Workshop on
Building U.S. Strategies
for 2013-2023 Scientific Ocean Drilling

April 30-May 2, 2012

Denver, Colorado

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Table of Contents

Executive Summary

In the upcoming decade, scientific ocean drilling is poised to create significant breakthroughs in understanding Earth's processes and dynamics. Building on considerable community input and recent ocean drilling discoveries, seventy-three representatives of the U.S. scientific community assembled for the *Building U.S. Strategies for 2013-2023 Scientific Ocean Drilling* workshop on April 30 to May 2, 2012 in Denver, Colorado. The workshop served to prioritize the fourteen scientific challenges outlined in the *2013-2023 Science Plan for the International Ocean Discovery Program (IODP)* and to identify new approaches for more efficient planning of scientific ocean drilling expeditions.

The workshop participants enthusiastically endorsed all of the *2013-2023 Science Plan* challenges. The four challenges listed below were judged to provide the strongest opportunities for rapid achievement of transformative science and for addressing questions of broad interest to the scientific community and society:

- In the **Climate and Ocean Change** theme, recently developed drilling strategies and analytical techniques will produce high-quality records to revolutionize understanding of *how the Earth's climate system responds to elevated levels of atmospheric* CO_2 (Challenge 1). The data collected from subseafloor sediments along ocean-wide drilling transects will be vital for assessing local and global climatic responses to increased atmospheric CO_2 levels.

- Research in **Biosphere Frontiers** has advanced rapidly as a result of recent expeditions to diverse microbial environments, adoption of metagenomic sequencing techniques, and the successful deployment of new *in situ* microbiological observatories. Researchers are now well positioned to determine *the origins, composition, and global significance of deep subseafloor communities* (Challenge 5) and to develop models of the overall distribution of subseafloor biomass.

- In **Earth Connections,** tectonic windows, hotspot tracks and large igneous provinces will be targeted to examine *the composition, structure, and dynamics of Earth's mantle* (Challenge 8). These accessible *JOIDES Resolution* objectives provide opportunities for major leaps in understanding deep magmatic and convection processes that shape our planet and will complement planned efforts to study the crust–mantle transition through very deep drilling by the *Chikyu*.

- Recent earthquakes and tsunami in Japan and Chile underscore the scientific and societal importance of the **Earth in Motion** challenge toward understanding the *mechanisms that control the occurrence of destructive earthquakes, landslides, and tsunami* (Challenge 12). These major events have reinforced the need for scientific ocean drilling and the development and installation of observatories to investigate geohazards.

The workshop participants developed an innovative model for implementing the *2013-2023 Science Plan*, including strategic scheduling of the *JOIDES Resolution* to increase scientific return and to use transits efficiently. In particular, several of the top priorities require drilling sites along transects, and this strategy provides opportunities to combine diverse scientific

objectives into single expeditions. Early announcement of ship tracks, with a commitment to visit every ocean basin at least once in the 2013-2023 program, would aid the scientific community in developing cooperative strategies early in the planning process.

Interdisciplinary science has always been a hallmark of the scientific ocean drilling programs, and workshop participants were energized by discussions about collaboration across research themes. Breakout groups focused on the interconnections inherent in the carbon cycle, the evolution of oceanic crust from formation through subduction, and the relationships among tectonics, climate, and the biosphere. The participants also recognized that full-time operation of the *JOIDES Resolution*, access to other drilling platforms, and contributions and collaborations with international partners are essential for making significant progress in all of the challenges outlined in the *2013-2023 Science Plan*.

Planning workshops will be important venues for developing strategies and identifying innovative ideas. Examples of research areas viewed as needing community building included magmatism and global climate change, the role of serpentinization in the carbon cycle and biomineralization, submarine landslides, and the impact of permafrost changes on high-latitude climate. Planning workshops will also build greater collaborations with international partners and other scientific programs such as GeoPRISMS, EarthScope, InterRidge, the Ocean Observatories Initiative, the International Continental Scientific Drilling Program, and the U.S. Geological Survey.

The workshop participants drew heavily from input provided by the 433 U.S. scientists who completed an online survey several months before the workshop. The survey participants represented 117 institutions from 39 states and included experienced scientists and a strong cohort of early career researchers and students, who represented the next generation for the program and its future leadership. The survey results reaffirmed the compelling and transformative nature of each of the challenges in the *2013-2023 Science Plan* and the strong interconnections among them.

In conclusion, the survey and workshop results confirmed the strong support by the U.S. community for continued flexibility in the program, allowing for the development and implementation of novel, high-quality science proposals and innovative new technological developments. Scientific ocean drilling is critical to the future success of ocean and earth science research, and the U.S. community is committed to maximizing the benefits from this important and unique research capability.

Section I: Introduction

The U.S. scientific ocean drilling community has driven innovative research since the beginning of the Deep Sea Drilling Project. That commitment continues today as we plan for the International Ocean Discovery Program, which would begin in 2013. The goals of the *Building U.S. Strategies for 2013-2023 Scientific Ocean Drilling* workshop were to determine U.S. priorities for the next program, discuss how planning and scheduling of the platforms can be optimized, and identify areas in which we need to build stronger research communities and gain new technologies.

A. Development

International planning for the post-2013 scientific ocean drilling program advanced in September 2009 when 584 participants from 21 nations met in Bremen, Germany, for the *IODP New Ventures in Exploring Scientific Targets* (INVEST) Conference. The scientific questions developed at the INVEST Conference were arranged into fourteen challenges under four themes: Climate and Ocean Change, Biosphere Frontiers, Earth Connections, and Earth in Motion. These challenges and themes form the basis of the *2013-2023 Science Plan for the International Ocean Discovery Program (IODP)*, which was published in May 2011(http://www.iodp.org/Science-Plan-for-2013-2023).

Table 1: Themes and challenges presented in the *2013-2023 Science Plan*.

Climate and Ocean Change
- Challenge 1: How does Earth's climate system respond to elevated levels of atmospheric CO_2?
- Challenge 2: How do ice sheets and sea level respond to a warming climate?
- Challenge 3: What controls regional patterns of precipitation, such as those associated with monsoons or El Niño?
- Challenge 4: How resilient is the ocean to chemical perturbations?

Biosphere Frontiers
- Challenge 5: What are the origin, composition, and global significance of subseafloor communities?
- Challenge 6: What are the limits of life in the subseafloor?
- Challenge 7: How sensitive are ecosystems and biodiversity to environmental change?

Earth Connections
- Challenge 8: What are the composition, structure, and dynamics of Earth's upper mantle?
- Challenge 9: How are seafloor spreading and mantle melting linked to ocean crustal architecture?
- Challenge 10: What are the mechanisms, magnitude, and history of chemical exchanges between the oceanic crust and seawater?
- Challenge 11: How do subduction zones initiate, cycle volatiles, and generate continental crust?

Earth in Motion
- Challenge 12: What mechanisms control the occurrence of destructive earthquakes, landslides, and tsunami?
- Challenge 13: What properties and processes govern the flow and storage of carbon in the subseafloor?
- Challenge 14: How do fluids link subseafloor tectonic, thermal, and biogeochemical processes?

The National Research Council (NRC; http://dels.nas.edu/osb) reviewed the *2013-2023 Science Plan* and concluded that it presents a compelling case for the next phase of scientific ocean drilling. The NRC also urged the scientific community to establish a mechanism to prioritize the fourteen challenges contained in the plan and to explore strategies to increase the program's efficiency. The National Science Foundation (NSF) echoed these sentiments and asked the U.S. scientific community for its goals and priorities within the international framework of the *2013-2023 Science Plan*. These recommendations led to the development of the *Building U.S. Strategies for 2013-2023 Scientific Ocean Drilling* Workshop.

B. Structure

The U.S. community developed the strategies and priorities presented in this report over a period of several months, with direct input provided by scientists through an online survey and an in-person workshop.

The online survey was an essential component of the planning process, as it was developed to assess the scientific interests, collaborations, and research directions of the overall U.S. scientific ocean drilling community. The survey also served as an application for workshop participants to represent the U.S. community and to develop the workshop agenda and focus areas. The survey was held online from December 1, 2011 to January 31, 2012. A total of 433 U.S. scientists representing 117 institutions participated in the survey. The survey results are discussed in Section II, with additional details presented in the separate *Building U.S. Strategies Survey Report* (http://iodp-usssp.org/workshop/strategies/).

The *Building U.S. Strategies* workshop was held in Denver, Colorado, from April 30, 2012 to May 2, 2012. The workshop was attended by 73 scientists from 45 U.S. institutions, with eleven observers from NSF, the U.S. Science Support Program (USSSP), the U.S. Implementing Organization (USIO), and IODP Management International. The workshop participants discussed the survey results and the new structure for the 2013-2023 IODP (as currently known) and then worked in breakout groups based on the four themes described in the *2013-2023 Science Plan*. The survey results indicated that U.S. IODP community members are highly interdisciplinary and have research interests that span multiple themes. To ensure that these factors were fully considered, a second set of breakout groups focused on cross-theme integration, with one group focusing on regional planning for *JOIDES Resolution* drilling.

C. Transition to New Program

Although planning for the new program is still underway, certain aspects of its design and function have begun to take shape. The community thus considered the following philosophical framework in developing the priorities and recommendations presented in this report.

1. There will not be a break in operations before the start of the new program.

The proposal being presented to the National Science Board has the new program beginning immediately after the completion of the current program. Given the time it takes to plan a successful expedition (from proposal writing to site characterization to scheduling), community organization in the preparation of high-quality ocean drilling proposals is key to ensure a smooth transition.

2. Funding is limited.

We must encourage drilling proposals that will achieve the goals of the *2013-2023 Science Plan* while saving fuel costs through an efficient ship track. Regional planning will allow for the establishment of research focus areas wherein multiple scientific challenges can be addressed most effectively.

3. The proposal review process has changed.

The process for evaluating IODP drilling proposals has been streamlined to decrease the time between proposal submission and drilling. This focus on more efficient decision-making creates a greater need for collaborations and community building during proposal development.

