NEXT: Scientific Ocean Drilling Beyond 2023

READING MATERIALS

May 6–7, 2019
Denver, Colorado

https://usoceandiscovery.org/next_workshop/

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Introduction to NEXT

This is a year of optimism in IODP as we celebrate 50 years of Scientific Ocean Drilling and the fact that the *JOIDES Resolution* is funded through 2024. However, we have also arrived at a turning point, with the current IODP science plan expiring soon, and the *JOIDES Resolution* in need of replacement. The stakes are high as we aspire to continue scientific ocean drilling beyond 2023.

We are meeting in Denver on May 6-7 with approximately 110 U.S. and 30 non-U.S. IODP community members to develop the U.S. plan for continued scientific ocean drilling beyond 2023. We believe this invited group provides the widest possible scientific breadth and vision. Your participation, energy, and ideas are critical as we work to secure the future of scientific ocean drilling, which requires the IODP community to come forward with an *innovative new science plan* and to provide a strong rationale for a new riserless drill ship to replace the *JOIDES Resolution*. Time is of the essence as both tasks are intensive and complex endeavors.

During the NEXT meeting we are seeking answers to the following questions:

- Looking beyond 2023: how, why and what IODP 2013-2023 science plan challenges need to be modified/expanded, and what new scientific challenges should be addressed in the new 2023-2033 program?
- What should be the framework or structure of the new science plan?
- What is needed in a new U.S. riserless drilling vessel (from coring to shipboard analysis) to answer the new or updated challenges in this new science plan?

The ultimate goals of NEXT are to provide a *proposed strawman structure* from the U.S. community for the 2023-2033 IODP science plan and a *prioritized list* of science challenges to be tested with future scientific ocean drilling. Both outcomes will be presented at the IODP Forum Meeting in Osaka (Japan) in September 2019 and we hope will form the "core" of future international scientific ocean drilling.

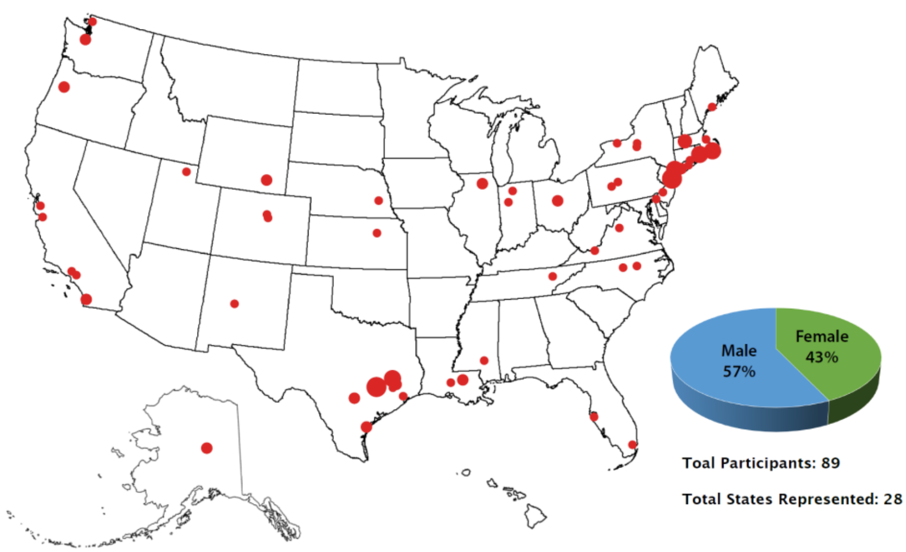
Pigeon Hole Polling Website

During NEXT we will make use of the https://www.pigeonhole.at polling website, using the password NEXT19 (all capitals). Please preload this on your phone and/or bookmark it on your laptop computer, so that you are ready to use it by the time you arrive in Denver. We will have four polls preloaded so you can test out this software; please fill out those polls before you arrive at NEXT as the outcomes will be presented on the first morning. You can use Pigeonhole either anonymously or with your name.

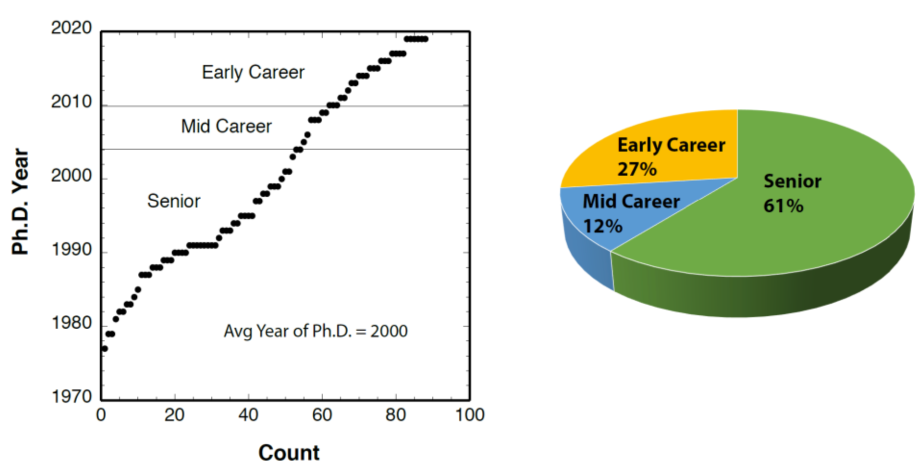
NEXT DEMOGRAPHICS

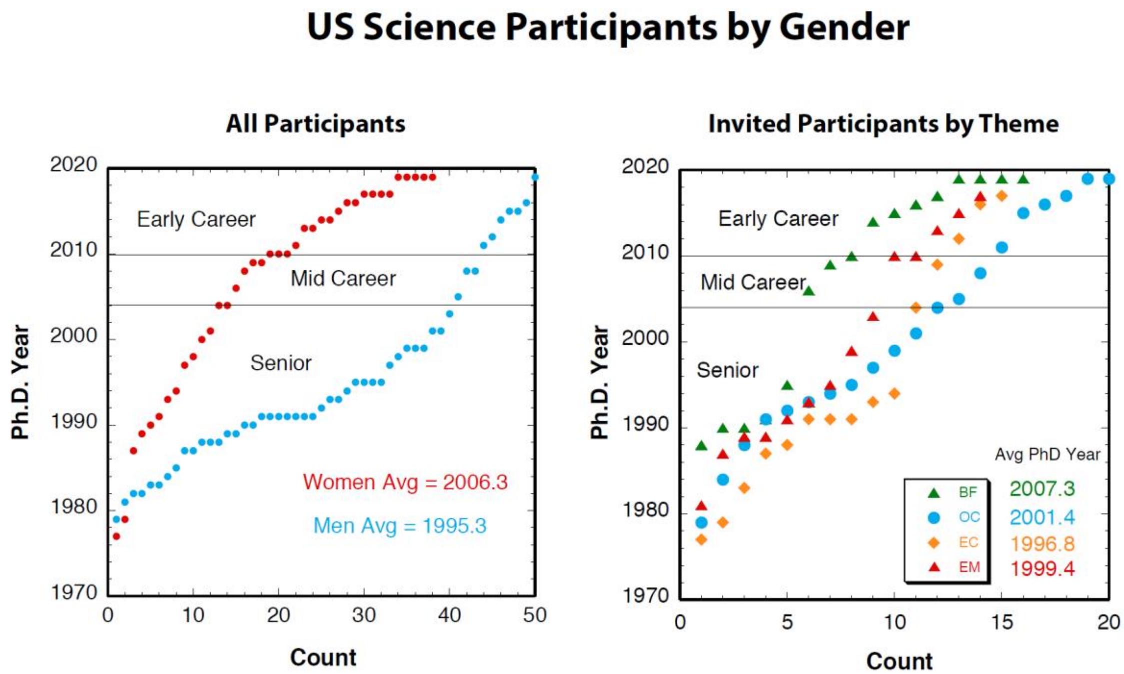
The ~110 U.S. workshop participants are well-distributed and represent 53 institutions in 28 U.S. states, with 43% being female and 39% being early- and mid-career scientists. The demography is not skewed for the *overall* participant pool, yet there is a clear difference in the age distribution between males (average PhD year 1995) and females (average PhD year 2006). Deep Biosphere is the youngest discipline group (average PhD year 2007) while Earth Connections is the oldest (average PhD year 1997).

U.S Science Representation at NEXT Workshop



US Science Participants by Career Level





MINI SURVEY RESULTS

The majority of the 140 participants filled in a mini-survey during their application. In this section, the NEXT steering committee provides summaries of the mini-survey results for each IODP theme group to be read in advance of the meeting. Note that these summaries are prepared by four different subcommittees (one for each theme) and thus some of the observations are repeated when they identified common issues, or when the observations are theme-non-specific or cross-linked.

Each report starts with a one/two-page overview, before reporting on the survey question by question. For reference, the three mini-survey questions were:

(1) Looking beyond 2023, what current IODP science plan challenges need to be modified or expanded? How and why?

(2) What new scientific challenges should be formulated in the next IODP science plan?

(3) What is needed in a new U.S. riserless drilling vessel (from coring to shipboard analysis) to answer these new or updated challenges?

