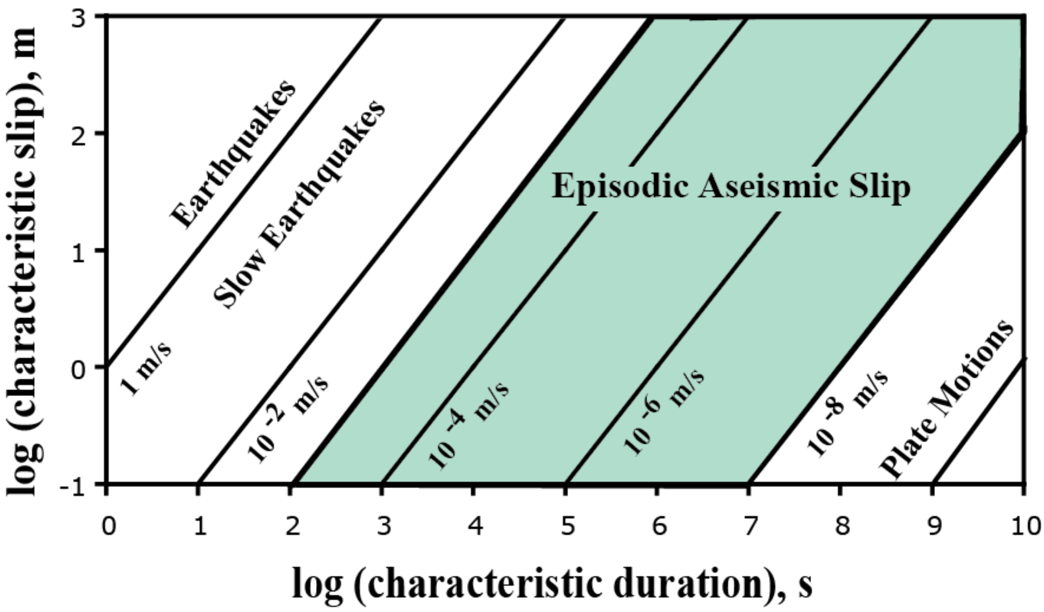

Figure 1. Plot of characteristic slip magnitude versus slip duration for various deformational processes. Normal and slow earthquakes both radiate seismic energy and occur at the fast end while plate tectonic motions occur at the slow end of the velocity spectrum. Most episodic aseismic slip (shaded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

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

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

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

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

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

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

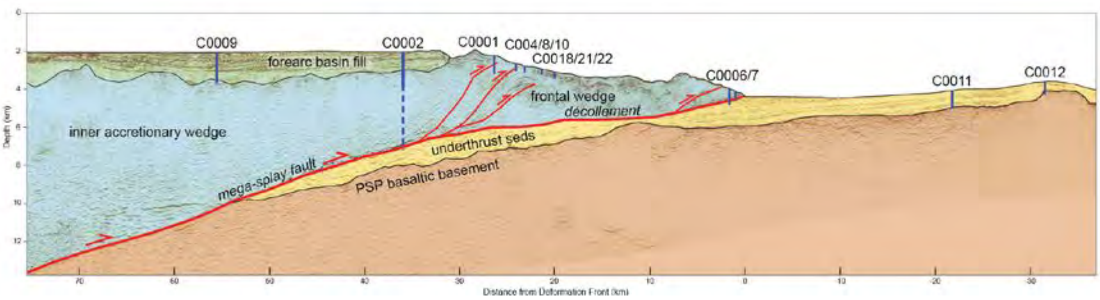

Figure 2. Cross section of the Nankai margin. Cross section shows existing riser holes (C0009 and C0002) plus riserless holes. Dashed portion of C0002 to be completed to reach megasplay fault during the remainder of the NanTroSEIZE project. Figure from Moore *et al.*, 2013.

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

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

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

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

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

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

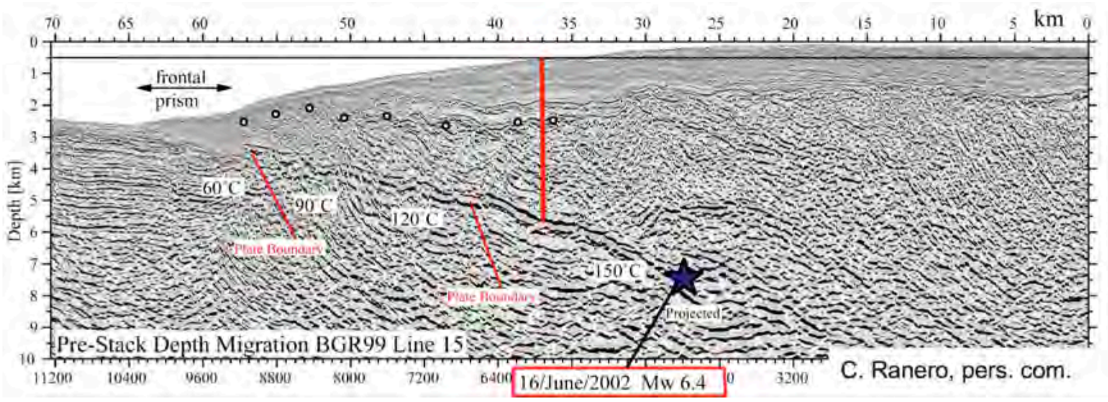

Figure 3. Cross section through the CRISP riser site. The proposed drill site is up-dip of the hypocenter of the 2002 earthquake, but in a thermal realm (> 120 deg. C) that lies in the upper limits of the traditional seismogenic zone. Figure provided by C. Ranero.