Section II: Survey of the U.S. IODP Community

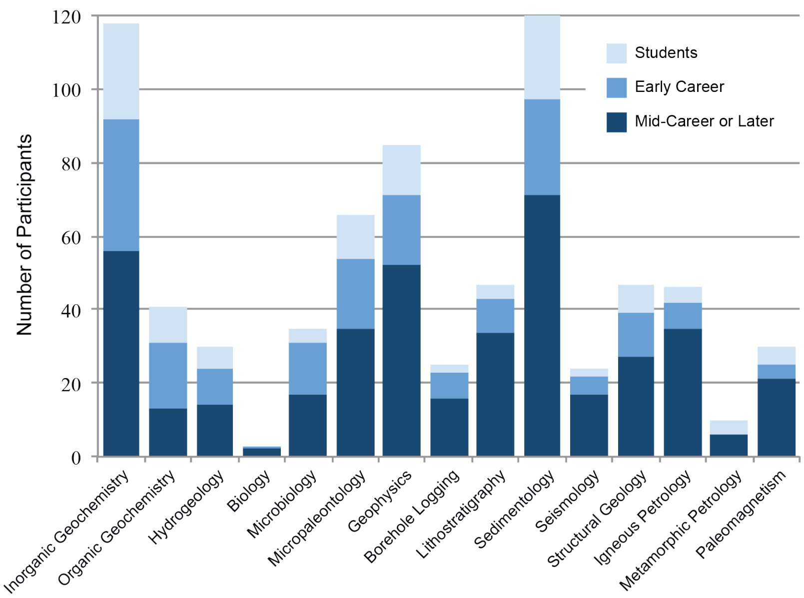
A. Overview of the Survey

The *Building U.S. Strategies* Steering Committee developed a survey for the U.S. scientific drilling community, and USSSP administered the survey online from December 1, 2011 to January 31, 2012. The purpose of the survey was to delineate the U.S. community's breadth and needs for future resources, assess new developments since the INVEST Conference, and provide input for the *Building U.S. Strategies* workshop in Denver, Colorado. All scientists interested in ocean drilling—either through participating in expeditions or using samples or data—were encouraged to participate. The survey also allowed respondents to apply to represent the community at the Denver workshop. This section summarizes the survey results most relevant to the workshop conclusions; a more detailed discussion of the survey can be found in the *Building U.S. Strategies Survey Report* (http://iodp-usssp.org/workshop/strategies/).

B. Demographics of Respondents

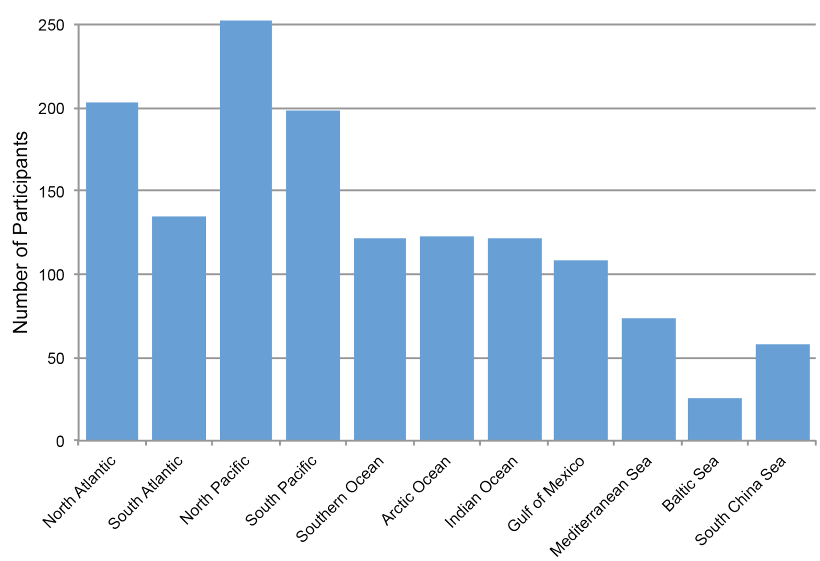
A total of 433 U.S. scientists participated in the community survey, from 117 institutions, businesses, and government agencies located in 39 states and the District of Columbia. Survey participants represented a broad range of disciplines and experience (Figure 1), with 19% at the student level, 25% at an early career stage (less than 10 years since student), and 56% at a mid-career or more senior stage (more than 10 years since student). The respondents also had a range of prior experience with scientific ocean drilling: 34% had served on an advisory or proposal evaluation panel, 49% had sailed on a DSDP, ODP, or IODP expedition, 31% had proposed a scientific drilling expedition, and 19% considered themselves new to the program. Of those who were new to the program: 49% were students, 25% were early career, and 26% were mid-career or more senior.

Figure 1: Disciplinary balance of survey participants. Participants could select more than one discipline and could also select the option "other", which was most often used to add a more detailed subdiscipline (e.g., $^{40}Ar/^{39}Ar$ geochronology) or a research interest that draws upon the disciplines selected (e.g., paleoceanography).



Based on their survey responses, the U.S. community has a wide range of global interests, with significant responses in all ocean regions (Figure 2).

Figure 2: Geographic interests of the survey participants.



The survey participants were asked to identify their primary theme or themes of interest among the four themes described in the *2013-2023 Science Plan*: 223 participants (52%) said they identified with Climate and Ocean Change, 77 participants (18%) with Biosphere Frontiers, 134 participants (31%) with Earth Connections, and 137 participants (32%) with Earth in Motion (Figure 3). The overlaps between themes shown on Figure 3 highlight the interdisciplinary nature of IODP and its research community, with particularly strong connections noted between Earth Connections and Earth in Motion.

Figure 3: Cross-theme interests among survey participants.

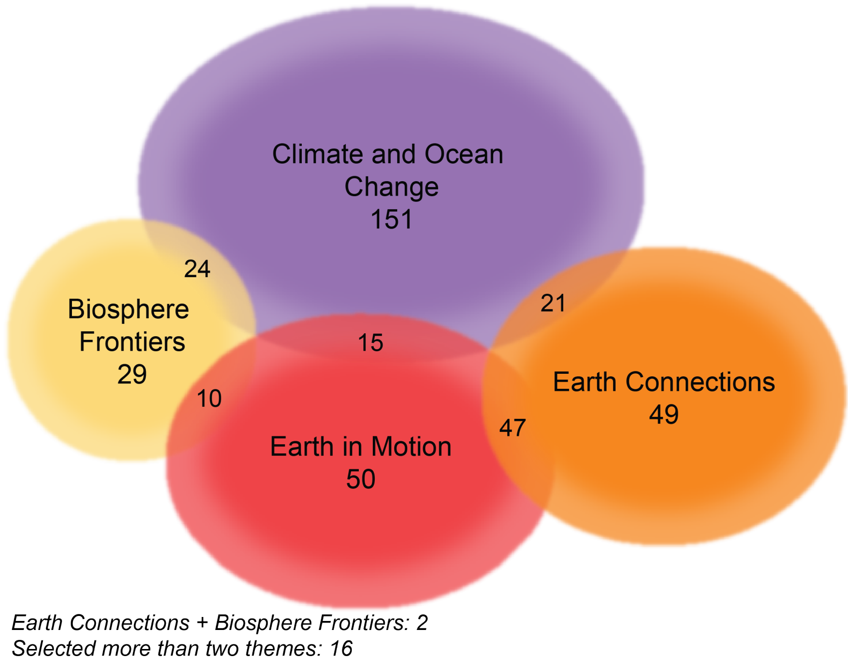
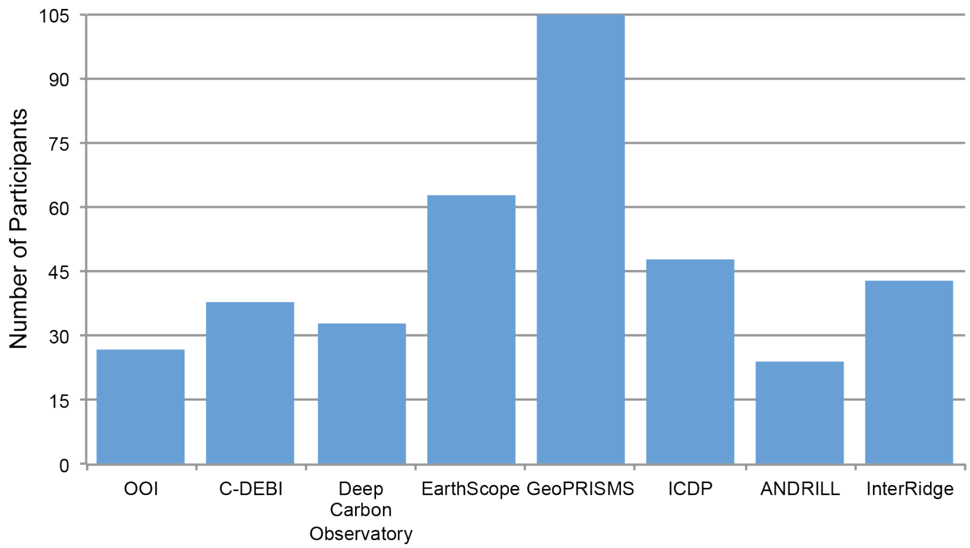


Figure 4 shows the research programs listed on the survey that received the highest number of responses; another 27 programs were mentioned in the optional "other" space provided (e.g., PAGES, GEOTRACES). The number of programs and diversity of research interests further reflect the interdisciplinary nature of IODP, as also seen in answers to other questions.

Figure 4: Participant involvement in other research programs and community initiatives.



C. Community Interest Level for Science Challenges

Interest in the science themes was addressed through questions about workshop and proposal planning (Figures 5 and 6). The survey also inquired about interest in sailing (or having a student sail) on an expedition related to each challenge, interest in requesting data or samples from an expedition related to each challenge, and interest in using results from an expedition related to each challenge (Figures 7-10).

Within Climate and Ocean Change, Challenge 1 (Elevated CO_2 Levels and Climate) received more interest in the questions about sailing, data requests, and applicable results (Figure 7), whereas Challenge 2 (Sea Level Rise) is slightly favored in the questions related to workshop and expedition proposal preparation (Figures 5 and 6). A significant number of scientists who do not identify themselves with the Climate and Ocean Change theme nonetheless find the results applicable to their research, as indicated by the lighter-shaded colors on the histogram (Figure 7).

Within Biosphere Frontiers, Challenge 5 (Subseafloor Microbial Life) and Challenge 6 (Limits of Life) received the most responses in the questions about proposal writing (Figures 5 and 6), whereas Challenge 7 (Ecosystem Sensitivity) received the most responses in the questions about sailing, data requests, and applicable results (Figure 8). Many scientists who do not identify themselves as Biosphere Frontiers are interested in these challenges and would sail, request data, or find the results applicable to their research, as indicated by the lighter-blue-shading portion of the bars. The inherently interdisciplinary nature of Challenge 7 (Ecosystem Sensitivity) was especially evident, and this challenge would likely garner interest through participation and data use from those who primarily identify with the other themes, particularly Climate and Ocean Change.

The preferred challenge within Earth Connections depends on the question asked. Challenge 8 (Earth's Upper Mantle) and Challenge 9 (Architecture of the Ocean Crust) generated the greatest interest in expedition and expedition proposal writing (Figures 5 and 6), whereas Challenge 10 (Seawater-Crust Exchange) and Challenge 11 (Subduction Zone Dynamics) received the most responses in the questions about sailing, data requests, and applicable results (Figure 9), with a significant proportion of the respondents (light orange) from outside the Earth Connections theme. We interpret this as reflecting the interdisciplinary nature of Challenges 10 and 11. Any expedition related to Challenges 10 and 11 would likely garner interest (through participation and data use) from researchers who identify with other themes. The disparity between interest in expedition proposal writing (Figure 6) and the scientific outcomes suggests that proposal pressure alone provides an incomplete picture of community interest.