Climate and Ocean Change

Subcommittee members: Beth Christensen, Ken Miller, Sandra Passchier, Kristen St. John

Overview

While the survey asked 3 specific questions, comments from climate and ocean change respondents also raised valuable perspectives on the overall framing of the next science plan, on science needs outside of the climate and ocean change theme, and education and public outreach. These perspectives are included below, along with the summary of comments on climate and ocean change challenges and needs beyond 2023. The subcommittee finds the survey comments useful in guiding workshop conversations and revisions of the long-range plan beyond 2023. We see valuable opportunities for ties to the Decadal Sea Change Report, for making connections to societally critical issues, for making links to the overall Earth systems (including hydrosphere, atmosphere, and magnetosphere), for ties to the terrestrial ecosystem, and for using deep sea data to evaluate and validate climate, ocean, and hydrosphere models. In summary the future science plan must appeal to a broader scientific audience, align to other (national) funding priorities, and appeal to a public audience.

Directly connect the new IODP science plan to the Sea Change Report: The National Academy of Science Sea Change report matched IODP with 5 of their 8 decadal science priorities: (1) Sea Level Change, (2) Ocean and Climate Variability, (3) Ocean Basins, (4) Geohazards, (5) Subseafloor Environments (table 3-2, p 42). Ideas on how to connect to this range from a short discussion of it in the next science plan to reorganizing the next science plan around these 5 priorities to improve the marketing and communication of IODP science (nationally and internationally). These science priority categories use terms that matter to funding agencies, policy makers, and the public. The reorganization may not be very difficult to implement because there is already significant overlap with our current themes. Alternatively, the cover of the existing science plan had themes that were more audience friendly too: climate, deep life, planetary dynamics, geohazards. At a minimum we need to have a non-jargon language in a summary document.

Highlight potential synergies between future scientific ocean drilling and terrestrial drilling/coring programs: Show that some of the big questions we want to address beyond 2023 have complementary questions from a terrestrial perspective – results of each program can inform future drilling proposals. Seek opportunities for paired terrestrial-marine drilling expeditions to address one or more common scientific challenges. Examples are ICDP, particularly in high latitudes, and lake drilling such as Lake El’gygytgyn in Siberia.

Highlight potential synergies between future scientific ocean drilling and extra-planetary processes: The current science plan has no discussion of extraterrestrial processes/analogs. Space science is a rapidly growing field, and there is tremendous potential to use IODP expeditions to test hypotheses about planetary development, habitability of extra-terrestrial bodies, the relationship between the deep biosphere and a number of other planetary processes. Expanding the scope of our current science objectives would facilitate recruitment of the next generation of scientists, and potentially expand the capabilities of future drilling endeavors.

Highlight connections to the NSF 10 Big Ideas: Navigating the New Arctic, Understanding the Rules of Life, Mid-scale Research Infrastructure, Growing Convergent Research, and Harnessing the Data Revolution.

Look for ways to connect the study of longer-term climate records to something more relatable to the public: This will likely require more direct interactions with large data sets and scientists measuring modern oceanography/weather, ecosystems, etc. Illustrate how understanding of past worlds with high CO2 and temperatures will be relevant as temperature increases in this century and beyond.

The future science plan should articulate measurable objectives and a strategic plan for improving IODP education and public (media) outreach: EPO needs more help and more resources and to be planned in a coordinated high impact way. It would be good to learn if and how current EPO programs are meeting their objectives to determine if these should continue as is, be modified, or expanded. We need (at least in the US) stronger expedition-coordinated EPO. Highly qualified EPO specialists (including both media specialists and education specialists) should be involved in expedition planning meetings with co-chiefs, and be better integrated with the science party in order to more effectively communicate the expedition science to target audiences.

The future science plan should add new section that directly addresses diversity and inclusion and connection to workforce development: Include historical looking statistics as well as future looking aspirations regarding the role of women, minorities, and students, in scientific ocean drilling. It will demonstrate success as well as goal for future. Language in the OSTP Ocean Plan (from last year) can help with workforce.

We should consider linking to the parallel need for maintaining the ability to acquire high quality site survey data: This is a symbiotic relationship between IODP and seismic survey capability Discuss the importance of encouraging not only portable seismic systems (e.g., the SO system), but also the deep seismic imaging capability currently afforded by the R/V Langseth.

Question 1: Looking beyond 2023, what current IODP science plan challenges need to be modified or expanded? How and why?

Summary: The current science plan is very comprehensive and challenges have only been partially addressed thus far. Mixed response on how to move forward with articulating challenges, however most favor no major redraft. Progress has been made on the 14 challenges which the community needs to succinctly summarize and highlight. We need to update the challenges to reflect the new science data and advancements in methods and tools, as well as new opportunities. We should also make tighter linkages between the themes/challenges, with future priorities should include questions focused on the relationships/interactions. Example comments to these points are listed below:

- In the time since the last science plan was written, the field of paleoceanography and paleoclimatology has become more quantitative, has developed more sophisticated insight into old and new proxies, and has employed novel interdisciplinary approaches. I would suggest updating existing, and formulate new, climate change challenges that build on recent achievements of all climate change research (not just that related to paleo-studies), re-state and more strongly emphasize the most important goals that we have not yet achieved, and take advantage of the exciting new directions in the field. This can be done with all the avenues of IODP research.
- The collection side is pretty good, but we are lacking is the ability to carry out a *coordinated experiment* to meet those challenges using the material that we do retrieve. We need more post cruise coordination.
- The next generation science plan needs to build off and, potentially, re-cast these questions and add a few critical ones. One way to do this is to think about where the disciplinary themes intersect. For example, the 'Climate and Ocean' and 'Earth Connections' themes intersect and overlap in the context of sea-level change. Solid Earth responses to ice sheet dynamics (e.g., glacial isostatic adjustment) is a critical component in improving predictions of sea-level change. Additionally, tectonic-climatic relationships associated with opening/closing of oceanic gateways is another problem that we really haven't solved.

<u>Summary responses specific to the current climate and ocean change theme</u>

Challenge 1: *How does Earth's climate system respond to elevated levels of atmospheric CO2?*
- Expand this so the focus is more than CO_2. Options: *How do ocean circulation, ocean/atmosphere exchange, and the ocean biosphere respond to a warming climate and increased CO2? How does Earth's climate and ocean ecosystem respond to rapidly changing levels of greenhouse gases? How is the transition to a Hothouse Earth manifested in the changes to physical, chemical, and biological systems?*
- Others think this should shift to exploring: *why/how CO2 is a driver and/or a propagator of global climate change?* Looking at timing and sensitivity. Need high resolution records.
- Continue focusing on records and time periods that will inform decisions about how best to deal with/understand life and climate in a world of 400 to 1000 ppm CO2.
- The role of scientific ocean drilling in addressing terrestrial paleoclimate and paleoecologic research should be made explicit, either as expansions of Challenges 1, 3 and 7 or collected in a new Challenge.
- Address gateways and influence on the climate questions, especially CO2

Challenge 2: How do ice sheets and sea level respond to a warming climate?
- Need better low latitude targets for our understanding of sea level changes, and need to test accuracy of terrestrial sea level records.

- Look at the ocean response more holistically (not just ice sheet and sea level responses). For example: How does the ocean/atmosphere/climate system responds to warmer climate condition? These better addresses future challenges facing society. For example, focus on paleo-analogies to the 1000 ppm climate world we expect in the coming centuries. (e.g., Miocene through late Eocene targets). However, others don't want future drilling to be limited to "just the warm periods".
- Focus on ice-marginal environments; more high latitude drilling. Rectify current logistical constraints that limit operations in high latitude waters/regions: The current approach to high latitude coring often results in low core recovery and significant sampling limitations in ice-proximal regions. A comprehensive, and overt, strategy to target high-latitude sites may be able to dramatically improve the cost-benefit relationship and provide critical new data from these climate sensitive regions.
- Integrating climate/ocean/ice sheet/sediment flux models with drilling to specifically assess the effects of ice sheet retreat on sedimentary systems to improve interpretation of recovered drill core record

Challenge 3: What controls regional patterns of precipitation, such as those associated with monsoons or El Niño?

- Broaden to include other regional to global processes of climate variability on multiple scales. Options: *How do long (e.g., hothouse-icehouse, glacial-interglacial) and short term (e.g., millennial to interannual - ITCZ, ENSO, Monsoon) variations in precipitation affect ecological and biogeochemical processes?*
- Broaden to focus on tropical to extratropical atm connections: *How does the global climate system move latent heat to the extratropics?*
- More emphasis on older records (pre-Neogene), especially for monsoon studies.
- More testing of dynamical frameworks/theoretical models of precipitation systems in a range of climate conditions.

Challenge 4: How resilient is the ocean to chemical perturbations?

- This is an example of a way to better connect challenges between different themes. It should be a co-owned challenge, by biospheres and C&O to ensure proper staffing and planning for expeditions. These are oceanographic problems, circulation, chemistry and biologic problems, organic matter burial/anoxia.
- Perhaps change to: *How do changes in seafloor spreading, volcanism and weathering affect seawater chemistry and implications to Earth climate?*
- Some want less emphasis on ocean acidification and more on broader issues of *why the ocean chemistry changed and how did it affect climate and vice versa (i.e., feedbacks).* However, other want to continue the emphasis on ocean acidification and target high resolution records, including carbonate platforms in the Miocene.