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

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

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

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

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

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

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

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

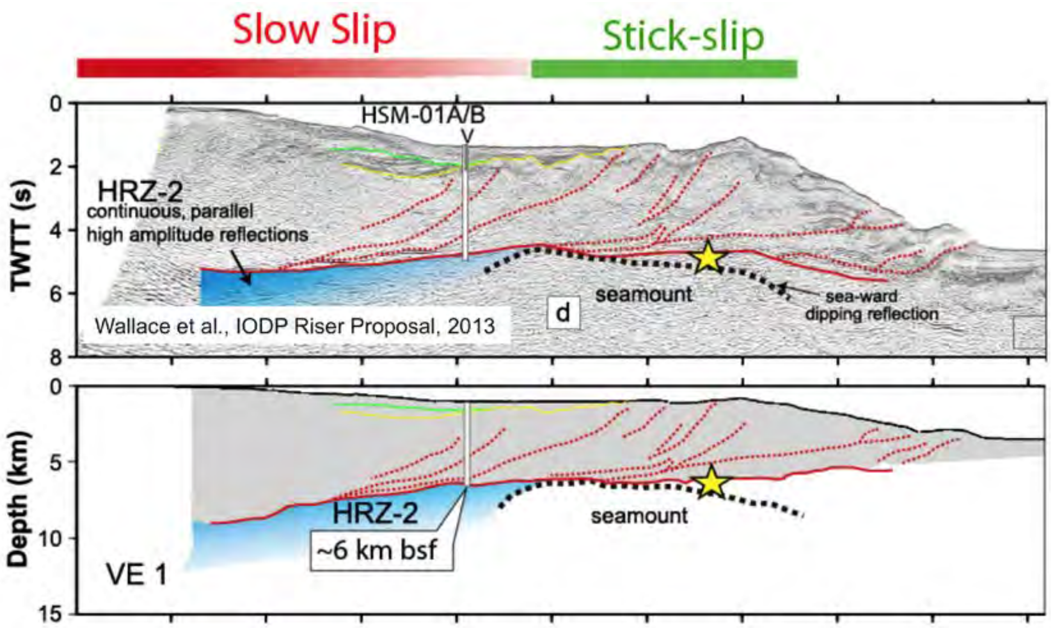

Figure 4. Time section and depth section across the proposed riser drilling locality at the Hikurangi Margin with the proposed deep hole penetrating the area of slow slip. Yellow star denotes location of 1947 tsunami earthquake. Figure provided by L. Wallace.

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

Discovery Project: Shallow and Extreme Slip (Japan Trench)

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

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

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

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

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

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

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

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

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

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

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

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

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

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

Other Projects:

Faulting in Oceanic Crust

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

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

Long-term Monitoring of Boreholes

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

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

Nicoya Peninsula, Costa Rica

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

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

Ocean Crust and Earth’s Mantle

Introduction

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

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

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

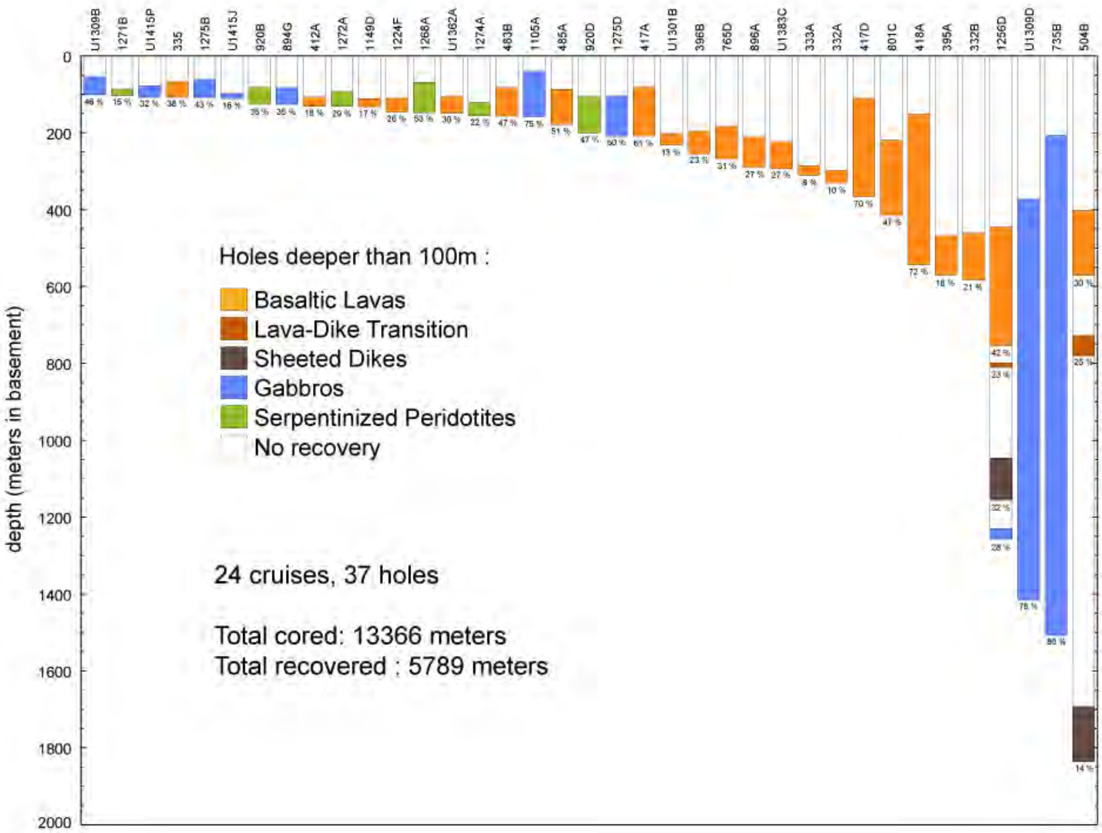

Figure 5. Compilation chart showing holes drilled deeper than 100 m (into basement, i.e., in hard rocks below sediments), intact crust, and tectonically exposed lower crust and upper mantle from 1974 to 2013. For each hole are indicated the hole number and the core recovery (in percent) for each lithology.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

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

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

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

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

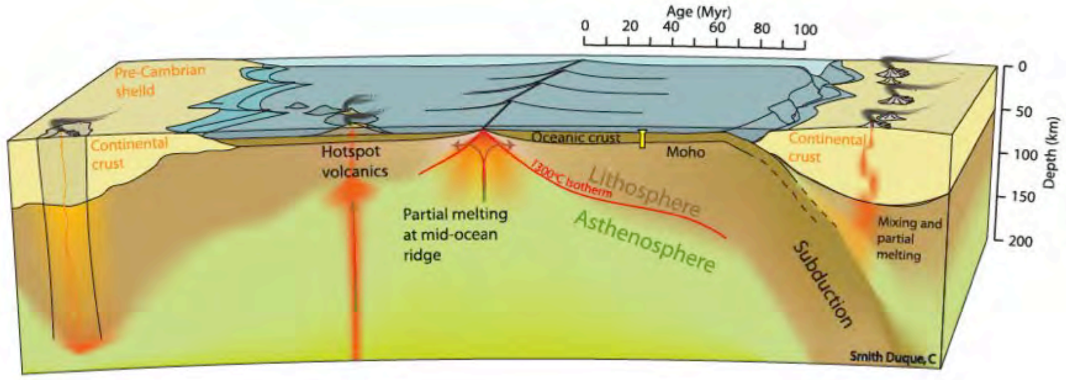

Figure 6. Sketch of the plate tectonic cycle showing the upwelling and partial melting of asthenospheric mantle to form new ocean crust at a mid-ocean ridge and the progressive growth of the lithospheric mantle as the plate conductively cools away from the ridge until it is subducted back into the mantle.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

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

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

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

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

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

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

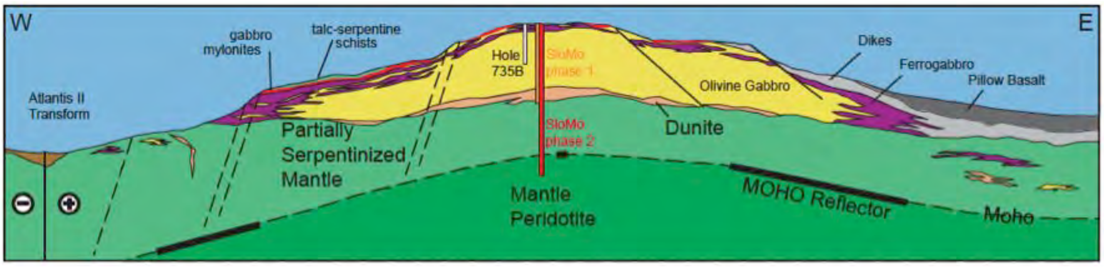

Figure 7. Cross section of Atlantis Bank through ODP Hole 735B and planned SloMo drilling (modified from a figure by H. Dick). Projected onto this line, ROV & submersible dives, over-the-side rock drills, Hole 735B and dredges show continuous gabbro outcrop, locally covered by a thin detachment fault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

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

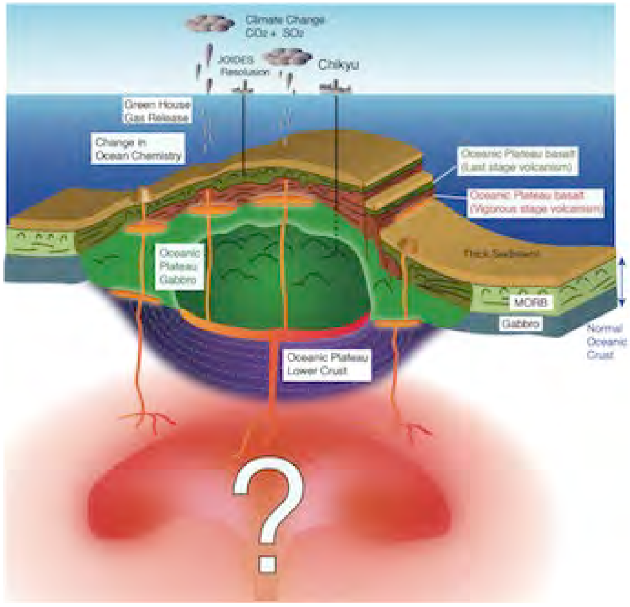

Figure 8. Schematic cross section of a Large Igneous Province (LIP), and targeted depth for *Chikyu* drilling. Figure provided by C. Neal.