Within the Earth in Motion theme, respondents indicate a preference for Challenge 14 (Subseafloor Fluid Flow) with respect to proposal development, participation during an expedition, and use and relevance of data after an expedition (Figures 5, 6, and 10). If we consider only the responses from participants who selected Earth in Motion (the darker red in each of the figures), the degree of preference among the challenges decreases, in some cases resulting in a slight preference for Challenge 12 (Geohazards).

Figure 5: Participant interest in developing a workshop proposal related to individual challenges in the *2013-2023 Science Plan*.

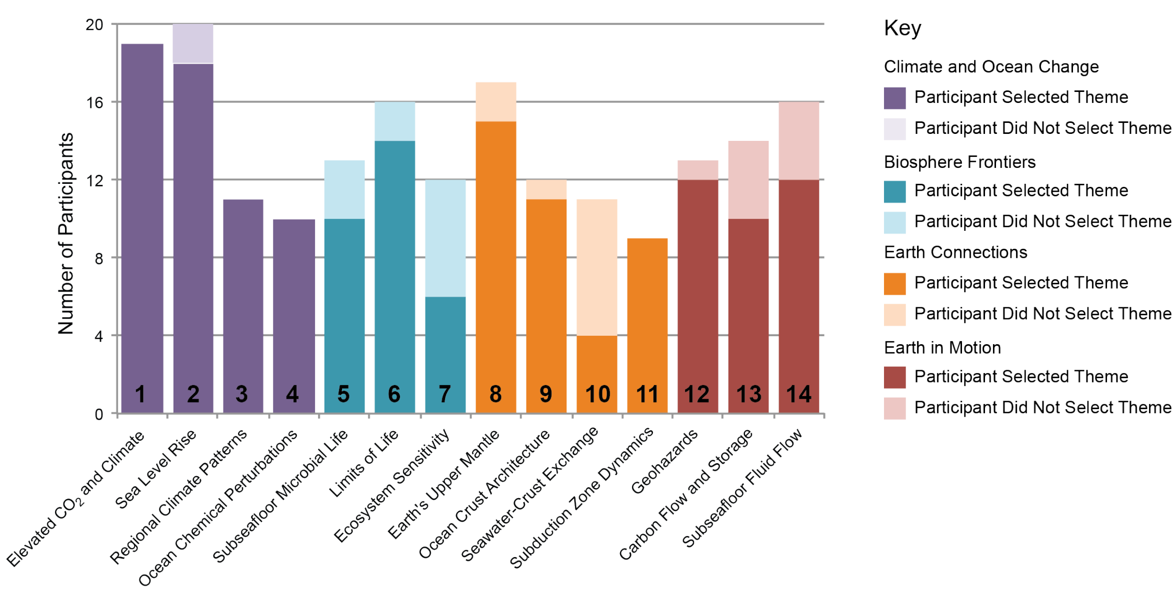


Figure 6: Participant interest in developing an expedition related to each challenge listed in the *2013-2023 Science Plan*.

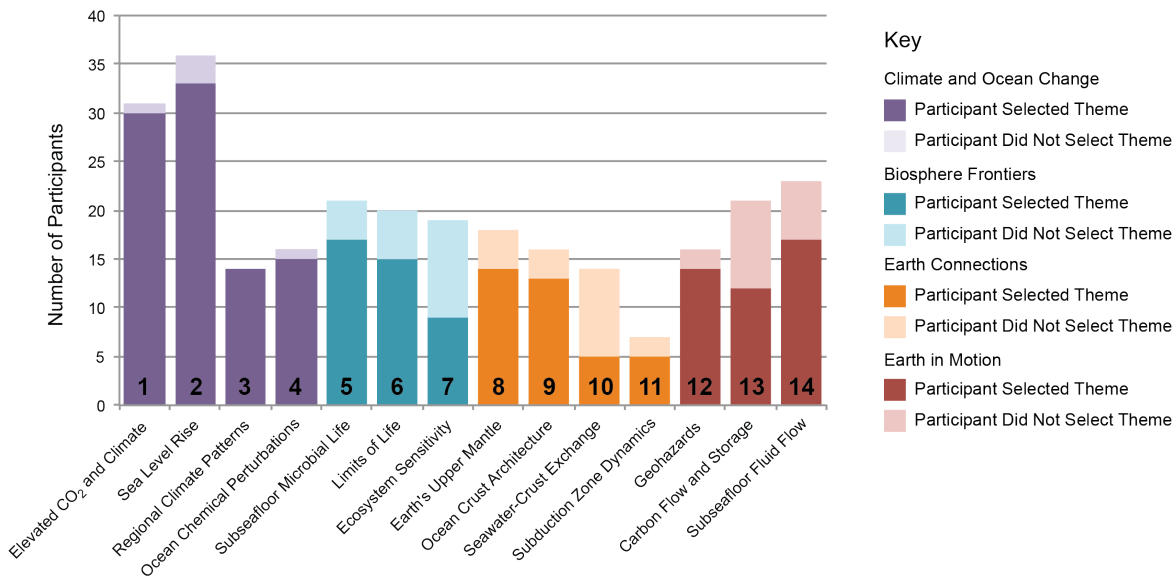


Figure 7: Participant interest for the Climate and Ocean Change challenges.

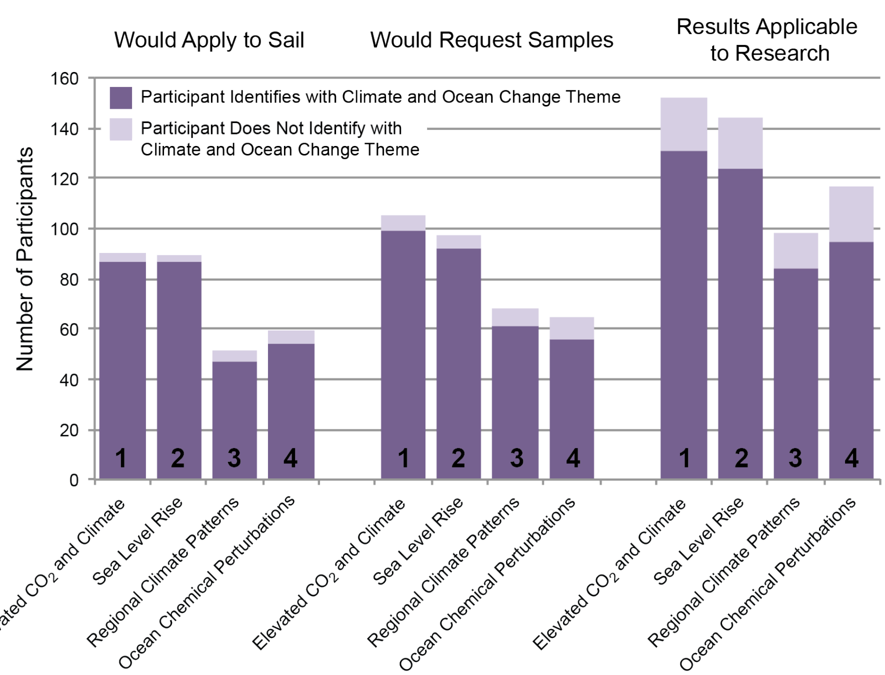


Figure 8: Participant interest for the Biosphere Frontiers challenges.

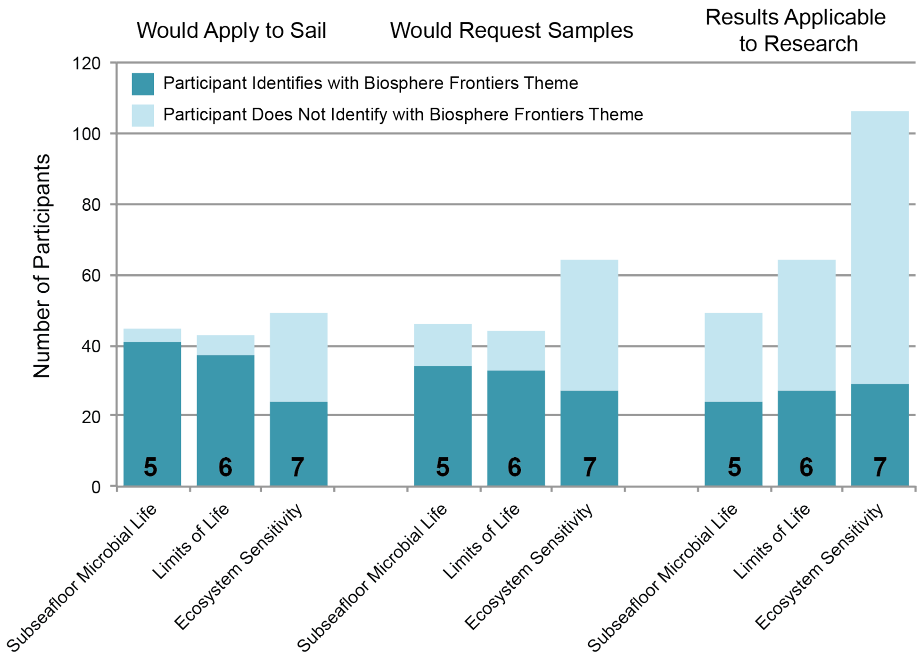


Figure 9: Participant interest for the Earth Connections challenges.