Question 1 continued: Responses that relate to other IODP science plan themes

Microbiology theme

- Challenge 7: keep question as is (*How sensitive are ecosystems and biodiversity to environmental change?*) but support it with need to study causes of extinction in the marine realm (changes in productivity, stratification, pH…); link extinction events to modern biodiversity loss. Also link to recovery from mass extinction events and how knowing this helps understand how the modern biosphere will recovery once negative anthropogenic pressures are removed; important for modern mitigation strategies. And bring in the need to recovery analogs of ocean deoxygenation and carbon burial to connect to modern day (Cretaceous records important).
- Develop a fully integral biosphere theme from proposal to sample collection and shipboard facilities. Our current approach often limits the success of biosphere science with a lack of overall integration with the shipboard science objectives. Incorporating biosphere science has the greatest potential for improving our understanding of process such as fluid-gas interactions (challenges 8 – 14), proxy integration (challenges 1 – 4).
- To achieve a better understanding of the role of microbes in past and modern biogeochemical cycles and direct and indirect connections to global climate change need to:
  - Focus on the relationships/interactions between the microbiological, the bio-geochemical and the physical/paleoceanographic components of subseafloor microbial habitats.
  - Focus on testing assumptions about the global seafloor biomass, sampling from deeper sites. Examining small-scale variability (not just depth profiles) in relations to geochemical/lithologic hotspots.
  - Focus on links to carbon capture and storage.
  - Integrate Biosphere and Climate and Ocean Change challenges better (e.g., Challenge 7 connects well with ocean and climate change too) in order to not just address how resilient the ocean is, but also the marine biosphere, of major importance in view of the serious problems of oceanic biodiversity in the present, expected to become aggravated with climate change in the near future, with potentially dire consequences for e.g. global fisheries.

Earth Connections theme

- Challenge 10 could also be expanded to include authigenic reactions within the sediment, not just the basalt. Both have very important implications for changes to seawater chemistry through time (past, present, and future).

Question 2: What new scientific challenges should be formulated in the next science plan?

Summary: There are suggestions for a few new challenges that emphasize time, rates, models, inter-theme connections, and geomagnetic change. In addition, there are suggestions for drilling strategies to improve spatial coverage and temporal resolution.

- **Add a challenge that emphasizes tipping points and recovery from rapid change:**
  - What conditions have served as "tipping points" for past episodes of rapid environmental change? What were the rates and processes of recovery?
- **Add a challenge to address the episodic and rapid nature of many processes that happen on Earth (and that matter to people) and how the ocean floor records these events.**
  - Maybe this fit with the challenge listed above, but examples are quite distinct.
  - Examples or rapid sediment delivery processes: hurricanes, earthquakes, volcanoes altering the landscape which facilitates erosion.
- **Add a challenge on recovering seafloor records to help the development and testing of climate models.**
  - Emphasize the two-way connections between observational/proxy data collected via the drilling program and the development and testing of climate models.
  - Seek to clarify spatial-temporal relationships important to models (e.g., between ice sheet, sea ice, ocean, and atm changes).
  - Involve more climate modelers involved in IODP from workshop and the proposal process level and as members of expedition teams.
- **Add new challenges that address connections between ocean and biosphere:**
  - How has ocean chemistry and the cycling of marine micronutrients changed over time?
  - How do post-depositional chemical reactions within marine sediment affect the overlying water column, subseafloor life, the paleo-record, and long-term climate?
  - What is the best proxy in our ocean for life on other planets?
- **Add new challenges that focus on causes and consequences of geomagnetic change.**
  - Paleomagnetism is a ubiquitous part of IODP, yet it is rarely considered as part of the science questions that drive it. We still know very little about why geomagnetic change occurs, though we are beginning to recognize patters that could be exploited that might allow for a deeper understanding. It would allow us to improve magnetic stratigraphy and the spatial and temporal resolutions employed, as well as provide opportunities to look at the impacts it has on Earth surface processes including life and climate.
- **Target drilling locations to fill in gaps in time and space to reduce bias and increase coverage.**
  - Added focus on recovering cores in locations (and time periods) that can provide needed observational data to test/improve models on past climate.
  - Very poor coverage in Indian Ocean and west African margin. Need more high sedimentation rate cores from low latitude regions to look at carbon cycling/sinks and climate tectonics relationships at multiple scales (ITCZ, ENSO, Monsoons).
  - Greater drilling in marginal seas and in US waters (e.g., Gulf of Mexico fits both).
  - Better link APC cores with modern deposition, including supporting more ultra-high-resolution sites. This would allow more precise correlation with shallow piston cores and ice cores and help refine sensitivity of climatic systems.
- **Target drilling to reoccupy legacy sites using new technology:**
  - Legacy cores from older expeditions are not suitable for modern paleoceanographic proxy studies both because of the incomplete recovery, the lack of splices, and the aging and rotting of the cores while they were sitting in the repositories.

    - Re-drilling legacy sites will also help the microbio community.
- **More emphasis on limits of life (e.g., under seafloor, under ice, and connections to space), the origin of life, and life on other planets.**
    - Aim to recover undisturbed biological samples to provide insight to the basic question of how early life may have evolved on earth and inform us about the possibility of life elsewhere.
    - A closer integration of climate change and its biogeochemical effects and biological effects - the interaction of earth and life is not well described in the present science plan.
- **More emphasis on the syntheses of records of Earth past.**
- **More emphasis on terrestrial paleoclimate and paleoecology.**
    - While these areas are broadly included in some of the existing IODP Challenges, the addition of an explicit 'terrestrial' Challenge would recognize the importance of drill cores in such studies and the opportunities for future discovery.
- **Other:**
    - More emphasis on climate and tectonic history in the Paleogene.
    - Add questions about how geodesy data is important to understanding coastal hazards.
    - Add/revise questions on how an understanding of methane clathrates what they mean for future energy, geohazards, and global warming

Question 3: What is needed in a new U.S. riserless drilling vessel (from coring to shipboard analysis) to answer these new or updated challenges?

Summary: Ideas primarily fell into categories on expanding drilling capabilities and lab capabilities/instrumentation. The aim is to recover higher quality records from a wider range of settings and substrates, and then analyze these with shipboard analytical tool shipboard that optimize the ability to effectively describe and interpret the records recovered.

<u>Ideas on Expanding Drilling Capabilities</u>

- **Improve the potential for shallower and deeper drilling. To involve:**
    - Improved dynamic positioning system.
    - APC coring at greater depths or to provide some type of replacement technology to use instead of the XCB which usually gives poor quality material.
    - Valuable for linking terrestrial and marine dynamics.
- **Improve the ability to recover more stratigraphically-intact sequences with variable degrees of consolidation/strength.**
    - Examples: gravel-bearing lithologies, interbedded sands and muds, interbedded semi-consolidated carbonates and muds.
    - Important for reconstructions of sea level and regional climate patterns, and of Paleogene-Cretaceous sediment targets.
- **Improve the ability to re-core targeted intervals without having to start a new hole.**

- **Improve the capability to better quality and larger samples from the sediment-water interface.**
  - These are fragile soft-sediment surface samples that would be useful for high resolution characterization of geochemistry (pore-water sampling) and microbiology (and macrobiology).
  - Deploy a box core (or comparable apparatus) to recover a clean sediment-water interface core immediately prior to beginning APC deep deployment.
  - IODP has not played a major role in proxy development from the perspective of linking modern properties with recent sediment sequences because it requires bona fide surface sediments.
  - It would provide the ability to link IODP cores to historical data in high sedimentation rate settings and improve regional climate pattern reconstructions, such as ENSO.
  - Especially important at the "ultra- high resolution" sites.
  - Consider role of a ROV in collecting data from water column/near sed-water interface.
- **Improve the ability to access high-latitude sites:**
  - Expanded ice access capability (even modestly so) will allow recovery of critical records that are often inaccessible to the JR today; valuable for linking terrestrial and marine dynamics.
  - New feedback on operating in high latitude waters from recently completed Exp 379 in the Amundsen Sea, Antarctica:
    - Capabilities JR relevant to operations in high latitudes now:
      - Can transit through 1-year sea ice and new ice
      - high recovery possible in high latitudes sediment drifts; this is undervalued in the community; HLAPC has extended APC coring to greater depth
    - SIEM is beginning to adopt "Polar Code" for JR during operations in polar waters: http://www.imo.org/en/MediaCentre/HotTopics/polar/Pages/default.aspx
    - Important restrictions JR and possible improvements:
      - JR cannot drill in contact with ice because of thrusters- <u>thrusters should be improved to polar code</u>
      - JR cannot move through multi-year sea ice – hull restriction – <u>improve ice strengthening of hull</u>
    - Regarding short periods of drilling when deep in the hole or on the shelf due to icebergs/sea ice.
      - <u>faster RCB</u> would be a huge improvement; also perhaps <u>BHA with APC/XCB/RCB</u> (but not sure it is possible).
      - JR or new ship should carry <u>re-entry systems with limited casing</u> for iceberg mitigation when in polar waters near floating land ice, also for deep-water sites. (More than 700 icebergs were tracked within the 12-mile zone around the ship during Exp 379 and drillers have contingencies on top of SIEM's conservative iceberg mitigation plan, especially deeper in the hole).
- **Increase in-situ sample/data collection capabilities:** downhole geochemistry, sterile in-situ fluid analyses; faster coring/tripping times, precisely oriented cores.
- **Increased core diameter (volume).**