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

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

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

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

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

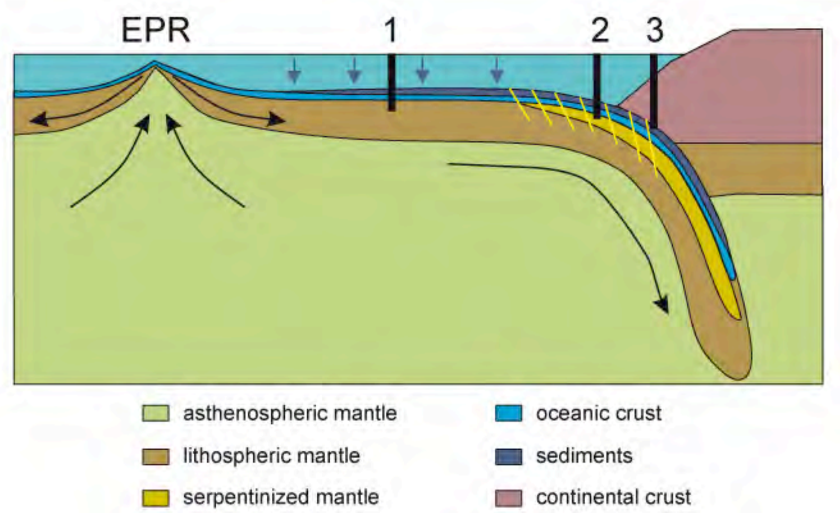

Figure 9. Schematic cross section of the Cocos plate from the East Pacific Rise to the Costa-Rica subduction zone, illustrating the concept of studying the complete life cycle of an oceanic plate. 1: M2M, 2: outer rise deep drilling, going through bent fault and reaching the serpentinized mantle, 3: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

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

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

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

Deep Life and Hydrothermal Systems

Introduction

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

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

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

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

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

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

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

Flagship of Opportunity

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

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

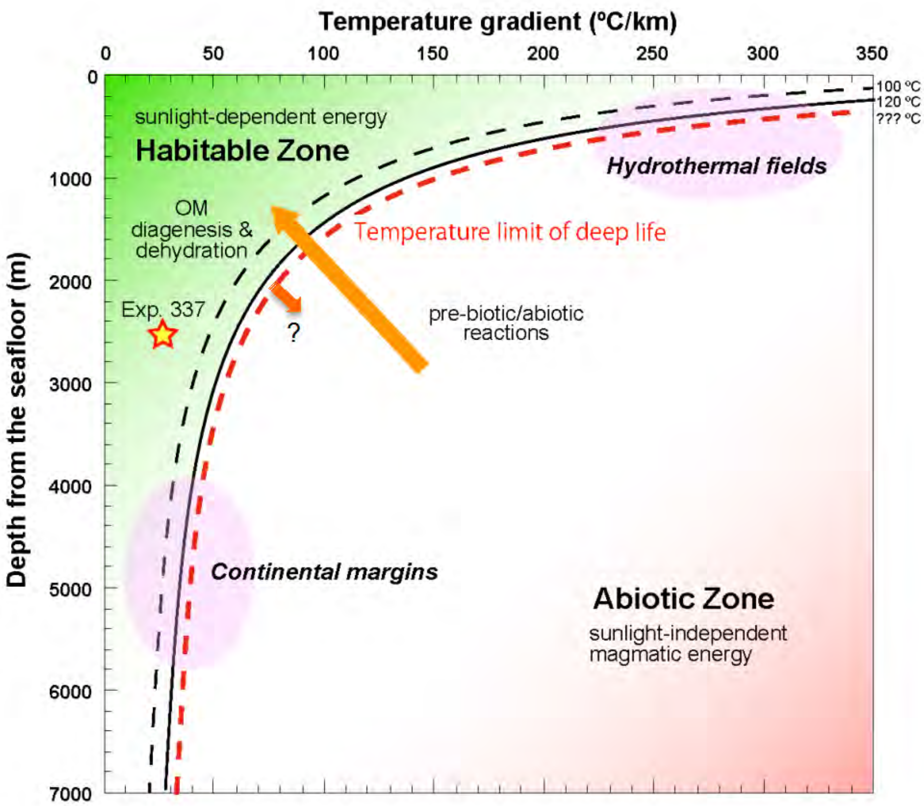

Figure 10. The transition between the habitable and abiotic zones is determined by temperature and may be very deep in areas of low heat flow such as continental margins. Hydrothermally active areas mark another end-member in the spectrum of habitats. The affect of energy input from the abiotic zone