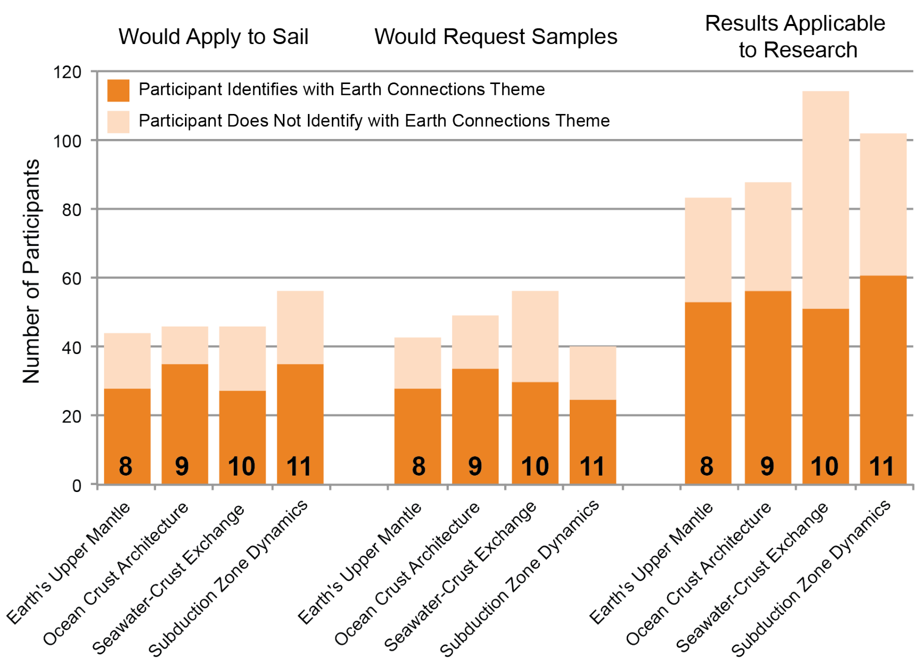
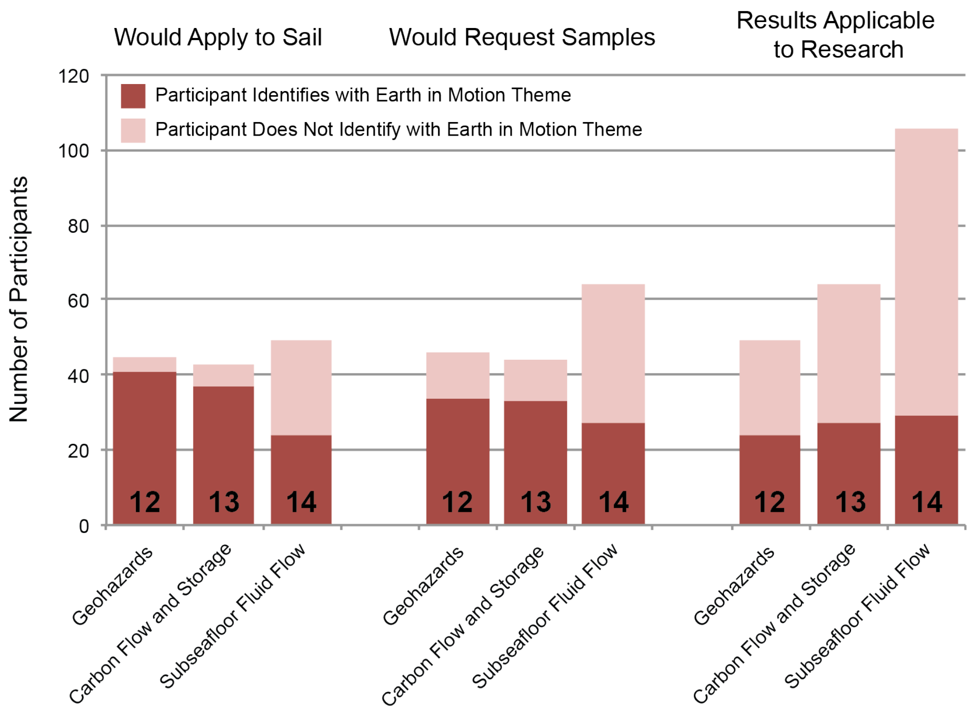


Figure 10: Participant interest for the Earth in Motion challenges.



Section III: Building U.S. Strategies Workshop

The *Building U.S. Strategies* workshop was held in Denver, Colorado, from April 30 to May 2, 2012. Participants were selected to ensure that the institutions, disciplines, and research areas of the U.S. community were well represented and that there was strong representation of early-career scientists. The meeting was structured to establish priorities within each of the themes listed in the *2013-2023 Science Plan*. Participants were asked to consider each challenge within a particular theme and how that challenge could best be addressed. Instead of thinking about implementing the challenges in traditional single or multiple two-month expeditions, participants were encouraged to think about broader operational options, across the boundaries of the new IODP research themes, and using the concept of regional research focus areas, particularly for the *JOIDES Resolution*.

A. Operational Considerations

The workshop participants worked primarily in breakout groups based on the themes in the *2013-2023 Science Plan* to assess scientific value and achievability within the decadal program time frame. They also considered objectives that contributed to multiple themes, possible requirements for instrumentation and sampling, and approximate implementation times.

The workshop focused on U.S. strategies; therefore, participants were asked to discuss primarily what could be achieved by the *JOIDES Resolution.* The U.S. scientific ocean drilling community also reaffirmed their strong support for the international partnerships, multiple platforms, and collaborative nature of IODP. Throughout the meeting, it was emphasized that this international cooperation is a major strength of the past and current scientific ocean drilling programs and should be continued in future programs.

Each of the themes requires a wide range of measurements and sampling techniques to meet their scientific objectives, as well as routine coring, downhole logging, and data collection. In particular, the Biosphere Frontiers and Earth in Motion themes also require the use of specialized instrumentation and observatories. Observatory systems are important for accessing samples and data that are otherwise unobtainable, allowing for *in situ* hydrologic and microbiological experiments, crustal exploration using cross-hole techniques, and for extending the legacy of ocean drilling long after the time when the drilling platform departs the field area. Observatory specifications depend on the specific objectives of each expedition and instrumentation and range from single-purpose monitoring (e.g., borehole temperature) to complex installations that include chemical and microbiological sampling and strain, seismometer, and geodetic instrumentation. Observatory infrastructure and instrumentation typically require investment from multiple funding sources.

B. Climate and Ocean Change

The Climate and Ocean Change challenges represent four interconnected science questions that are all scientifically compelling and societally important. Recent achievements have positioned us well to address these challenges and revolutionize our understanding of climate dynamics within the next decade. The ocean drilling programs have provided crucial data and materials to reconstruct the general history of climate change over the past 100 million years and have perfected drilling strategies for recovering high-quality records spanning that interval. In addition, the development and testing of multiple organic biomarker proxies allow us to quantify ancient sea-surface temperatures and provide better estimates for past levels of atmospheric CO_2.

Low-risk and high-reward drilling strategies in the next program will build upon this foundation to produce exciting results and enable unprecedented climate model integration with scientific ocean drilling data at all timescales of relevance, ranging from 4 Ma to 100 Ma. Within the Climate and Ocean Change theme, the science priortization accords with the community survey results that showed Challenges 1 and 2 rising consistently to the top in respondent interest.

1. Top Priority: Challenge 1

How does Earth's climate system respond to elevated levels of atmospheric CO_2?

One of the most significant developments in the climate sciences over the past few years is the recognition that climate sensitivity to atmospheric CO_2 levels is not linear, but varies with overall climate state. As a result, we need estimates of mean ocean temperature and past levels of atmospheric CO_2 to evaluate the precise response of the climate system to elevated levels of CO_2. These data do not yet exist; therefore, obtaining new high-fidelity data to quantify the sensitivity of the climate system to changes in atmospheric CO_2 at levels above ~500 ppmv is the highest priority within the Climate and Ocean Change theme. The drilling capabilities of the *JOIDES Resolution* are ideally suited to recovering sediments required to elucidate the evolution of atmospheric pCO_2 and sea-surface temperatures over the past 100 million years.

To quantify the climate sensitivity to increasing levels of atmospheric CO_2 we must recover sediments deposited during Late Cretaceous through early Pliocene time. Enhanced geographic coverage in each of the ocean basins is required throughout this time interval. Transects from low to high latitudes will evaluate polar amplification and establish meridional temperature gradients, and depth transects along margins will characterize vertical gradients. These analyses require that we recover sediments that accumulated at a sufficiently high rate during a targeted time interval to preserve crucial carbonate microfossils and organic biomarkers with orbital-scale temporal resolution. As recently demonstrated with the tropical IODP Expeditions 320 and 321 (Pacific Equatorial Transect), a single hole will not yield appropriate sediments to reconstruct the entire span of time. Instead, a successful strategy would be to drill transects of boreholes on Cenozoic oceanic crust to recover the basal sediments spanning the target age range.

In addition to the *JOIDES Resolution*, mission-specific platforms are needed, primarily in the Arctic, to revolutionize our understanding of the response of the Earth system to elevated CO_2 in the high latitudes.

2. High Priority: Challenge 2

How do ice sheets and sea level respond to a warming climate?

Ice sheets on Antarctica and Greenland today store enough water to cause the equivalent of approximately 64 meters of sea-level rise. During the colder glacial intervals of the Pleistocene and Pliocene, the potential sea-level change was significantly higher, but we do not yet know how much higher. Furthermore, we do not yet know when significant ice began accumulating at either pole or whether ice-sheet fluctuations impacted sea level during the warmer climates of the Late Cretaceous and Paleocene.

Ocean sediments record the history of sea-level change and serve as an important proxy for ice-sheet growth and decay. Due to the dynamic topography caused by ice-sheet gravitational effects and differences in regional deep mantle flow, deducing a truly eustatic record of sea level dependent on ice-sheet fluctuations alone has proven to be very challenging. The response of ice sheets and sea level to warming is considered a fundamental and important issue, and this challenge is a high priority for the Climate and Ocean Change community.

Expeditions addressing this high-priority challenge will advance our understanding of ice-shelf decay, maximum ice loss during warming events, the source of ice melt, and rates of sea-level rise. They will also contribute to a more accurate synthesis of eustatic sea level, building on the rich legacy of previous ocean drilling programs. The target time interval expands to the Late Cretaceous because evidence for eustatic sea-level change has been reported and debated for most of this interval that spans the last 100 million years. Of particular interest are past intervals of relatively warm climate. The mid-Pliocene (between approximately 3 and 3.3 million years ago) is the most recent of these warm periods, and patterns of ice-sheet behavior and sea level are being used to inform climate models for the present trend of global warming.

Scientific ocean drilling of sediments near ice margins, along passive margins, and of coral and atoll sequences can provide the necessary data to constrain these key variables. The materials recovered to address this challenge will also contribute directly to investigations of the climate response to elevated CO_2 (Challenge 1). Several proposed expeditions dedicated to the investigation of sea-level change already exist and offer the potential to make rapid progress in the next few years. Beyond these proposed expeditions, significant planning is required to identify drilling targets that will enable us to ascertain the relationship between sea-level and ice-sheet change, the role of sea-level change in methane hydrate releases, and the effect of long-term changes in seafloor spreading rates on eustatic sea level.

3. Important Priorities: Challenge 3 and Challenge 4

What controls regional patterns of precipitation, such as those associated with monsoons or El Niño?

The inter-annual variability of regional precipitation patterns is a growing societal concern, especially the relationship between climate change and drought, flooding, and storms. Phenomena such as the El Niño-Southern Oscillation (ENSO) and monsoons reflect climate connections that likely varied as a function of overall climate state. The reconstruction of the geologic history of these processes provides important constraints on the regional response to global climate change, and how a single global forcing may impact areas differently. Regional drilling coverage, particularly in monsoonal regions, is currently too sparse to address this challenge. Targeted drilling will enable us to address the history of precipitation in monsoonal regions and directly compare hydrological processes to the climate record.

Within the time frame of the new program, data can be collected to reconstruct the long-term hydrologic history of climate phenomena such as monsoons and ENSO using biomarker compounds and directly correlate these records with surface temperature and CO_2 records. These records also will provide crucial links to terrestrial archives, as found in speleothems and lacustrine records. Furthermore, drilling in the Indian Ocean will elucidate connections between Tibetan and Himalayan tectonic uplift and related changes in hydrological conditions. Drilling in the Indian Ocean as well as the western Pacific will provide exceptional records in key areas related to monsoonal and ENSO variability at glacial–interglacial and Cenozoic timescales.