Ideas on Expanding Lab Capabilities and Instrumentation

- **Differing opinions on expanding shipboard lab capabilities vs focus on traditional and fundamental core description and generation of age model.** Recognition that core description and age model generation have traditionally been highest priorities shipboard. Some think this should remain as highest priority. Others think it limits our ability to address current challenges (especially biochem challenges).
- **Include increased analytical suite and sterile bio sampling environment.** This would help address biosphere theme challenges.
- **Add an XRF.** This would be useful for correlation to other physical property measurements and to aid the sedimentologists. However, this may slow-down core flow; would broad sample spacing and low scan time per sample be worth it? Perhaps prioritize it for major lithologic transitions? Then more detailed follow-up could take place after the cores are at their respective repository.
- **Add the ability to get x-radiograph imaging of the split core surfaces.** This would help for high latitude expeditions for characterizing IRD abundances, sediment structures, and perhaps also for bioturbation estimates in any expedition.
- **Consider adding a particle size analyzer.** This would be easy to maintain on the ship and could add quantitative lithological information.
- **Consider adding a CT scanner for core characterization and smarter sampling post-cruise.**
- **Consider swapping out some analyses that are producing data that is underutilize with new instrumentation that will produce data in demand.** Perhaps cut NGR data collection for this reason.
- **Question:** *Is the "floating lab" model is still relevant, with telepresence and other technological capabilities?*
- **Ideas on lab layout:**
  - Efficient floor layout for easy core flow and storage.
  - Design the labs to be more flexible for use; for a rapidly changing research environment.
- **Better continuity between cruises for the calibration and care of the various instruments on board.**
- **Improved software to run the shipboard instruments, analyze data (especially micropaleo), and log the data.**
  - The software should be more user-friendly, but versatile and overall just have fewer bugs. Is it possible to have more transparency and open-source software on the JR?
  - New age modeling software, improved stratigraphic correlation software.
  - Digital data curation and analysis.
  - Continue to explore benefits/cost of integrating micropaleo data into the Paleobiology Database. Aim to integrate all paleontogical ship-based and shore-based data in a database that is actually used by the community, and that will make it easier to integrate micro- and micropaleontology data (see report from December 2018 Earthrates workshop 'Bringing Micropaleontology to the Paleobiology Database').
  - New possibilities: automated species level taxonomic identification by neural networks (or other AI) is making considerable advances. By 2023 this field should have evolved

considerably, and should be made available for use onboard ship (either on the ship itself or remotely, shore-based).

- **Consider adding semi-automated micro sieving apparatus**.
- **Improved routine shipboard curation for biological/molecular/genomic studies.**

Other ship improvement ideas:

- Better fuel efficiency and an eco-friendlier method of disposing garbage
- A helideck that is away from where exhaust fumes are pumped out. It would be an excellent place to exercise and maintain scientist morale/health.
- A quality gym.
- Larger science party.
- More time on sites.

Deep Biosphere

Subcommittee members: Dick Norris, Brandi Reese, Jessica Labonte, Beth Orcutt

Overview

There were a large number of "Biosphere" respondents—they greatly outweigh any other theme, including the Climate theme. Nearly all respondents suggest broadening the "Biosphere" theme to include (1) microbial processes and community structure rather than continuing to hunt for the "deepest", "hottest" or "lowest activity" milestones of the last plan; and (2) more linkages with fluids in the crust, crustal structure (like fluid-flow along faults), hydrocarbons, sediments, diagenesis in sediments and tectonic setting.

A common sentiment is that the current Challenges are fine: But there should be more linkages between themes such as "microbes-diagenesis-sediment-climate", "microbes-fluid flow-tectonics", or "microbes-crustal age-community structure".

Numerous "Deep Biosphere" respondents argued that we should reorganize the "Biosphere" theme around "Planetary Habitability" questions linked to Exobiology: These include links between IODP and NASA to study Exobiology, and "Habitability" issues; some also talk about links to the NSF "Sea Change" themes.

"Ecosystem sensitivity" (Challenge #7) should be in the climate section, not in the "Biosphere" section: This "ecosystem" focus should expand to include microbial communities, whereas the "Biosphere" and "Climate" stovepipe structure could be more integrated.

The ship should have an X-ray, XRF core scanner, CT scanner and Clean Room: An alternative to a very expensive clean room would be a clean van that could come and go as needed. Some people suggest an EDS for the desk top SEM.

We should look to link themes of many drilling legs in order to look at global processes: Such as interocean productivity cycles, microbial communities in different tectonic settings and ice sheets at the poles (among others).

Outreach should be explicitly identified in the science plan: Outreach should be aimed at voting-age people rather than K-8 and should emphasize more video production and media relationships. This idea of focusing on the public (as opposed to classrooms) would emphasize "Community Engagement" for all of IODP rather than for individual Expeditions. The idea is to build an IODP "Brand" with video production on each leg having a common 'look and feel' to build brand awareness. Video and other products (like tweets, mini-blogs and photos should be widely distributed through social media, not just Facebook. EPO specialists should be incorporated in cruise planning and better integrated in the science party.

Question 1: Looking beyond 2023, what current IODP science plan challenges need to be modified or expanded? How and why?

Deep Biosphere Challenges

- There is a common sentiment that the "Biosphere" section should focus on the distribution of the deep biosphere as a function of lithology, microbial activity and diagenesis. There are several possible Challenges that revise parts of the current plan:
  - How do subsurface ecosystems evolve with depth, lithology and oceanographic setting? How do they change over time?
  - How do subseafloor taxa interact with each other and how do their communities evolve in response to changes in the environmental conditions and community interactions?
  - How do microbes meet energy needs in low organic matter sediments?
  - Are there microbial blooms in vent systems?
  - How do uncultured groups of microbes contribute to biogeochemical cycles?
  - How does crustal style and structure affect associated biological communities?
  - What are the fluid pathways between crust and the seafloor?
- A number of these challenges require greater integration of biosphere concerns with other research areas including chemistry of subsurface environment, process-oriented thinking and microbial-hydrothermal linkages. It is also necessary to draw the connection between biosphere and the lithosphere. As in the current plan, we have on-going needs to drill different types of crust, different ages and sediment-basement interfaces.
- For instance, we should use crustal age transects to evaluate role of crustal process in microbial community structure; quantify the extent, rate and influence of fluid flow that influences microbial composition and investigate whether fluid flow is higher than thought on >50 Ma crust. Overarching questions concern the connections between microbial communities and faulting, landslides, and mud volcanoes. The fit of microbial ecology to serpentinization, and core-complex formation are related topics.
- Also consider the evolution of microbial lineages. "What is the deep biosphere doing, what is its ecology, and what is its global significance? "

- Deep Biosphere concerns require more multidisciplinary legs-- Coupling groundwater to geochemical fluxes, nutrient fluxes and subseafloor life. Think about the linkage of the 'spheres'—geosphere, biosphere, hydrosphere, atmosphere and cryosphere. Look at the interactions between these.

Surface Biosphere Challenges

- Deep time offers great examples of how ecosystems recover from mass extinction We can use of mass extinctions as a system to understand mitigation strategies in the face of anthropogenic forcing to Earth's communities and ecosystems;
- Ocean deoxygenation is understudied but drill cores can be used to understand how and why hypoxia develops, particularly rates of change relative to past Oceanic Anoxic Events (OAEs). A related topic is to study OAEs as a model system to understand the biosphere response to changes in ocean productivity.
- Some respondents suggest moving the "Ecosystem sensitivity" challenge to Climate and Ocean Change" and point out that the silo structure of the current plan should end with more integration of research themes including closer integration of climate change with its biogeochemical effects and biological effects. Likewise, Challenge 4 on acidification is 'co-owned' by climate and biosphere Indeed, all the climate challenges have fairly direct biosphere links.

Question 2: What new scientific challenges should be formulated in the next science plan?

Integration of themes and other science programs

- Align the science plan with NSF's "Sea Change" and "NSF's Big Ideas", as well as "Geovision"; Add a "Workforce" section to the plan and change the name of the program. An opposing view suggests that renaming the program would lose the 'branding' and public awareness of the program that has been built over the last two Science Plans (20 years). A compromise would be a new name that preserves the acronym: The "International Ocean Drilling Program" (to keep IODP as the "brand").
- We are too siloed in our subdisciplines. We should broaden the challenges to be more interdisciplinary and broaden the applicant pool for shipboard positions.
- Some people argue we should fold NSF's "Sea Change" into the science plan, specifically the themes: "sea level change, ocean and climate variability, ocean basins, geohazards, and subseafloor environments".
    - Challenge 1 would become: "How does Earth's climate and ocean ecosystem respond to rapidly changing levels of greenhouse gases?"
    - Challenge 3 would become: "How do long and short-term variations in precipitation affect ecological and biogeochemical processes?"