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

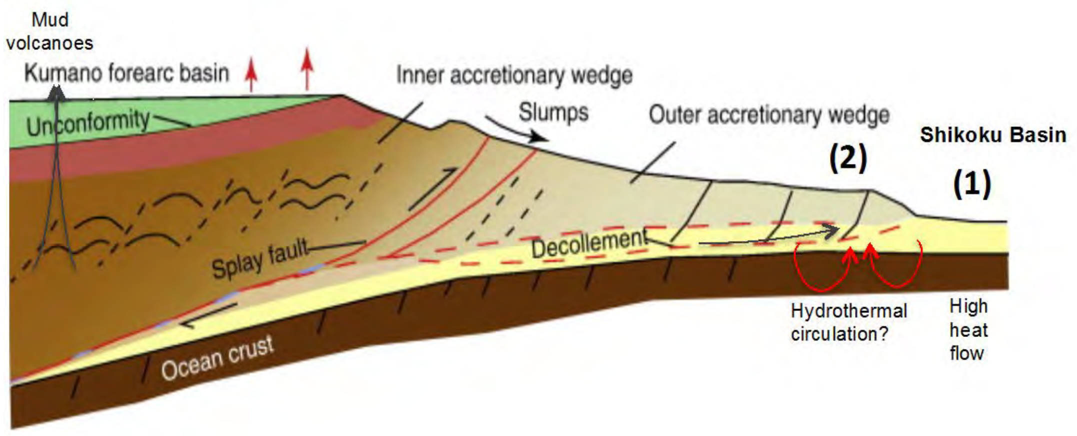

Figure 12. Schematic view of the setting of three of the discovery-type project ideas revolving around deep life in drastically different settings in convergent margins.

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

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

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

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

Specific project ideas for Hydrothermal Systems hosted in arc volcanoes

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

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

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

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

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

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

Other projects

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

Continent Formation

Introduction

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

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

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

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

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

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

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

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

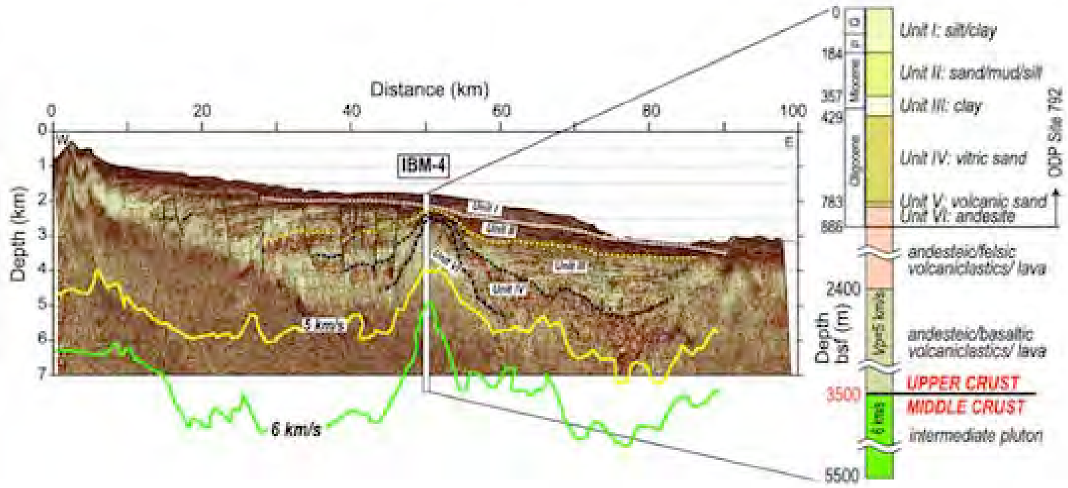

Figure 13. Lithological interpretation of the seismic image across the IBM-4 proposed site based on the results of ODP site 792, Leg 126 (Taylor *et al.*, 1992). Iso-V_p contours of 5 km/s and 6 km/s are also shown. Figure from Tatsumi *et al.*, 2010.

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

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

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

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

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

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

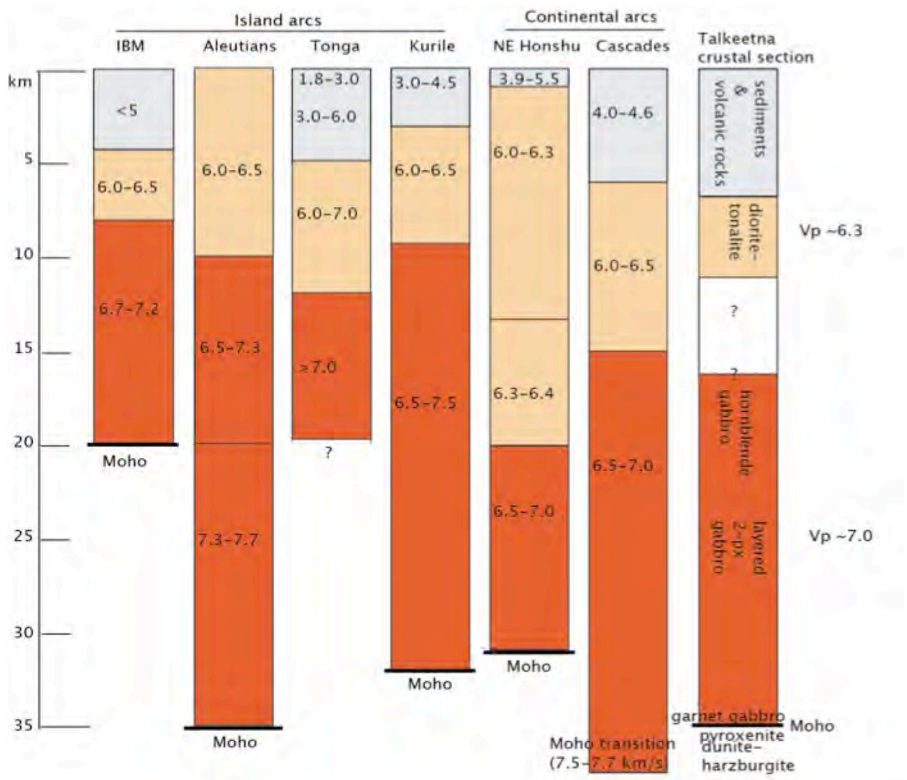

Figure 14. Seismic velocity models of various modern island arcs and continental arcs. Figure from DeBari and Greene (2011).