The community is poised to accomplish these goals early in the new program as highly ranked proposals are scheduled or ready to be scheduled and the track of the *JOIDES Resolution* is projected to begin in the western Pacific and Indian Ocean.

How resilient is the ocean to chemical perturbations?

Perturbations to biogeochemical cycles have the potential to impact biological communities at all levels. Much attention has focused on ocean acidification; however, deoxygenation, particularly in a warming ocean, is emerging as a growing concern. Studies of past perturbations recorded in marine sediments provide crucial information on rates, feedbacks, and biotic consequences. This is an important challenge, and ocean drilling is required to obtain appropriate records to advance the state of the field. Because this challenge is highly aligned with the top Climate and Ocean Change priority, drilling targets proposed to address the response of the climate system to elevated levels of atmospheric CO_2 will also enable investigation of transient perturbations of the marine biosphere. For example, drilling aimed at recovering thick accumulations of sediments spanning the peak of Cenozoic warmth during the late Paleocene and early Eocene will provide the opportunity to investigate the causes and consequences of these biogeochemical perturbations. The Late Cretaceous, middle Eocene, early middle Miocene, and early Pliocene also provide rich opportunities to understand better the biogeochemical perturbations and biosphere response during episodes of global warming.

C. Biosphere Frontiers

IODP has recently made significant progress in deep biosphere research. Three expeditions tested specific hypotheses regarding factors that control the distribution, community composition, and activities of the deep biosphere in a diverse array of subseafloor environments. These environments included extremely low energy sediments (Expedition 329: South Pacific Gyre), an active hydrothermal vent region (Expedition 331: Okinawa Trough), and a well-characterized fluid-flow environment in oceanic crust (Expedition 336: North Pond). These expeditions demonstrated the rapid maturation of deep biosphere research and the critical contributions provided by scientific ocean drilling.

The subseafloor microbiological community has successfully adopted techniques from other fields, such as metagenomics, and pioneered new technologies, including the successful deployment of *in situ* microbiological observatories. The deep-biosphere research community has also succeeded in attracting external funding to support the installation of observatories (e.g., Moore Foundation) and post-expedition research (e.g., National Institutes of Health). These funding sources are new to IODP and point toward sustainability of this area of research within the new program and its increased relevance to the Earth science community. Breakout group discussions considered the survey input from the larger community, in which Challenge 5 (Subseafloor Microbial Life) and Challenge 6 (Limits of Life) received the most responses in the questions about proposal writing (Figures 7 and 8) and Challenge 7 (Ecosystem Sensitivity) showed very strong interconnections with other themes, particularly Climate and Ocean Change.

1. Top Priority: Challenge 5

What are the origin, composition, and global significance of subseafloor communities?

Workshop participants selected Challenge 5 as the top priority because of the fundamental aspects of the research and its potential for extensive cross-theme synergies within the *2013-2023 Science Plan*. The deep-biosphere community of researchers aspires to develop predictive models for the entire ocean regarding the distribution of subseafloor biomass and associated activities that mediate the exchange of metabolically active compounds among the oceanic crust, sediments, and the overlying water column. These models can be achieved only through comprehensive and global sampling of the seafloor for microbes and the parameters that are thought to control their distribution and composition (e.g., fluid-flow rates, energy sources, temperature).

The workshop participants emphasized the global significance of this priority, and circumnavigation of the *JOIDES Resolution* lends itself very well to addressing this top priority. Microbial communities residing within representative environments—including passive and active margins, oceanic gyres, ocean basins of ranging maturity and age, and transects across hydrothermal ridge systems—should be characterized, along with chemical and physical properties. As we learn more about the environmental factors that control the distribution and structure of microbial communities in the subsurface, we can begin to model these distributions globally based on the relative composition of the subseafloor with respect to the representative environments. Drilling in subseafloor environments (e.g., margins or gyres) will either confirm or force a reconsideration of our assumptions regarding the factors that control the distribution of subsurface microorganisms.

The global nature of this research objective means there is tremendous potential to develop proposals that will simultaneously address this challenge and challenges within the other three themes. In particular, routine microbial sampling during all expeditions, regardless of the primary focus, would greatly support the global aspect of the challenge. This new approach will minimize additional drilling time, and it requires integration of microbiological work into the routine core flow onboard the *JOIDES Resolution* and other platforms. This includes training of shipboard technicians and scientists on the stringent requirements for sampling and storage of samples that will be used for microbiological studies, as well as the long-term archiving of samples stored under the appropriate conditions (e.g., -80°C) at the IODP core repositories. The use of *in situ* observatories, particularly within oceanic crust, provides a means for long-term observations and microbial growth experiments.

2. High Priority: Challenge 6

What are the limits of life in the subseafloor?

Defining the limits of life is fundamental to understanding the deep biosphere and is a high priority for Biosphere Frontiers research. As with Challenge 5, this challenge can be addressed through routinely collected microbiological samples to discover new environmental parameters that affect growth rate and cell biomass within the subsurface. Additional high-resolution, targeted sampling will also recover subsurface material from extreme environmental conditions (e.g., high temperature, extreme pH, low organic carbon, low fluid flow) that have been previously identified to limit life. Through careful coordination, additional drilling time will be relatively minimal while the probability for significant, transformative results is high. This challenge will also benefit from *in situ* experiments and observations to test limitations predicted from the recovered samples.

3. Important Priority: Challenge 7

How sensitive are ecosystems and biodiversity to environmental change?

Survey results indicate the strong overlap of Challenge 7 with the Climate and Ocean Change theme. In particular, this challenge is closely interlinked with changes in CO_2 (Challenge 1) and the resiliency of the oceans to chemical perturbation (Challenge 4).

Biological communities are impacted by ocean acidification and deoxygenation. Investigating past perturbations recorded in marine sediments provides crucial information on rates, feedbacks, and biotic consequences. Ocean drilling is required to obtain appropriate records to advance the state of the field. Because this challenge is highly aligned with Challenges 1 and 4, drilling targets proposed to address those challenges will also enable investigation of transient perturbations of the marine biosphere.

Fine-scale resolution of temporal shifts in Earth's climate will frame data collected to address this challenge. Past success with coral drilling expeditions highlights the potential for a better understanding of biosphere shifts. Other targets for examining ecosystem sensitivity include transitions to or from past warm periods such as the Paleocene–Eocene thermal maximum (PETM), past anoxic events of the Cretaceous, the Monterey carbon excursion and climatic optimum of the middle Miocene, and glacial–interglacial climate transitions.

D. Earth Connections

The Earth Connections theme of the *2013-2023 Science Plan* presents four challenges related to deep Earth processes and their impact on Earth's surface environment. The community survey demonstrated significant interest in all four of the challenges with no clear prioritization. This was interpreted to reflect a strong interconnectedness among the challenges and the likelihood that significant progress could be made in more than one challenge during any expedition related to Earth Connections. In prioritizing these challenges, the workshop participants focused on potential synergies and on the progress that could be made specifically by the *JOIDES Resolution*. Complementary drilling by the *Chikyu* and MSPs is also very important to this theme and is strongly supported by the U.S. community.

1. Top Priority: Challenge 8

What are the composition, structure, and dynamics of Earth's upper mantle?

Determining the nature and dynamics of processes in the Earth's mantle is fundamental to understanding the construction of oceanic crust, which covers more than 60% of the Earth's surface. The workshop participants identified three drilling strategies that will address different mantle characteristics: (1) drilling in tectonic windows to study the crust–mantle transition; (2) hotspot tracks to define past mantle flow better; and (3) sediments in basins proximal to large igneous provinces to determine the entire history and environmental impacts of the largest volcanic accumulations on Earth.

Understanding the nature of the crust–mantle transition and the Mohorovičić discontinuity (Moho) has been a longstanding goal of scientific ocean drilling. Significant progress can be made by drilling in a tectonic window where faulting or reduced magmatic accretion has positioned the crust–mantle transition relatively close to the surface. An example location is Atlantis Bank on the Southwest Indian Ridge, where gabbro is exposed at the surface. This strategy will allow us to sample mantle compositions directly, test models of mantle melting, and address whether the Moho is a lithologic alteration or tectonic boundary. The results would lead to a major leap in understanding the deep processes that shape our planet and complement proposed drilling by the *Chikyu* that aims to penetrate and recover a complete oceanic crust section and the underlying upper mantle.

Results from ODP Leg 197 defined the motion of the Hawaiian hotspot in Earth's mantle, exposing the potential to use hotspots as recorders of past mantle flow. Recent results from IODP Expedition 330 suggest motion between the Louisville and Hawaiian hotspots, thus defining mantle flow within an ocean basin. Additional drilling is essential to understand how these motions relate to global mantle convection patterns. These drilling experiments will also test the hotspot reference frame that has been used to provide an absolute framework for studying geographic climate responses into geologic time.

Large Igneous Provinces (LIPs) are vast accumulations of mafic igneous rocks that are emplaced over short time intervals and provide important insight to the nature of the mantle from which they are derived. Some LIPs are thought to be associated with deep mantle plume heads, while other LIPs might have a shallow mantle origin, but they clearly represent an intermittent and very dynamic mantle state. There are also interdisciplinary aspects addressed by studying LIPs. LIP emplacement releases gases to the ocean–atmosphere system, triggering a chain of biogeochemical climate feedbacks and affecting ocean chemistry, carbonate biomineralization, and primary productivity, and perhaps playing a role in mass extinctions. Recovery and biostratigraphic analyses of sediments deposited during LIP eruptions would constrain the age and duration of the eruptions and document for the first time the variability in mantle processes during a LIP episode.

2. High Priority: Challenge 11

How do subduction zones initiate, cycle volatiles, and generate continental crust?

Material from Earth's surface is recycled into Earth's interior at subduction zones. Subduction of oceanic lithosphere also results in the release of volatiles, melting in the mantle, and some of the world's most hazardous volcanic eruptions, earthquakes, and tsunami. Determining how subduction initiates, volatiles are recycled, and oceanic island arcs are constructed is key to understanding the evolution of the solid Earth system and, in particular, how the building blocks of continental crust are formed. While drilling with the *JOIDES Resolution* can contribute significantly to studies of subduction initiation and volatile recycling, drilling by *Chikyu* is required to test directly the generation of continental crust by drilling deep into arc middle crust. Expeditions using the *JOIDES Resolution* to target the forearc oceanic crust can constrain how mantle melting evolves during subduction initiation. This information is key for building and testing subduction initiation geodynamic models. An expedition to drill pre-arc crust at Izu-Bonin Mariana is tentatively scheduled for 2014 and will result in substantial progress on this challenge early in the new program.

During subduction, heat and pressure release a significant fraction of volatile constituents that drive melting in the mantle above the subducting plate. Quantifying the fluxes of volatiles, particularly water and carbon, remains a key goal of scientific drilling studies. A large uncertainty on the influx to subduction zones is the magnitude of the carbon and water within the down-going crust. In particular, faults at the outer rise may allow access of seawater that drives serpentinization. Drilling in diverse arc settings using the *JOIDES Resolution* will constrain spatial and temporal evolution of arc magmas and how mantle flow and melting vary during arc evolution and with lateral distance from the fluid-rich subducting slab.