Earth's Biosphere as an analog to the character and discoverability of life on other planets

- Numerous respondents argue for closer thematic integration with the issues of "Planetary Habitability", the search for life on other planets, "Exobiology" and the use of Earth as a test bed for learning how to prospect for life on other worlds.
    - A challenge is: "How do subseafloor communities inform the field of exobiology?"
    - Another way of putting this is: "What is the best proxy in our ocean for life on other planets?
- The Planetary community is increasingly interested in "Ocean Worlds". Ocean drilling can be used explicitly to prepare for future missions to icy ocean worlds. Related topics are study of the role of fluid flow in microbial communities.
- The "Habitability" issue includes analogs for extra-planetary processes and links to the limits of life, origin of life and life on other planets as well as authigenic reactions within the sediment column. We can look at clathrates and permafrost and their response to climate change through in-situ sampling and monitoring of clathrates and associated microbial communities.
- Other themes include the role of different tectonic settings in the structure of subseafloor communities. There are also issues of the spatial response of microbes to habitable conditions; community metabolic health and the roles of rock type, structure, flow rates, porosity as governing features of microbial community structure and biodiversity.
    - A challenge could be "How do transition zones in the subseafloor impact microbial processes such as how carbon is stored and cycled?
- There are also topics of migration of microbial communities, the extent of life in subduction zones and fractures where we have not looked yet, and connectivity of the microbial "biosphere" from continents to the crust.
- We could integrate paleoclimate with other biological indicators (thinking of the deep biosphere); interest in "Earth Energy" related to hydrate drilling. There are also links between climate dynamics and 'dark energy life'.
- Another broad theme is: "Carbon in the carbon cycle"

Biosphere, Geochemical cycling and Diagenesis

- Many respondents note that it would be better to explore process-oriented science in the deep biosphere rather than the "oldest", "deepest", "hottest" approach of the present program. A goal is to understand the deep biosphere around hydrocarbon reservoirs, sapropels, gas chimneys, salt diapirs, and hydrates where the metabolic and geochemical signatures may be most pronounced. We can also look at microbially initiative diagenesis and couple incubations & gene expression with diagenesis geochemistry to distinguish between living and dead systems. We should use diagenesis more to understand microbial community change and link microbiology closer to sedimentology.
- We should focus on mechanisms and extent of chemical exchanges between the crust and seawater-biosphere to understand the limits and impact of the biosphere on crust-seawater interactions. These goals integrate porewater geochemistry with microbiology to

characterize the deep biosphere. Data collection would feed into models to link C-burial to reactive transport in the crust/sediment column;

- There is interest in the flow and storage of carbon on and in the Earth. This carbon cycle theme relies on greater integration of the present four science themes. For instance, we could look at the impact of submarine volcanism on ocean productivity and nutrient cycling/biodiversity both within the subseafloor biosphere and the surface ocean ecosystem. There is also the relevance of the microbial world to cycling of CO2 in the ocean and atmosphere.
- One respondent suggests modifying Challenge 10 to include exchange of fluids and chemicals with sediments as well as crustal rocks and studying the role of deep biosphere in modulating global biogeochemical fluxes. This Respondent likes Challenge 7 that asks a question about sensitivity of communities to environmental change. Another topic is the role of microbial methane production in seafloor stability.
- One respondent suggests that the climate themes are 'mature' whereas the biosphere themes are still "cutting edge." This respondent argues that climate themes can regain novel discovery by completing a 'temporal and geographic' picture'. Biosphere themes need to move from survey mode to link ecological communities to geologic processes such as "Earth in Motion" themes based on role of fluid pathways and fluid chemistry;
- Possible theme: "Fluid Flux and Biosphere Evolution" or "What is the composition of subseafloor communities relative to their origin and what are the similarities in communities between analogous environments?" This challenge addresses how carbon is stored in the deep biosphere. A related topic is to look at similar tectonic environments to contrast the structure, biodiversity and function of subseafloor communities.
- Challenge 7 on sensitivity of ecosystems could be expanded into a new challenge:
  - How do microbial communities evolve as sediments (like sapropels, for instance) are buried?
  - How do post-depositional chemical processes affect the overlying water column, subseafloor life and the paleorecord of long-term climate?

<u>Links between environmental change and plankton, invertebrates, plants & large animals</u>

- Consider more integrated drilling campaigns to examine process-oriented linkages between ocean basins; these are needed to understand interbasinal exchanges of nutrients and CO2 and exchanges between high and low latitudes; A particular need is for more focus on paleoproduction. Some related challenges include:
  - "Does the Earth have a Productivity Heartbeat?"
  - A "Planetary Sensitivity" theme where we look at: "How sensitive are Earth's ecosystems, climate and biogeochemistry to change on different timescales—where are the tipping points?"
  - How do ecosystems on land, in the ocean, and in the subsurface biosphere shift in response to forcing?
  - Challenge addressing the episodic and rapid nature of many processes that happen on Earth. For example: "What are the links between fire and erosion history?"

  - A related theme is understanding terrestrial ecosystem-responses to warm climates. Drilling should also explicitly address terrestrial paleoclimate and paleoecological research. These topic areas can use leaf waxes and plant microfossils, PAHs, charcoal, terrestrial sediment proxies in marine cores, or can be part of IODP-ICDP collaborative drilling efforts.
- A continuing theme is the ecosystem response to warmer-than-modern climates; Focus on warm climate periods with Miocene to late Eocene where pCO_2 is like the near future (400-1000 ppm). Interest in the Middle Miocene Climate Optimum; Interest in coral reefs under higher pCO_2 than today; did reefs die in the Miocene? These topical areas could forge linkages to NSF's 10 big ideas such as the "Rules of Life".
- We consider a theme of "Ocean Health" that contrasts present day ocean conditions and those projected for the future with past 'natural variation' as seen in the sediment record.

Biosphere and Earth's Resources and CO_2 storage

- A new element is the suggestion to use the drilling program to address solutions for climate change or sustainable use of ocean resources. These include active experiments:
  - What are the challenges that must be overcome to store CO_2 in the ocean crust or sedimentary cover? Put another way, this idea becomes: "What amounts of carbon can be captured and sequestered in ocean crust?" A theme on resources could include the issue of Carbon-storage in the ocean.
  - What is the sensitivity and directionality of change in ecosystems and locations of tipping points in the climate system? The tipping point issue includes the rates and processes of ocean response and recovery to perturbation.
- The potential to store CO_2 in subsurface rocks raises the question of how the deep biosphere might help advance CO_2 sequestration. Microbial communities are also involved in generating gas hydrates, novel mineral deposits, and useful compounds.
- Another new challenge addresses the "Human impact on the ocean" that considers the distribution and character of potential seafloor resources such as REE in red clay, mineral deposits and clathrates. This challenge fits with a suggested theme of "Ocean-Human Interactions" about how we interact with the ocean floor.

Question 3: What is needed in a new U.S. riserless drilling vessel (from coring to shipboard analysis) to answer these new or updated challenges?

Drilling Strategy

Where and how to conduct Expeditions
- There are calls to rethink our strategy for putting together multi-leg programs. These include programmatic interest in targeting specific geographic regions and time periods to study warm periods, the high latitudes (mentioned by many) and presently lightly-sampled such as the Indian Ocean. A related suggestion is to redrill legacy sites like Maud Rise.
- There remain calls for organizing multi-leg programs to drill deep into the crust.

- There is interest in linking IODP and ICDP more closely to look at integration of terrestrial and ocean studies. Several respondents also asked for more integration of deep biosphere work into "normal" drilling legs.

Debate over Fully Staffed Expeditions

- Another theme was questioning or defending the value of ship-based coring programs. The argument is that "Scientific drilling is overcapitalized on a global basis" in as much as we pay too much for the JR when MSPs are fairly rare relative to JR operations; also, unclear what China's goals are relative to the JR operations. We also need to ask if the floating lab model is still relevant; might some legs be better done with telepresence to replace some of the shipboard staff?
- Others strongly advocate continuation of the fully-staffed Expedition model. The shipboard experience is what holds the program together and provides the social/scientific interaction needed to maintain a vibrant community.
- There are some complaints about how co-chiefs are selected as well as science party; but argues that a shipboard science party is essential.

Drilling capability

Drilling Technology

- For microbiological sampling, contamination control should be fully integrated into the workflow and sampling scheme. Efforts should also be made to conduct downhole geochemistry and sterile coring, sterile fluid sampling in-situ, and sample collection for deep biosphere work. There are also calls for pressure coring to recover microbial communities at subseafloor pressures and temps.
- Contamination control could benefit from riserless mud recovery.
- Ice capable ship as MSPs are too limited in number and capability;
- An AUV for site selection and an ROV to characterize the macrofaunal biota on the seafloor. Others argue that an ROV could be a poor use of an expensive ship; do this with a different vessel unless there is a direct connection to the drilling program.
- There are renewed calls for coring technology capable of recovery of chert/chalk, better recovery of what are now XCB intervals and high temperature coring; There are related calls to improve hard-rock core recovery as well as diamond coring.

Ship laboratories

Microbiological Research

- Many microbiological respondents argue that redesign of the ship labs should include a "clean room" for sample processing as well as a clean space for incubations and shipboard microbiological experiments. Gene expression work requires rapid processing on the ship as RNA is short-lived. It would be useful to conduct cell counts on the ship.
- There should be a short distance between clean lab spaces for microbio samples.

- An alternative to a clean room is a van for genomics; A specialized van is a good compromise to avoid making specialized labs in the science stack that are used infrequently.
- Microbiological labs should include anaerobic storage and facilities for contamination tracing. The ship should have the ability to conduct standardized tracer analysis to detect contamination.
- There should also be the ability to freeze microbiological samples as quickly as possible.