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

Sediment Secrets

Introduction

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

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

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

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

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

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

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

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

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

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

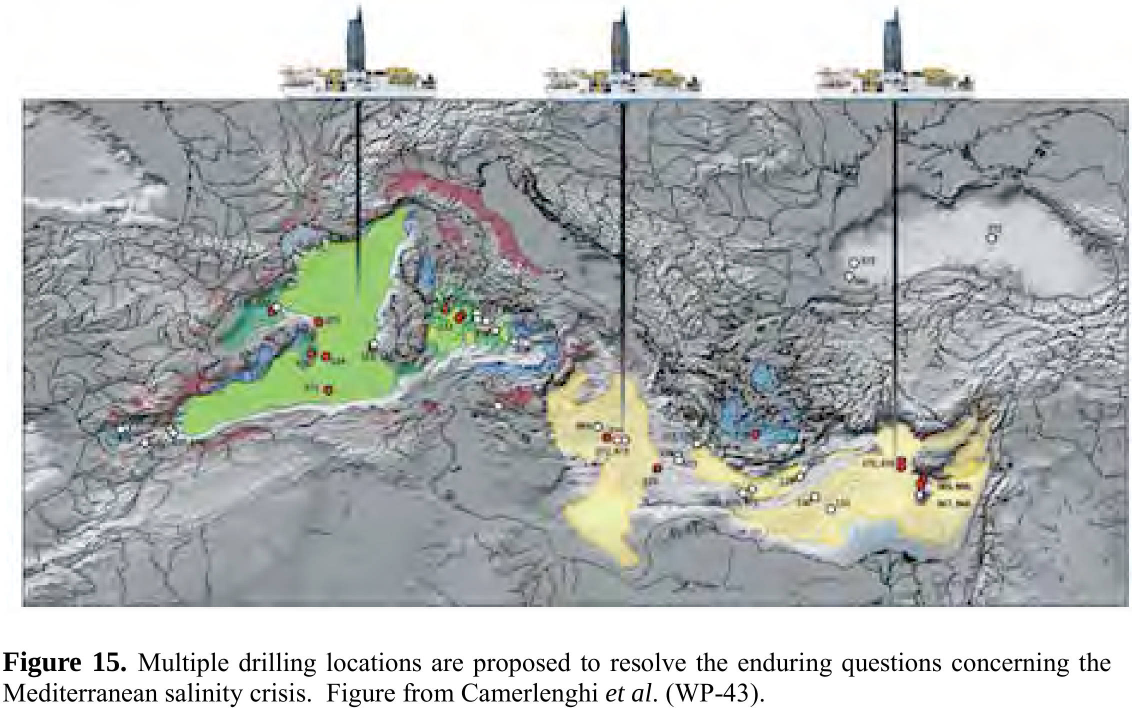

Figure 15. Multiple drilling locations are proposed to resolve the enduring questions concerning the Mediterranean salinity crisis. Figure from Camerlenghi *et al*. (WP-43).