3. Important Priorities: Challenge 9 and Challenge 10

How are seafloor spreading and mantle melting linked to ocean crustal architecture?

There are substantial differences in the composition and architecture of the crust generated at fast and slow spreading ridges. The processes that generate these heterogeneities are poorly constrained, despite their fundamental importance in paving two-thirds of Earth's surface over the last 200 million years. Challenge 9 is directly linked to the objectives of Challenge 8, and similar approaches, such as drilling into tectonic windows, should result in major progress in both challenges.

Asymmetric spreading and low magma supply influence a large percentage of crustal production at slow and ultra-slow spreading centers. In addition, a quarter of the rocks exposed at the seafloor may be mantle rocks exposed via crustal-scale faulting. Drilling in an along-axis direction where tectonic windows exist, combined with drilling normal to the ridge on the conjugate side of an asymmetric spreading ridge, will reveal lateral variability and improve our understanding of how the mantle melting regime is linked to oceanic crustal architecture at slow-spreading centers. Although fast-spreading crust has been better sampled by scientific drilling to date, additional sections could provide valuable information to test competing models of magmatic accretion.

Mantle melting that generated large igneous provinces yielded especially thick oceanic crust. One problem in making progress in understanding the generation and emplacement of LIPs themselves, and the volcanic stages that encompass their constructional histories, is that access to earlier-stage erupted lavas is difficult. An approach that holds considerable promise is to drill in a deep canyon in a LIP that, either through faulting or erosion, provides access to the deeper-level architecture of this special type of ocean crust. Such drilling could result in a major advance in understanding LIP oceanic crust architecture which, when combined with a syn-LIP drilling approach in Challenge 8, could result in a breakthrough in understanding LIP generation and relation to large-scale mantle dynamics.

What are the mechanisms, magnitude, and history of chemical exchanges between the oceanic crust and seawater?

Quantifying the geochemical consequences of seawater interaction with mafic and ultramafic oceanic crust and the contribution of these processes to geochemical budgets is of fundamental importance in global cycling and in regulating the chemical composition of the oceans. Such research requires ocean drilling to constrain the balance between high- and low-temperature fluid flows and the variability in reactions that occur across a range of seafloor ages. Challenge 10 is strongly linked to other challenges in the Biosphere Frontiers and Earth in Motion themes, and any borehole drilled into basement rock will enable studies of rock alteration.

Low-temperature seawater–basalt exchange starts at the ridge crest and continues for at least 65 million years, even as the crust is buried beneath sediment that slows fluid exchange. Although crust of 0 to 20 million years age has been studied, there are currently few samples of basement ranging from 20 to 70 millions year old, a period of significant thermal and hydrogeologic transition. Substantial progress can be made by filling in this gap of crustal sampling along a plate tectonic flowline or transect to determine the time-integrated products of fluid–rock reactions as the crust ages and matures.

An important component of fluid–rock reactions is the high-temperature alteration that occurs in active hydrothermal systems on mid-ocean ridges. Drilling into active or recently active volcanic- or ultramafic-hosted hydrothermal systems on or near the ridge axis is problematic because of the high temperatures in these environments. The role of high-temperature hydrothermal systems in chemical exchange and in the formation of massive sulfide and other mineral deposits could be quantified by drilling into inactive hydrothermal sites that are now located off-axis. A key challenge will be to locate such sites that may now be covered in sediments. This currently active area of research using geophysical methods is likely to mature over the next few years. Achieving this goal may be possible in the later stages of the next program, with some new technology development to improve recovery rates in sulfide deposits.

Deeply penetrating faults, such as bend faults that occur on the outer rise of the trench at subduction zones, may enable more hydration and alteration of the mantle than previously recognized, possibly making serpentinization of ultramafic rocks a key process in chemical exchange. The work is closely interrelated with subduction zone volatile cycling of Challenge 11. Drilling through bend faults, as well as fault zones in younger oceanic crust, would help assess the pathways of fluid flow and associated water–rock reactions in these environments. Because this finding is relatively new, proposals will need to be developed that could result in discoveries of alteration processes and the occurrence and extent of hydration of the mantle.

E. Earth in Motion

The Earth in Motion theme of the *2013-2023 Science Plan* addresses questions involving fundamental Earth system processes, including those underlying major geologic hazards that occur at timescales of seconds to years. The community survey demonstrated significant interest in all three of the Earth in Motion challenges, with the greatest overall interest in Challenge 14 (Subseafloor Fluid Flow) (Figure 12). Interest in this theme and in Challenge 13 (Carbon Flow and Storage) was particularly high among those who did not identify with these themes, reflecting strong interdisciplinary ties. For example, biosphere research and studies of seawater–crust exchange rely on characterization of fluid flow.

1. Top Priority: Challenge 12

What mechanisms control the occurrence of destructive earthquakes, landslides, and tsunami?

As noted in the NRC report, advances in the capability for short-term prediction of geohazards would be “truly transformative.” Recent large earthquakes and tsunami have highlighted the need for better understanding of submarine geohazards, and current offshore and onshore studies have produced mature hypotheses. IODP is positioned to provide offshore leadership, as scientific drilling is the only means to access deep archives of past events or active fault zones in critical offshore regions. This is also a topic of considerable interest to society at large.

Earthquake research has comprised an important part of the current phase of scientific ocean drilling, particularly through the Nankai Trough Seismogenic Zone Experiment (NanTroSEIZE). Deep drilling and observatory work is a key part of NanTroSEIZE, but many objectives can be addressed through shallower coring, sampling, and logging while drilling. Future expeditions to other subduction zones or adding single sites to drilling plans will provide a global view of the earthquake processes and insight into different slip mechanisms.

The Tohoku earthquake emphasized that documenting the properties of the shallow portion of fault zones is critical to understanding tsunamigenesis. These properties may be sampled by conventional drilling. Analyses and experiments on cores will allow reconstruction of previous events along the fault-slip plane and determination of the frictional properties of the fault zone and parent material. Drilling of sediment deposits can extend the history of paleotsunami and paleoearthquakes beyond the range accessible by piston cores. Stress histories can be reconstructed from core records, and current stress state can be assessed by studying fractures created during drilling. Borehole observatories may include combinations of thermistors, fluid pressure sensors, seismometers, strainmeters, or geodetic instrumentation.

Landslide research shares much common ground with earthquake work because sediment strength and frictional properties are crucial, as is the distribution of fluid pressures. The distribution of landslide-prone regions is much wider than that of earthquake generation, encompassing passive margins such as those surrounding the Atlantic Ocean, active margins, and volcanic bathymetric highs. Addressing landslide objectives will require development of suitable strategies to sample and date older landslide deposits and to instrument incipient slope failures to address process-based questions. Progress within the new program will require additional organization and planning to tap the knowledge of an active community of submarine and terrestrial landslide researchers.

2. High Priority: Challenge 13

What properties and processes govern the flow and storage of carbon in the subseafloor?

The flow and storage of carbon below the seafloor has profound implications for energy production and for the global responses to changes in the carbon dioxide content of the atmosphere and ocean. In addition, this challenge links with all three of the other themes in the *2013-2023 Science Plan* and has potential ties to industry and opportunities for programmatic partnerships. Drilling strategies focus on gas hydrates and carbon dioxide sequestration—both natural and anthropogenic—within oceanic crust.

Past ocean drilling expeditions have explored gas-hydrate formation, stability, and extent, with clear implications for topics such as slope stability, the subseafloor biosphere, energy resources, and the rapid delivery of methane to the ocean and atmosphere. Special sampling and monitoring tools have also been developed for application to hydrate provinces during scientific drilling. Frontiers in this area will relate gas hydrates to microbial activity, influences on hydrate production and dissolution over time, and response to short-term perturbations. Ties to microbial activity will use microbial sampling and population studies, organic and inorganic geochemistry, and biomarkers, as well as mapping biological presence and activity in boreholes. Active perturbation studies will provide data on the formation and decomposition of hydrate deposits, including those linked to subsea permafrost at high latitudes.

There is considerable interest in carbon dioxide sequestration below the seafloor, as a natural process that has operated through much of earth history and as a potential strategy for mitigating excess flows of carbon dioxide to the atmosphere. This is a new topic for scientific ocean drilling and is a technical and scientific frontier that requires understanding of serpentinization and carbonation of volcanic seafloor rocks, multiphase and reactive transport, and complex interactions between volcanic, hydrogeologic, geochemical, and biological systems. IODP is uniquely poised to provide global leadership in these efforts, but work is needed to find suitable sites, design experiments and instruments, and complete pilot studies. A variety of seafloor settings may be suitable for drilling and associated experiments, including the sediments along continental shelves, the upper oceanic crust, and areas of exposed ultramafic rocks of the lower crust and upper mantle.

3. Important Priority: Challenge 14

How do fluids link subseafloor tectonic, thermal, and biogeochemical processes?

Fluids play fundamental roles in numerous global processes, including heat loss from the deep Earth, mineral deposition, earthquakes and landslides, and carbon and nutrient cycling in coastal waters. Flowing fluids support submarine biomes and exotic seafloor communities, contribute to seismicity and crustal cracking and cooling, control patterns of lithospheric alteration, and transfer volatiles to and from subduction zones. The submarine hydrogeologic cycle is also linked to groundwater systems on land, including massive flows between terrestrial and marine realms across continental margins. The workshop participants recognized broad cross-disciplinary benefits from projects focused on Challenge 14 and noted that many of these objectives would be addressed, in part, through leveraging of opportunities based on other challenges.

The potential targets for Challenge 14 span geologic settings, including divergent plate boundaries and their flanks and passive and convergent margins. Long-term observations of pressure, temperature, fluids, and microbiology are an important part of this challenge, as are active perturbation experiments using single boreholes and borehole observatories. Conventional coring and sampling will also provide critical information to assess the global significance of fluid flow throughout the seafloor. Organic and inorganic geochemical, microbial, and thermal data will constrain fluid sources, flow rates, and impacts of fluid flow on subseafloor physical, chemical, and biological processes.