Core Analysis

- Many respondents argue for a shipboard XRF.
- Other instruments suggested include a MicroCT scanner, particle size analyzer and CT scanner (although others argue the latter would be too big). A CT scanner would be useful for both hard rock and sedimentary cores including (for example) identification of drop stones before a core is cut.
- Automated sieving system for paleolab.
- Hard rock respondents suggest an EDS system on the SEM (EDS could also be quite useful for sediments too).
- Compact XRF system for discrete samples.
- Would be nice to be able to measure bulk carbonate d18O and d13C as well as XRF.
- Update data capture to include changes in age models after a cruise; addition of biostrat data or time/depth/space; Suggests new storage approaches—working-frozen (for instance)

Micropaleontological Labs

- Better micropaleo data input on the ship for real-time data entry into LIMS.
- A hood in the micropaleo lab for pollen work.

IODP Database

- There is interest in developing a more wholistic database to capture Expedition data before cruises (like seismics), during a cruise (shipboard data) and after a cruise (post-cruise refinements to data sets) that would allow better integration of multiple expeditions.
- An IODP integrated database would permit more data synthesis projects and could link to external databases such as PANGEA, MACROSTRAT, MAGIC, The PALEONTOLOGICAL DB, or GENBANK and others.

Education and Public Engagement (EPE)

Focus on "Community Engagement"

- Outreach should be aimed at voting-age people rather than K-8; Expresses worry about accuracy of educational products;
- Communicating our science to the public should be a key priority
- Reach out to the public through diverse social media.
    - Twitter, Snap Chat, Tumblr, Instagram, Sina Weibo, WhatsAp, Qzone…
- Establish a distinct IODP "Channel" with branded video and blogs for the program, not just for individual Expeditions. The current approach in which EPE activities are individualistic to

cruises, and have no programmatic themes, prevents IODP and NSF from developing a clear public image.
- Videos would go through a video editor to make uniform logo, 'style' and typeface.
- Ship would have a video 'booth' with a teleprompter, camera and audio recording equipment.
- Aim for 1-minute videos and short blogs connected to visual media.

Educational Challenges
- Outreach should be identified in the Science plan with some "Educational challenges" such as increasing public awareness of science drilling and training students.
- EPE specialists should be incorporated in cruise planning and better integrated in the science party.
- EPE should include more video production and media relationships; These include improving capabilities (particularly bandwidth) ship-shore video.

Earth Connections

Subcommittee members: Cara Burberry, Gail Christeson, David Mallinson

Overview

Survey responses from the Earth Connections community appear to show that there is considerably more that can be done within, and to expand, this Theme while looking beyond 2023. Challenge 8, for example (concerning the upper mantle) is largely unanswered unless deeper drilling can be achieved into multiple environments, and Challenge 11 (subduction initiation) is seen by some as limiting the potential to ask questions and to drill into additional tectonic environments (e.g. LIPs, rifts, submerged arcs, transform faults). New Themes (e.g. Ocean-Human Interactions) and big-picture questions were proposed (e.g. how does the convection regime work?) together with a series of questions that link strongly to the existing Biosphere Frontiers Theme. With regards to a new riserless vessel, the community opinion could be divided into ideas that were more general recommendations, ideas that related to improved drilling, coring and logging capabilities, and ideas that related to improved laboratory support.

Question 1: Looking beyond 2023, what current IODP science plan challenges need to be modified or expanded? How and why?

Summary: The community felt that three of the four Challenges under the Earth Connections Theme needed to be more comprehensively or systematically addressed, focusing on drilling deeper or in different oceanic environments, drilling systematically along multiple transects along tectonic flow lines, and in areas other than Izu-Bonin-Mariana to plumb the depths of the science considered under each challenge. A general comment that was made suggested that challenges needed to be better framed, to be more intuitive and more general, and in order to more clearly emphasize societal relevance. An example is that Challenge 11 is considered to narrow and should include subduction ending as well as initiation, the far-field forces causes these behaviors, and the entire life cycle of a tectonic plate in-between.

General comments

- Theme titles should be more intuitive as Earth Connections is more than just linkages.
- Challenges need to be better framed in ways that emphasize societal relevance.

Summary responses specific to the current climate and ocean change theme

Challenge 8: What are the composition, structure, and dynamics of Earth's upper mantle?
- This challenge is largely unanswered unless we drill deeper than 1km into oceanic crust in multiple environments including oceanic plateaus, and more oceanic core complexes.
- Drilling into Earth's mantle should also include the forearc region that captures mantle preserved from subduction initiation (links to Challenge 11).
- The question of "what is the nature of the crust/mantle boundary/Moho" has not yet been answered and this falls under this Challenge.

Challenge 9: How are seafloor spreading and mantle melting linked to ocean crustal architecture?
- No comments were noted on Challenge 9.

Challenge 10: What are the mechanisms, magnitude, and history of chemical exchanges between the oceanic crust and seawater?
- This Challenge needs to be more systematically approached via multiple transects along tectonic flow lines in all ocean basins, more of a Mission style approach to proposal writing.
- This Challenge would benefit by being expanded to include all of the oceanic lithosphere, that is to include the mantle and not just the crust.

Challenge 11: How do subduction zones initiate, cycle volatiles, and generate continental crust?
- This Challenge is considered to be too narrow – could be expanded to include an investigation of how variations in subducting slab parameters affect arc-crustal architecture and growth processes.
- The end of subduction, as well as the initiation, and far-field forcing is also important.
- Other regions besides IBM need to be found to sample subduction initiation processes.

Question 2: What new scientific challenges should be formulated in the next science plan?

Summary: The community had a wide range of ideas for potential new challenges, focusing on LIPs and its impact of the environment and mass extinctions, rifting and ocean basin formation, the maturation of ocean crust, additional tectonic settings as well as the subduction zone focus of existing Challenge 11, and on a coherent plan to drill the lower oceanic crust. A better link with deep Earth geodynamics is proposed in order to study large low shear velocity provinces (LLSVPs) and the roles of plate tectonics and mantle plumes in triggering the formation of new subduction zones and new ocean basins. The evolution of mantle and oceanic volcanism is still poorly understood. A series of new themes were proposed, including challenges with a significant link to the existing Biosphere Frontiers Theme, such as how does ocean crust alteration help sustain a life presence and how does volcanism contribute to biodiversity, as well as some significant big-picture questions that do not fit into the existing Challenge structure.

- **One potential new Challenge concerns a series of questions formulated around LIPs.**
  - Questions include - What are the environmental effects during the formation of LIPs? Are hotspots fixed or do they move? Are all LIPs associated with hotspots and how do they develop? What is the connection between LIPs in continental settings and potential plume tails in ocean settings? What is the linkage between LIPs and LLSVPs (large low shear velocity provinces)? What are the roles of plate tectonics and mantle plumes in triggering the formation of new subduction zones and new ocean basins? How does mantle and oceanic volcanism evolve?
  - Questions related to this Challenge that have linkages to other Themes include – what is the feedback mechanism between volcanism and climate? Can we better collect and analyze gas emissions related to active sea floor venting or volcanoes?
- **One potential new Challenge concerns rifting.**
  - The primary question here, phrased in several ways, was "how do rifts at various scales form and develop?"
- **One potential new Challenge has a significant link to the Biosphere Frontiers Theme as follows:**
  - Questions in this Challenge include – How will alteration of oceanic crust help to sustain a life presence? What is the impact of submarine volcanism on climate, ocean productivity, trace element nutrient cycling and biodiversity? How do different types of crust at and below the seafloor affect the associated biologic communities and what are the fluid pathways between the crust and the seafloor? What can we learn about the interactions between biosphere and lithosphere at seafloor hydrothermal systems or at mid-ocean ridge settings? What is the relationship between continents and life?
- **Participants felt that there needed to be a coherent plan to drill the lower ocean crust and to determine its architectural variability.**
  - Under this plan, questions such as "how does ocean crust mature?" could be targeted and answered.
- **Participants asked for drilling to focus on a variety of other tectonic settings as well as the subduction zones listed in Challenge 11. For example:**
  - Drilling to answer questions about a complete understanding of the lower crust and upper mantle processes at mid-ocean ridges and back-arcs
  - Drilling into submerged arc systems
  - Investigating the structure and nature of oceanic transform fault zones
  - Answering questions about serpentinization and the formation of Core Complexes

  - Drilling a magnetic reversal boundary, investigating linkages between core-mantle boundary dynamics and the geomagnetic field
- **New themes or cross-cutting linkages were suggested:**
  - Ocean-Human Interactions
  - Planetary Science
    - E.g. How does the record of asteroid impacts in oceanic domains modify and complement the counterpart continental record?
  - More direct encouragement of linkages between on-land studies and ocean drilling
  - Arctic drilling
  - Natural resources
    - The geologic framework that controls the natural resources on and beneath the sea floor, including the seafloor as a potential storage environment for CO2
    - Contribute to science in areas of intense hydrocarbon exploration
- **Several big-picture questions were posed:**
  - Has Earth experienced true polar wander?
  - How does the convection regime work?

Question 3: What is needed in a new U.S. riserless drilling vessel (from coring to shipboard analysis) to answer these new or updated challenges?

Summary: Survey responses to Question 3, as they related to Earth Connections, revolved around three critical needs categories. These include needs related specifically to vessel design (general recommendations, not necessarily directly related to EC), drilling/coring/logging capabilities, and laboratory support. The clear goal of these recommendations is to have the ability to collect cores faster, in expanded water depths (shallower and deeper), with better recovery, and with expanded bore-hole and laboratory analytical capabilities.