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

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

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

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

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

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

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

***Pegasus Basin*:**

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

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

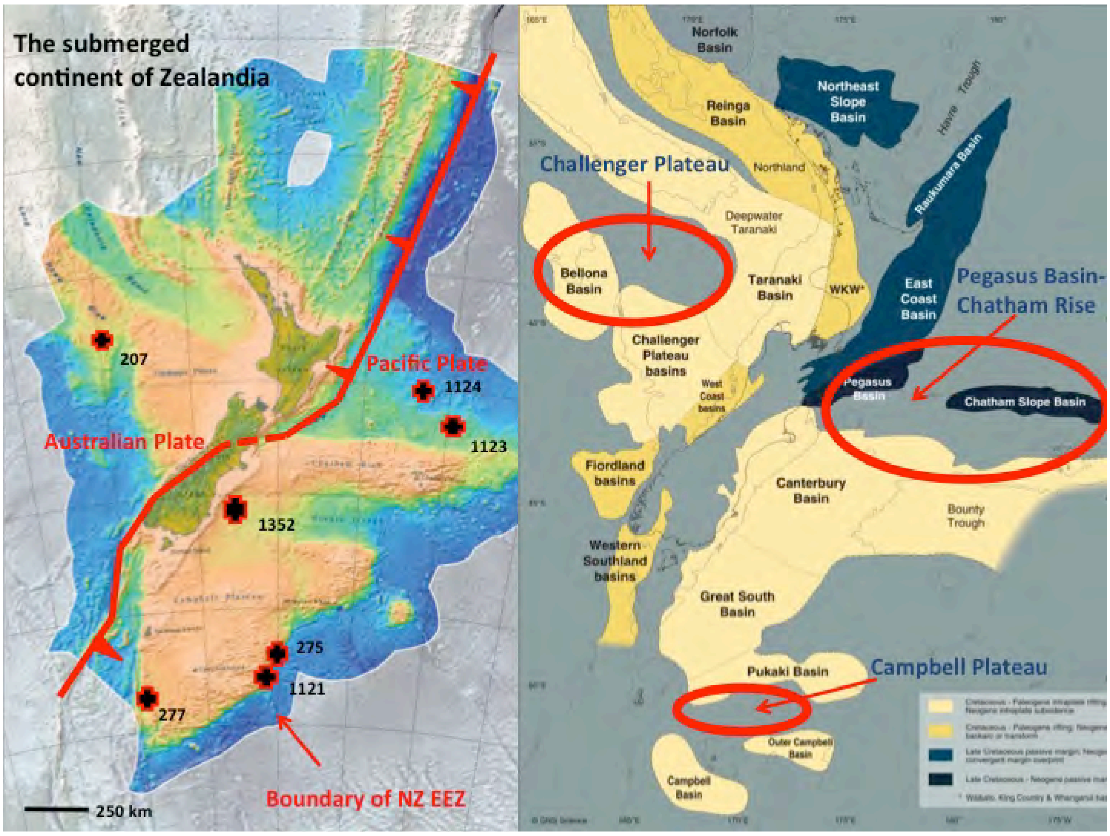

Figure 16. On the left, Boundary between the Australian and Pacific Plates in the southwest Pacific Ocean. On the right, locations of possible drilling explorations in the southwest Pacific Ocean. Figure from Browne and Hollis (WP-42).

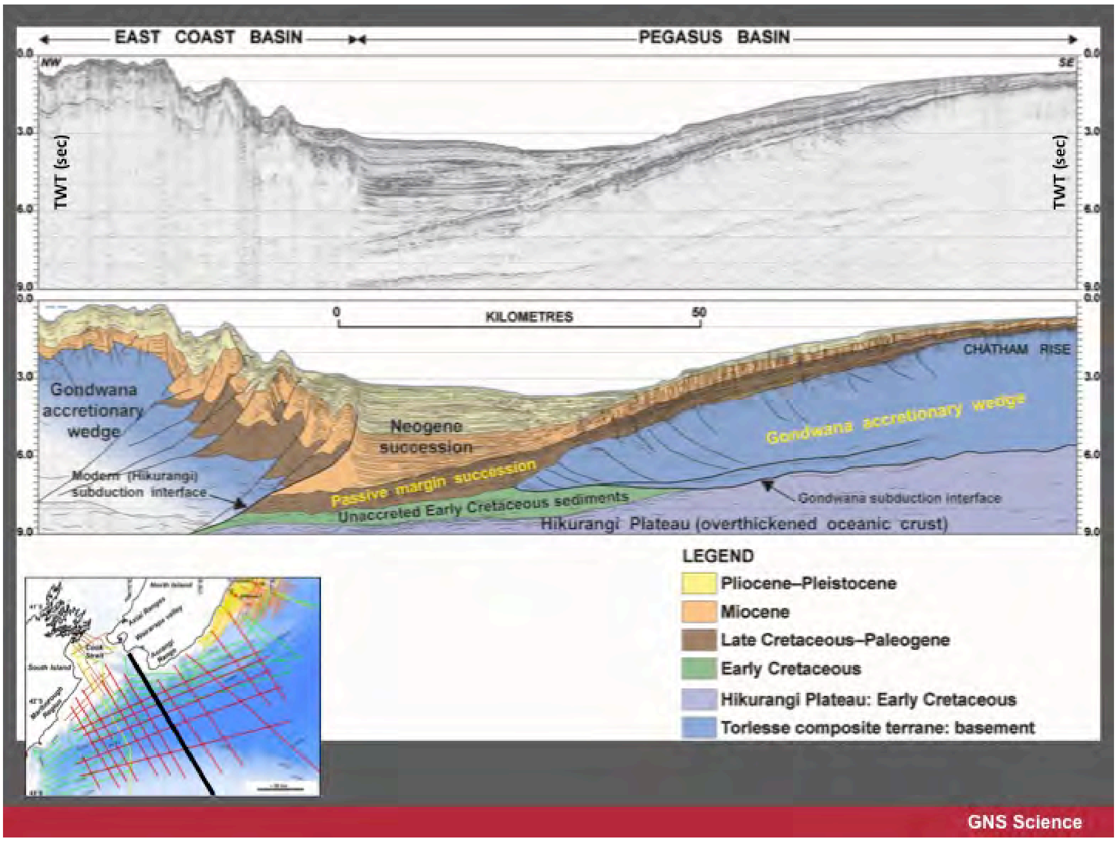

Figure 17. NW-SE seismic line showing the main sedimentary sequences of the Pegasus Basin and the modern Hikurangi subduction interface. Figure from Browne and Hollis (WP-42).