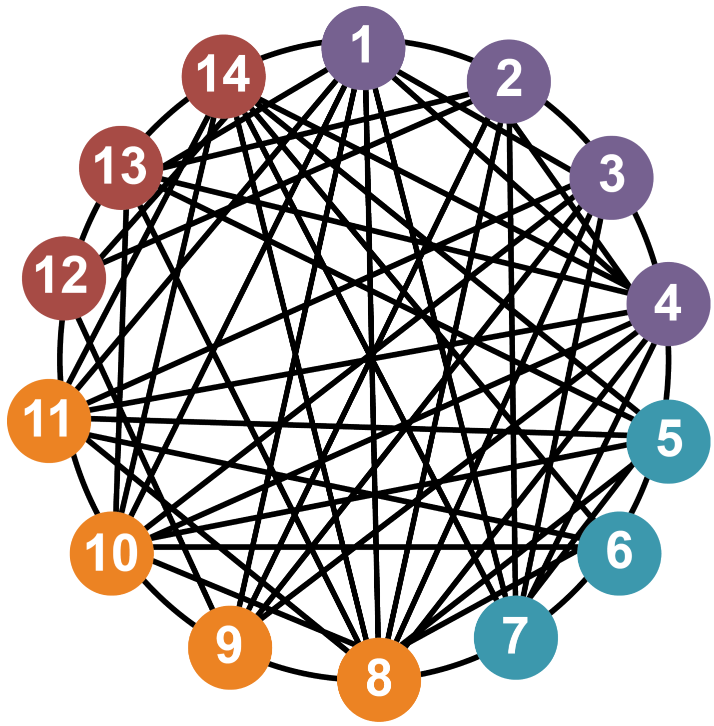
F. Cross-theme Linkages

Interdisciplinary science has always been a hallmark of the scientific ocean drilling programs, and strong interconnections among scientific themes were apparent in the survey results. The close links among the challenges were also noted in the *2013-2023 Science Plan* and in the NRC report. At the workshop, the participants expanded on these relationships (Figure 11) in the following cross-theme breakout groups:

- Interactions between Tectonics and Magmatism and Climate and Ocean Changes
- The Carbon Cycle: Connections between Biosphere and Climate
- Construction, Evolution, and Subduction of Ocean Crust: Relations to Hydrosphere, Biosphere, and Hazards

These cross-theme breakout groups discussed how the new program could build collaborations early in the planning process to ensure that the thematic recommendations take into account research topics that occur within multiple *2013-2023 Science Plan* themes and to assess where collaborations need to be developed. The cross-theme groups also served to highlight the connections with other initiatives or organizations within the U.S. and internationally.

Figure 11: Connections among *2013-2023 Science Plan* themes as identified by the workshop participants.



1. Examples of Major Science Linkages

a. Eruptions and Volatiles

Volatiles such as CO_2 are released during large igneous eruptions and are drawn down during weathering of silicate minerals. As a result, deep Earth processes (Challenge 8) impact atmospheric CO_2 and Earth's climate system (Challenge 1) and cause hydrologic and chemical perturbations (Challenges 3 and 4). Detailed timing of large eruptions relative to climate fluctuations and extinctions could be constrained by drilling and dating of sediments deposited in basins near LIPs. Intervals of more intense and widespread subduction-zone volcanism, such as the Eocene to Oligocene, can also alter atmospheric volatiles (Challenges 1 and 11).

b. Mountain-Building and Global Climate

Erosion and weathering of silicate minerals follow mountain building and create a sink for carbon dioxide. In turn, the hydrologic cycle (Challenge 3), particularly monsoon patterns, contributes to erosion and can drive uplift and mountain building. IODP is poised for near-term progress in untangling these relationships. For example, sediment fans built by rivers draining the Himalayas provide ideal locations to investigate the connection between mountain building and the hydrologic cycle. Other orogens have also affected atmospheric and oceanic circulation patterns and offer an opportunity to test competing hypotheses.

c. Tectonics and Sea Level

Flow within the Earth's mantle controls the topographic response to changes in the weight of overlying ice and water. As a result, sea level response to changing ice-sheet volumes depends on mantle viscosity. On the longer term, oceanic crust production rates have varied through time, adding complexity to unraveling the links between climate, carbon dioxide, and sea level. This link also relates to the biosphere because the flooding of continents impacts the evolution of life in shallow seas.

d. Carbon Storage in Gas Hydrates and Permafrost

Destabilization of subsea permafrost and gas hydrates occurs due to long- and short-term temperature changes and links carbon flow and storage (Challenge 13), fluid movement (Challenge 14), climate (Challenges 1, 2, and 4), and the biosphere (Challenges 5, 6, and 7). Furthermore, decomposing permafrost could contribute to slope failures (Challenge 12). Drilling on the Arctic shelf and slope provides an opportunity to assess this connection.

e. Roles of Fluid Flow

Subseafloor Fluid Flow (Challenge 14) and Seawater–Crust Exchange (Challenge 10) both showed strong cross-theme interest in the survey and through the workshop. These challenges are closely interrelated, with the main distinction being timescales and the focus on flow process versus the rock record of fluid interaction. Fluid flow impacts chemical and thermal fluxes, and thus microbiology. Close working relationships have already been initiated between fluid flow and microbiological research in oceanic crust through observatory work on the Juan de Fuca Ridge flanks and the Mid-Atlantic Ridge (North Pond), and additional proposals are active within the system. Some of these studies target high-fluid-flow regimes on recent, short timescales. At the other end of the spectrum, low-fluid-flow environments are also targeted for assessing the impact on the biosphere on longer timescales.

f. Serpentinization

Alteration of crustal and mantle rocks occurs when they are accessed by seawater. This can occur at slow-spreading ridges, where the deep crust and mantle are exposed, or, as recently hypothesized, where bend faults might allow seawater to reach sub-crustal depths at the outer rise of subduction zones (Challenge 11). Serpentinization impacts the long-term carbon cycle (Challenge 13), alters the ocean balance of calcium and magnesium, and may encourage unusual microbial ecosystems due to abiotic methane production and high alkalinity (Challenge 5 and 6). Serpentinization also weakens the mantle rock and may impact subduction dynamics and geohazards (Challenge 12).

<u>2. Connections with Science Initiatives and Organizations</u>

a. GeoPRISMS

The subduction zone focus on volatile and fluid cycling (Challenges 10, 11, and 14) and geohazards (Challenge 12) provides a clear link to the GeoPRISMS (Geodynamic Processes at

Rifting and Subducting Margins) program. This link is particularly strong in the GeoPRISMS focus areas offshore the Pacific Northwest, Alaska, and New Zealand.

The GeoPRISMS initiative on Rift Initiation and Evolution also shares thematic ground with the Earth Connections objectives concerning crustal architecture (Challenge 9), fluid exchange (Challenge 10), and mantle dynamics (Challenge 8) and the Climate and Ocean Change objectives examining the climate–tectonic links related to topographic changes (Challenge 3). Specific interests at the eastern North America focus site include submarine landslides and carbon and water venting, which are closely related to Earth in Motion Challenges 12, 13, and 14.

b. EarthScope

EarthScope objectives dovetail with many of the science challenges. Mantle upwelling beneath North America shares common ground with Earth Connections objectives concerning mantle dynamics (Challenge 8). Close ties exist between drilling and observatory work at the San Andreas fault zone and IODP fault zone studies, as each contributes to new understanding of fault-zone properties. In the Pacific Northwest and Alaska, EarthScope data provide onshore constraints on subduction-zone volatile cycling and subduction-zone hazards. On the East Coast, EarthScope geodetic work complements offshore studies of sea-level rise (Challenge 2).

c. U.S. Geological Survey

The potential impact of offshore earthquakes, tsunami, and landslides on the U.S. provides a tie between Challenge 12 and the U.S. Geological Survey (USGS) Hazards Program. These links are particularly strong in the Pacific Northwest and Alaska. The USGS Hazards Program also encompasses volcanic hazards, linking it to Challenge 11 (subduction-zone volatiles); coastal geology, which is impacted by sea-level changes (Challenge 2); and changes in the Earth's magnetic field, an area where scientific ocean drilling has and continues to provide crucial data. The USGS Energy Resources Program is actively investigating the potential of continental shelf gas hydrates and carbon sequestration, linking it to Challenge 13.

d. Ocean Observatories

The Ocean Observatories Initiative (OOI) and NEPTUNE Canada cable networks on the Juan de Fuca plate will rely on scientific ocean drilling boreholes for their access to the subseafloor. Experiments within these boreholes will drive advances concerning geohazards (Challenge 12), carbon flow in gas hydrate zones (Challenge 13), and subseafloor fluid exchange and the subseafloor biosphere (Challenges 14 and 5).

e. International Continental Scientific Drilling Program

The International Continental Scientific Drilling Program (ICDP) science plan shares many objectives with IODP, including interests in climate change, the geobiosphere, mantle plumes, oceanic crustal accretion, continental rifting, and earthquake processes. Onshore–offshore pairing of drilling objectives have linked ICDP and IODP in the past and will address critical science questions that cross the shoreline.

f. InterRidge

Studies at oceanic spreading centers closely align with understanding oceanic crust architecture (Challenge 9), mantle processes (Challenge 8), crust–seawater exchange (Challenges 10 and 14) and the biosphere (Challenges 5-7). Investigations of back-arc spreading overlap with Challenge 11 concerning subduction zone processes.

g. Additional Connections

Other synergies exist with C-DEBI and the National Institutes of Health (NIH) and Biosphere Frontier challenges, EarthCube for infrastructure for data related to all challenges, ANDRILL for Antarctic studies, NASA Astrobiology, and NOAA Ocean Exploration. Work on carbon flow and storage (Challenge 13) and subseafloor landslides (Challenge 12) are tied closely to the U.S. Department of Energy and the energy industry. The Deep Carbon Observatory's objectives are also aligned with IODP, as scientific ocean drilling provides critical access to the Earth's interior carbon reservoirs.

Section IV: Conclusions and Recommendations

The *Building U.S. Strategies for 2013-2023 Scientific Ocean Drilling* survey and workshop highlighted the fundamental strengths of the scientific ocean drilling programs: exciting science driven by proposals, a strong collaborative culture, and scientific and logistical leverages due to international partnerships and associated multiple platforms. The program has fostered teams of scientists, students, engineers, and educators who value a truly collaborative and multidisciplinary approach to understanding Earth systems. IODP has successfully mentored young researchers with experience in international and interdisciplinary collaboration. This mentorship bodes well for leadership at scientific and technical frontiers, and within the larger workforce. The survey results and workshop discussions demonstrated the energy, dedication, and team spirit of the U.S. community for the *2013-2023 IODP*. The conclusions and recommendations presented below focus on the U.S. ocean drilling research priorities, regional planning, and workshops.

A. U.S. Ocean Drilling Research Priorities

The workshop participants prioritized the fourteen scientific challenges outlined in the *2013-2023 Science Plan* from a U.S. perspective. Prioritizing the challenges was deemed necessary to maximize scientific progress in the 2013-2023 IODP because developing drilling proposals is time and resource intensive. At the same time, the workshop participants confirmed their support for flexibility in the program, allowing for the development and implementation of novel, high-quality science proposals and innovative new technological developments when outstanding opportunities arise.

The workshop participants considered the scientific value and achievability of each challenge within the decadal program, as well as input provided by the 433 U.S. scientists who completed the open, online survey. They support focusing resources for workshops, site characterization, and observatories on the top-priority challenges to complete these objectives during the program's timeframe.

The workshop participants identified four top-priority science challenges:

- Challenge 1: How does Earth's climate system respond to elevated levels of atmospheric CO_2?
- Challenge 5: What are the origins, composition, and global significance of deep subseafloor communities?
- Challenge 8: What are the composition, structure, and dynamics of Earth's mantle?
- Challenge 12: What mechanisms control the occurrence of destructive earthquakes, landslides, and tsunami?