Ideas on Vessel Design

- A faster vessel would reduce transit time and allow for greater time on-station, and more coring.
- A more fuel-efficient vessel is proposed to minimize costs, and to reduce the overall carbon footprint.
- More laboratory floor space to accommodate instrumentation.
- A more stable vessel with better heave compensation.
- More bunks and better accommodations for crew.
- Better internet connectivity and speed.
- Ability to work in polar regions (enhanced hull strength).
- Improved dynamic positioning and thrusters to enable easier drilling under higher current conditions.

Ideas on Expanding Drilling/Coring Capabilities

- Faster drilling to depth and targeting specific intervals, faster pipe tripping and LWD
- Improve the potential for shallower- and deeper-water drilling.
  - Requires improved dynamic positioning (for shallow water), and greater ability to carry drill pipe (for deeper-water and deeper subsurface drilling).
- Improve the recovery of hard rock under all conditions, but especially in fractured, high temperature (>200°C), low pH conditions.
  - Improved heave compensation and control of pressure on bit.
  - Diamond bit drilling system.
- Ability to spud into hard rock with minimal sediment cover.
- Design a method for orienting hard rock cores for structural and paleomagnetic work.
- Enhanced bore-hole logging capabilities with LWD and new technologies.
- Improved measures to avoid contamination for microbiology purposes.
- The potential to manage borehole conditions using sea-bed templates (like that tried on MSP Expedition 381).

Ideas on Expanding Lab Capabilities and Instrumentation

- Greater laboratory floor space to accommodate additional instrumentation (also described under vessel design).
- Improved high end analytical equipment and support (XRF and CT scanning; ICP-MS; XRF; SEM/EDS).
- Ability to analyze borehole logs for information such as stress orientations.
- A second shipboard 2G magnetometer fitted with a RAPID automated sample handling system to allow automated paleomagnetic analyses of discrete samples

Earth in Motions

Subcommittee members: Patrick Fulton, Sean Gulick, Ross Parnell-Turner

Overview

There was a common view among respondents that new science plan should focus on all forms of **geohazards** expanded to a broader scope to include earthquakes, tsunami, volcanoes, and slope failure.

- There should be increased emphasis on societal impacts of the research in this theme, which have clear public interest.
- Efforts to understand earthquake hazards should be expanded to include the full spectrum of slip behavior that we now know are important in the seismic cycle, including slow slip and creep, for example.

- The science plan should be expanded look at spatial and temporal differences within and along fault systems, including along strike differences, such as sedimentary or igneous inputs to subduction zones.
- The new plan should highlight a focus on understanding factors controlling tsunami.

A large number of respondents suggested that a concept of **"Monitoring Earth"** should be added to the science plan, with the objective of understanding dynamics and temporal change with respect to hazards.

- This approach will require sustained monitoring of hazard systems, through repeat surveys and long-term instrument installations in a variety of settings.
- There is a need to understand how fault zones evolve over time, which includes phenomena such as healing and sealing of faults during the seismic cycle.
- Numerous respondents highlighted the need to measure mass and fluid fluxes, including the fluid budget of subduction zones, and the carbon cycle for example.

Respondents commonly suggested increased **cross-theme integration**.

- There is a need to emphasize the linkage between geohazard, climate and biosphere themes, since many respondents consider that climate change is itself a geohazard.
- The new science plan should take the opportunity to integrate between active tectonic margins, mountain building and removal, dynamic topography and the marine record of time-dependent (four-dimensional) tectonic and climatic processes.
- Sub-seafloor hydrology and relationships to chemical fluxes, biology, geomechanics.
- Encourage big data analysis techniques to efficiently mine 50 years of ocean drilling data
- Synthesize knowledge of ridge flank hydrology and observatories built up over many years – e.g. integration with cabled arrays.

Critical **technological needs** for a new vessel in Earth in Motion theme are:

- Onboard access to x-ray CT, XRF, and better/deeper coring.
- Standard drill pipe diameter to leverage technology from industry and increase flexibility.

Question 1: Looking beyond 2023, what current IODP science plan challenges need to be modified or expanded? How and why?

There was a common view that Earth in Motion should be expanded to include a wider range of geohazards, and more specifically, to investigate what *mechanisms* control the occurrence of those geohazards. For example, the fundamental process of fault zone mechanics has not been fully addressed, and would require more emphasis upon materials that are fed into subduction zone systems. A more comprehensive geohazards theme would include earthquakes, tsunami, slope failure and landslides, and gas hydrate stability.

Another common theme from respondents was that a new Earth in Motion theme would require an improved understanding of the dynamics and temporal change within fault systems, including continuous monitoring. This could include repeat surveys, long-term instrument deployments, or real-time monitoring networks.

Respondents highlighted the need to build upon what has been achieved during the existing science plan, by examining the full spectrum of fault locking and slip behavior. This will require samples from a diverse range of fault zone lithologies and conditions, and an effort to move beyond clastic, quartzofeldspathic sediments, for example. A better understanding of the spectrum of slip behaviors will shed light on the properties, conditions, and processes occurring along the plate boundary interface, and will also elucidate the mechanisms behind the occurrence of large magnitude seismic events.

Increased emphasis on societal relevance of the program, through hazards, climate, and discovery-oriented research. This has been done to an extent through elements of the existing four themes, but should be developed further. The societal relevance should also include a focus on the outcomes of the program in human resource development- i.e. driving innovation in instrumentation and integration of engineering/technology and science, training a next generation of scientists and engineers.

Question 2: What new scientific challenges should be formulated in the next science plan?

Integration with other IODP themes, and with external programs

- A new challenge could straddle the existing Biosphere Frontiers and Earth in Motion themes, building upon emerging evidence that biologic assemblages vary with the age/composition of fluid seeps. This would also link with efforts to understand the possibilities for extra-terrestrial life, leading to synergies with NASA programs
- Some respondents suggested that new projects should take a fully integrated approach, rather than addressing each theme independently. For example, dynamic systems like the coupling of groundwater fluxes, nutrient fluxes, sub-seafloor life or groundwater-seawater interaction.

New themes or challenges

- Many respondents felt that a revised Earth in Motion theme should address all forms of geohazard, and new challenges should specifically address phenomena such as tsunami
- Several respondents suggested including challenges that address spatial and temporal change in fault systems, through the use of real-time monitoring networks, repeat surveys and measurement of evolving aqueous geochemistry, for example
- A recurring view was that a new challenge that addresses carbon cycling, burial and destabilization of methane hydrates, and seafloor resources should be added
- Respondents also suggested a new challenge or theme related to technological development, with emphasis on integration or co-ordination with other observational

platforms such as cabled arrays, submersibles such as autonomous underwater vehicles (AUVs), or surface vehicles such as wave gliders.

Question 3: What is needed in a new U.S. riserless drilling vessel (from coring to shipboard analysis) to answer these new or updated challenges?

Drilling Strategy

- Stable support for year-round operations, and more support for post-expedition activities to make better use of data acquired immediately after each leg.
- Capability to support other platforms on the new vessel, such as AUVS, to properly characterize the drill site and get better value through simultaneous operations

Drilling Capability

- Strong consensus to retain current JR capabilities, in terms of APC, XCB and RCB tools.
- Respondents mentioned the need for improved downhole pressure and temperature measurements
- Respondents highlighted the potential benefits of using larger diameter pipe to allow deployment of industry logging and downhole tools for some objectives (e.g., modular dynamic testers, logging while drilling tools), which are of particular relevance to the Geohazards theme.

Shipboard Laboratories

- Many respondents made a strong case for modern X-ray CT and XRF capabilities, which are critical to many science challenges. Respondents highlighted the comparison to facilities on board Chikyu.
- In the context of a broadened Geohazards theme, vertical seismic profiles (VSPs) were suggested as an important, but often overlooked method, to characterize fault zone structure and properties, at minimal incremental cost
- Several respondents suggested the need for improved access to stratigraphic, logging and seismic software licenses
- Infrared scanning capability was suggested to allow rapid detection of methane hydrates

IODP Science Plan 2013-2023

For reference, we list here the four current science plan themes and fourteen challenges:

Climate and Ocean Change
Reading the Past, Informing the Future

1. How does Earth's climate system respond to elevated levels of atmospheric CO2?
2. How do ice sheets and sea level respond to a warming climate?
3. What controls regional patterns of precipitation, such as those associated with monsoons or El Niño?
4. How resilient is the ocean to chemical perturbations?

Deep Biosphere
Deep Life, Biodiversity, and Environmental Forcing of Ecosystems

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

Earth Connections
Deep Processes and Their Impact on Earth's Surface Environment

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

Earth in Motion
Processes and Hazards on Human Time Scales

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

EXAMPLE STRAWMAN SCIENCE PLAN STRUCTURES

The ultimate goals of NEXT are to provide a *proposed strawman structure* for the 2023-2033 IODP science plan and a *prioritized list* of science challenges and hypotheses to be tested with future scientific ocean drilling. Based on the mini-survey results the NEXT Steering Committee has put together *three ideas* that could serve as strawman structures for a future science plan, to help us “kick start” the discussion during the meeting.