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

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

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

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

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

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

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

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

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

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

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

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

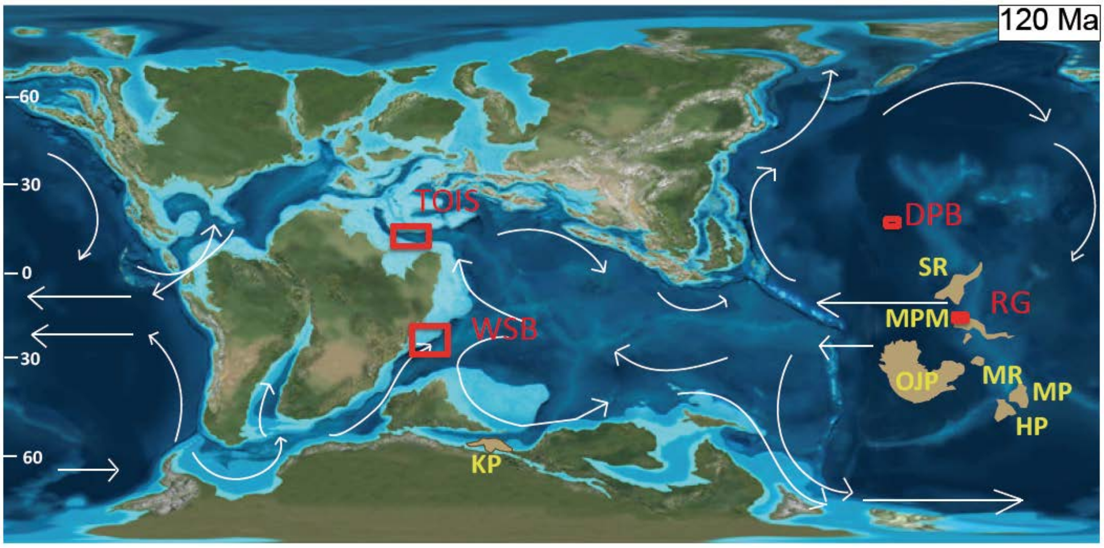

Figure 18. Palaeogeographic and oceanographic reconstructions of the Cretaceous world at about 120 Ma (source http://www2.nau.edu/rcb7/globaltext2.html). Key areas are in yellow: OJP=Ontong Java Plateau; SR=Shatsky Rise; MPM=Mid-Pacific Mountains; MR=Magellan Rise; MP=Manihiki Plateau; HP=Hikurangi Plateau;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

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

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

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

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

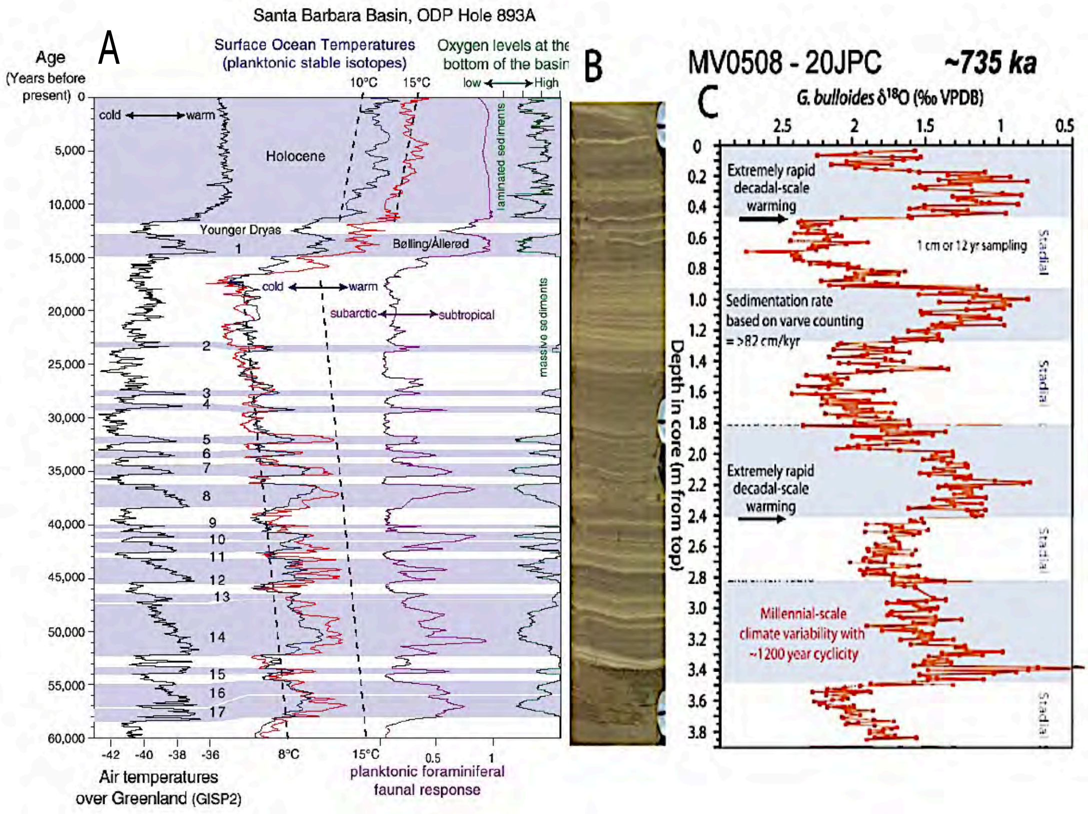

Figure 19. (A) Comparison of $\delta^{18}O$, planktonic assemblages, and laminations from ODP Site 893 in Santa Barbara Basin with air temperature over Greenland; (B) Section of Core MV0508-7 (~300,000 years ago) showing annual (varved) laminations; (C) isotopic record from Core MV0508-20 (~735,000 years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

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

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

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

CONCLUSIONS

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

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

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

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

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

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