The U.S. community can make significance progress on high-priority challenges in the next program if enough resources are available for full-time operations, planning workshops, site characterization, and observatories. Several challenges would benefit from investment from outside organizations, foundations, and other funding agencies.

The workshop participants identified four additional high-priority science challenges:

- Challenge 2: How do ice sheets and sea level respond to a warming climate?
- Challenge 6: What are the limits of life in the subseafloor?
- Challenge 11: How do subduction zones initiate, cycle volatiles, and generate continental crust?
- Challenge 13: What properties and processes govern the flow and storage of carbon in the subseafloor?

The workshop participants strongly reaffirmed the compelling and potentially transformative nature of each of the challenges in the *2013-2023 Science Plan*. The challenges not listed as top or high priorities generally have broad-based appeal and could be partially achieved through expeditions to address other challenges. In other cases, these challenges were seen to require longer-term planning than the top-priority challenges, or they are already close to achievement, requiring few additional planning resources. Strategic scheduling and development would help assure progress on these challenges.

The workshop identified six important science priorities:

- Challenge 3: What controls regional patterns of precipitation, such as those associated with monsoons or El Niño?
- Challenge 4: How resilient is the ocean to chemical perturbations?
- Challenge 7: How sensitive are ecosystems and biodiversity to environmental change?
- Challenge 9: How are seafloor spreading and mantle melting linked to ocean crustal architecture?
- Challenge 10: What are the mechanisms, magnitude, and history of chemical exchanges between the oceanic crust and seawater?

- Challenge 14: How do fluids link subseafloor tectonic, thermal, and biogeochemical processes?

B. Increasing Efficiency in *JOIDES Resolution* Planning

During the current scientific ocean drilling program, the track of the *JOIDES Resolution* has been driven primarily by the availability of highly ranked science proposals that are ready for drilling. This has sometimes resulted in long transits between scientific expeditions, which can comprise a costly and an inefficient use of ship time.

A goal for the new program is to develop more efficient ship tracks that minimize transits and maximize scientific output in relation to time and cost. This requires consideration of the geographic distribution of highly ranked drilling proposals and several years advance notice to the scientific community about the expected operating regions of the *JOIDES Resolution*. Other potential efficiencies may be achieved through integration of multiple science objectives into operational plans over several expeditions in a given area.

There are significant benefits to this longer-term and regional planning approach. The scientific community will be aware earlier of the expected ship track and potential research opportunities, they will have more lead time for necessary technology development and site characterization, and more opportunities to seek external funding or other resources. Extending the IODP planning horizon will be particularly important for multidisciplinary and technically challenging expeditions, for which careful planning and capacity building is essential so as to achieve the greatest scientific return for funding and time invested.

Currently the *JOIDES Resolution* is expected to complete fiscal year 2013 in the western Pacific Ocean. Scheduling of expeditions for fiscal year 2014 is underway and is expected to include four expeditions in the same geographic region. Expectations are that the ship will remain in the western Pacific and Indian Oceans for about two years. Beyond fiscal year 2015, a strong portfolio of proposals is needed to assess the locations where drilling will be required.

To facilitate the development of efficiencies in conducting operations on the *JOIDES Resolution*, workshop participants drafted a set of principles to guide the program in the construction of ship tracks and expedition objectives. These principles were developed based on the assumptions that the *JOIDES Resolution* will be dedicated to scientific ocean drilling for twelve months a year. It is noted here that introduction of operations external to IODP (e.g., funded by industry) may modify the efficiencies that the guiding principles are projected to achieve.

- The *JOIDES Resolution* should circumnavigate the globe *at least* once during the program. Completion of many of the high-priority scientific objectives requires drilling at focused, widely distributed sites and meridional or zonal transects across vast stretches of different oceans. Hence, at least one circumnavigation is required to meet the scientific goals of the program. There is a strong possibility that two circumnavigations are preferable because this would allow a return to a location later in the program to build on research discoveries. IODP is an international program addressing global problems and a circumnavigation will enable it to maintain a consistent high profile in member countries.

- Within a geographic region, the ship track and the time spent in that area should be driven by the scientific research agenda. Science demands in a geographic area will vary depending on the variety of challenges that are being addressed. In addition, it will be necessary to account for seasons and weather windows in scheduling, particularly in high latitudes.

- Transits should be used to conduct transects (or sites that contribute to transects) as appropriate. A number of the high-priority science objectives identified here require transects of boreholes across ocean basins. Transits provide the opportunity to conduct such transects (or portions of transects) while moving to the next focus site. With careful planning, there may also be opportunities to address multiple objectives with this approach, such as combining climate transects from the tropics to subtropics with studies of the aging process of oceanic crust.

- Short transits provide excellent opportunities to conduct hands-on shipboard programs for students and educators. This would address key *2013-2023 Science Plan* objectives of introducing the next generation of scientists to ocean drilling, and of assisting educators in developing new materials for use in the classroom. It will also facilitate better integration of education into the program.

- Where possible, ship tracks should be based on a “spoke and hub” concept in which the high-priority scientific challenges addressed in the program include a mix of drilling at specific sites (“hubs”) and transects of sites that have certain environmental requirements but are flexible in specific drilling location (“spokes”). In these situations, ship tracks may be developed to move between hubs while completing sites for other purposes along the spokes that join them. Wherever possible, these non-site-specific objectives should be at locations with existing site characterization data to minimize surveying costs.

- For maximum efficiency, integration of multiple objectives will require a range of approaches. These may vary from the inclusion of multiple science objectives in the earliest stages of proposal development to combining multiple proposals late in the process before scheduling. Optimizing operational efficiencies by integrating multiple science objectives into expeditions or series of expeditions is a new paradigm for the scientific ocean drilling community. The advisory structure should be alerted to this new paradigm so that multi-faceted proposals are not perceived as lacking focus.

- Combining objectives late in the process will be particularly important for proposals already within the advisory system. Multiple proposals for a given geographic region could be integrated by an *ad hoc* regional integration working group to maximize operational efficiency and scientific output.

- The community recognizes that many funding decisions are handled on a year-by-year basis, but this does not preclude IODP from indicating an intended program plan two to three years in advance. This will encourage better project planning, more interdisciplinary collaboration, and increased access to external resources.

The expense of site characterization is a critical limitation on future drilling progress. Several activities already described, including co-located objectives and aiming non-site-specific objectives at previously characterized sites, will partially mitigate this limitation. Additional strategies include improved access to existing site characterization data and careful review of the expectations of the site characterization panel to consider the minimum, rather than ideal, level of characterization for successful pursuit of the science objectives.

The workshop participants foresaw a need for additional proposal pressure to help in the development of an efficient ship track. As a result, they recommended that a call for proposals should be issued in July 2012. This call should publicize the plan for at least one circumnavigation of the *JOIDES Resolution* and request pre-proposals for all geographic areas to assess interest in regions. As the new program begins, these pre-proposals can provide guidance for future planning. Proponents can then build full proposals based on input from the advisory structure and the planned ship track.

In addition, the initial proposal call should highlight the western Pacific and Indian Oceans as focus areas for the first two to three years, and request either new or updated full proposals for that region to ensure highly ranked scientific proposals ready for implementation. It is envisaged that proposal calls will indicate the general expected direction of the *JOIDES Resolution* track so that the community can plan their proposal submissions accordingly.

C. Community Building and Planning Workshops

Workshops advance collaborations and planning for expeditions by providing a venue for discussions around a focused scientific objective. As such, workshops can inspire new proposals or improve existing proposals. They also build research networks by exposing early career researchers and scientists involved in other initiatives to the scientific opportunities accessible through ocean drilling. Workshops can also be excellent venues for building operational efficiency early in the proposal development process. Cross-disciplinary foci could bring together potential proponents to assess the practical considerations of co-located sites or combined expeditions.

Many of the top-priority challenges contain objectives and targets that are linked to other challenges, and thus workshops could be a valuable step in accessing the expertise of a larger community while achieving important goals. Workshops can also be used to improve standard operational and sampling protocols and to educate the broader community about the unique capabilities of IODP. The workshop participants identified the following workshop topics based on the top-priority challenges; they also recognize that this is not a complete list of potential topics and encourage innovative workshop proposals that will advance the community's priorities.

- *Drilling of Transects*. Careful planning of drilling transects could potentially advance science across all *2013-2023 Science Plan* themes.

- *Volcano–Climate Connections.* Investigating the effect of volatiles released by volcanism on the global climate requires combining climate and solid-earth research. Strategies for these studies could include drilling sediments that were deposited near large igneous provinces during major eruptions.

- *Serpentinization.* Understanding serpentinization of the mantle integrates solid-earth and fluid research, and regions undergoing serpentinization provide a unique location to study the biosphere.

- *Landslide Hazards*. Further planning is needed to determine where and how to access subseafloor records of paleo-landslides, to sample incipient landslides, and to monitor changes of hazards beneath the seafloor. A workshop would also present an opportunity to engage communities studying landslides on land and in offshore industries.

- *Subduction Zones Studies.* In addition to IODP, GeoPRISMS, EarthScope, and the U.S. Geological Survey are pursing research objectives related to subduction zones, particularly concerning earthquakes and tsunamis. Workshops would provide an opportunity to coordinate these efforts better to examine subduction zones from onshore to offshore.

- *Microbiological Sampling.* A workshop to standardize microbiological sample collection and processing could allow the Biosphere Frontiers challenges to be pursued on expeditions with other primary objectives.

Section V: Acknowledgements

The Consortium for Ocean Leadership organized and supported the workshop under the U.S. Science Support Program, as funded through a cooperative agreement (OCE-0652315) with the National Science Foundation.

The workshop co-chairs would like to thank the steering committee—Donna Blackman (University of California, San Diego), Gabe Filippelli (Indiana University-Purdue University, Indianapolis), Andy Fisher (University of California, Santa Cruz), Susan Humphris (Woods Hole Oceanographic Institution), David C. Smith (University of Rhode Island), and Debbie Thomas (Texas A&M University)—for representing the diverse disciplines, research interests, and experience levels associated with the U.S. IODP community. Gail Christeson (University of Texas at Austin), Mark Leckie (University of Massachusetts-Amherst), Heath Mills (Texas A&M University), and Anja Schleicher (University of Michigan) served as breakout group chairs during the workshop and brought fresh perspectives to the issues and contributed significantly to this report. Brandon Dugan (Rice University), Matthew Jackson (Boston University), John Jaeger (University of Florida), Christopher Junium (Syracuse University), Brandi Reese (University of Southern California), Evan Solomon (University of Washington), and Sam VanLaningham (University of Alaska Fairbanks) served as scribes during the workshop and ensured that the participants' ideas were recorded during the fast-passed discussions. Charna Meth from the U.S. Science Support Program organized the online survey and workshop and provided support and guidance throughout the planning process.

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