It is our ask to you to provide *new ideas* during NEXT that could help us establish an innovative new science plan for scientific ocean drilling beyond 2023!

Mission Earth (Example 1)

1. **Planetary Habitability**
2. **Ecosystem Sensitivity to Environmental Change**
3. **Earth Resources**
4. **Deep Earth Dynamics**
5. **Hazards and Society**

Planetary Habitability directly links IODP to NASA/NSF in life on other planets, particularly ocean worlds; The subthemes include how microbial life is distributed in the “Deep Biosphere” and how these communities are organized. Drilling provides pointers toward both looking for life on other planets/moons, and understanding the diversity of habitats, activity levels, evolution of communities and connections to other parts of the biosphere. The habitability issue also includes fluid and geochemical dynamics in the crust connected to the ocean since these are intimately connected to how life operates in the Deep Biosphere.

Ecosystem Sensitivity is response of biological ecosystems (not just microbial ones, but also oceanic & terrestrial ecosystems) to environmental change and what governs the rate and magnitude of biological response. This theme includes the issue of where tipping points exist in ecosystems, how rapidly biological systems can change, and how drastically they change in terms of species diversity, function and recovery from perturbations. Many parts of the climate system also fit into this theme of rates and tipping points, particularly precipitation, the drivers of glaciation or deglaciation, orbital drivers of environmental change, acidification, aridification (on land), gateways, marine & terrestrial productivity and carbon cycling.

Earth Resources includes traditional resources like REE, mineral deposits, and hydrocarbons, as well as environmental resources such as the ecosystem's ability to store carbon and sequester industrial CO2. Here, we want to understand the distribution and character of seafloor mineral resources as well as the dynamics of systems that could be used to store greenhouse gases.

Deep Earth Dynamics covers the themes of how the Earth's interior works—geochemical cycling through the crust and subduction zones, tectonics, the geomagnetic system, Moho, and crust formation through LIPs, seafloor spreading and rifting. Many of these themes are directly connected to other themes by being sources of mineral resources, sources of energy to microbial systems and to fluid circulation, and sources of hazards such as earthquakes, and volcanism.

Hazards and Society encompasses the traditional "Hazard" themes of earthquake genesis and history, tsunami genesis and history, volcanism associated with major environmental change (like the PETM, Deccan Traps), local and climatological effects of volcanism, submarine slides, ice-sheet collapse and sea level rise, and extraterrestrial events. The overarching themes are about discovering historical archives that show how Earth dynamics could directly affect human society including the rates of change, the magnitude of events, and the extent of damage to ecosystems we depend upon.

Mission Earth (Example 2)

1. **Environmental Change**

2. **Planetary Habitability & Deep Biosphere**

3. **Deep Earth Processes**

4. **Planetary Hazards**

5. **Resources & Society**

Environmental Change addresses past environmental changes and biological ecosystems response, including the rate and magnitude. It evaluates causes and potential "tipping" points of environmental changes, including temperature, precipitation, glaciation/deglaciation, orbital drivers o, acidification, aridification, tectonic gateway impacts, marine and terrestrial productivity and carbon cycling.

Planetary Habitability & Deep Biosphere directly links interests in the origin and limits of life on Earth and other planets with microbial studies of the Earth's "Deep Biosphere", including diversity of habitats, activity levels, evolution of communities and connections to other parts of the biosphere. The habitability issue also includes fluid and geochemical dynamics in the crust as constraint on the operation of the Deep Biosphere.

Deep Earth Processes addresses how the Earth's interior works: geochemical cycling through the crust and subduction zones, tectonics, the geomagnetic system, Moho, and crust formation through Large Igneous Provinces, seafloor spreading and rifting. This theme is closely connected to other themes since these processes control sources of mineral resources, sources of energy to microbial systems and to fluid circulation, and sources of hazards such as earthquakes, and volcanism.

Planetary Hazards encompasses earthquake genesis and history, tsunami genesis and history, volcanism associated with major environmental change, local and climatological effects of volcanism, submarine slides, ice-sheet collapse and sea level rise, and extraterrestrial events. The overarching themes are about discovering geological archives that show how Earth dynamics could directly affect human society including the rates of change, the magnitude of events, and the extent of damage to ecosystems we depend upon.

Resources and Society includes traditional resources like mineral deposits and hydrocarbons, as well as environmental resources such as the ecosystem's ability to store carbon and sequester industrial CO2. Here, we want to understand the distribution and character of seafloor mineral resources as well as the dynamics of systems that could be used to store greenhouse gases.

Pathways (Example 3)

Pathways provide the cross-links between the interdisciplinary themes. They would fit on top of any theme-based structure, whether it is the structure of the current science plan or any new structure, such as for example the proposed Mission Earth concepts (see above). Pathways are here defined as “tie-lines” between themes and the processes that shape the overall Earth and its environment.

Example pathways are “time slices”, “time transects” and “time scales” that allow us to study the interconnected Earth processes in a particular time period of interest, across a long stretch of geological time, or as a function of timescale, in order to see the evolution of Earth and its effects on today’s Earth as we experience it as humans. Other example pathways are “cycles” and “fluxes” to study both the large- and small-scale Earth processes as functions of the carbon or hydrological or magmatic cycles and the fluxes between different Earth reservoirs. Other pathways could be “regional” or “transects” to study the interconnected Earth processes as a function of tectonic setting or its position relative to the Earth’s poles and equator.

Pathways will come with their own set of challenges to be tested. With this concept in mind, in the future 2023-2033 scientific ocean drilling program it could be envisioned that proponent teams write “theme” and “pathway” proposals, whereby the first are the more traditional disciplinary proposals and the latter the new cross-cutting and interdisciplinary ones. Pathways would “force” new cross-linked and cutting-edge proposals that break away from the traditional scientific ocean drilling projects of the last 50 years.

Sea Change-Inspired Structure (Example 4)

The *Sea Change: 2015-2025 Decadal Survey of Ocean Sciences* report by the National Research Council of the U.S. National Academy of Sciences was released in 2015 to provide the Ocean Sciences Division at the National Science Foundation (NSF) with an assessment of its current infrastructure, including IODP, relative to eight science priorities. This report identified that IODP is *critical* or *important* for making progress in five out of the eight science priorities, and in this strawman science plan structure for future scientific ocean drilling, the five themes are chosen to align directly with those five *Sea Change* science priorities. This approach may ensure greater exposure with policy makers and funding agencies as the recommendations of the *Sea Change* report (to a large extent) have been taken over by the NSF, including recommendations with regard to the IODP. It is important to note that this decadal survey runs into 2025, beyond the start of the new program for future scientific ocean drilling.

- **Sea Level Change**
- **Ocean and Climate Variability**
- **Ocean Basins**
- **Geohazards**
- **Subseafloor Environments**

Download the *Sea Change* report from **HTTPS://DOI.ORG/10.17226/21655**

JOIDES RESOLUTION ASSESSMENT WORKSHOP (JRAW) 2018

Executive Summary

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

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

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

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

As outlined in the National Research Council's report Sea Change: 2015-2025 Decadal Survey of Ocean Sciences, scientific ocean drilling is critical to the future success of ocean and earth science research because of the unique types of samples and data collected by IODP. During the 5 first years of the program, IODP expeditions conducted with the *JOIDES Resolution* have contributed to five of the eight Sea Change research priority questions, and future expeditions will provide insight into two more.

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

Conclusions and Recommendations

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

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

The survey results were used to guide discussions in terms of the broad community's interest in IODP. The in-person workshop participants reviewed IODP expeditions implemented by the *JOIDES Resolution*, discussed the impact of regional operational planning, documented efficiencies, and identified how the *JOIDES Resolution* facility is contributing to addressing science priorities outlined in the National Academy of Sciences Sea Change report.
Using the survey results and in-person discussion, the workshop participants determined that IODP's successes rests largely on the operationally diverse capabilities of the *JOIDES Resolution*. The ship expertly recovers both hard rock and sediment cores, effectively operates in many different environments, and addresses a myriad of scientific objectives. Specific example of how the *JOIDES Resolution*'s capabilities support IODP include:

- The ship is exceptional at recovering continuous sedimentary core for deep time studies.
- The ship can operate in a broad range of water depths to address thematic science
- goals, such as marine-terrestrial ecosystem evolution and microbial ecosystems.
- The ship's operational flexibility and new procedures decrease drilling time while increasing core quality.
- The ship is able to address important societal questions by drilling into fault zones and examine carbon flow and storage in the subseafloor.
- The ship's equipment improvements in lab areas have markedly increased the analytical capabilities and decreased the turn-around time for data collection.
- The ship is the most cost-effective vessel in the world for routinely recovering and analyzing continuous cores to specific depths. 48
- The ship can efficiently and effectively install CORKs and similar observatories in the subseafloor.
- The ship's onboard analytical facilities provide the real-time data required to guide drilling operations and accomplish expedition objectives.

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

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

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

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

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

Overall, the workshop participants offer the following recommendations:

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

improve recovery in hard and/or fractured rocks, the development of tools to sample liquid in fractured rock and take in situ measurements, improvements in heave compensation, and the ability to orient APC and XCB cores are also important to advancing the science carried out by the *JOIDES Resolution*.

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

Download the full *JRAW Final Report* and the *Community Survey Report* from HTTPS://USOCEANDISCOVERY.ORG/WORKSHOP-JR-ASSESSMENT/