Reaching the Mantle Frontier: Moho and Beyond

A Three-Day Workshop Summary Report

February 7, 2011

Steering Committee: N Abe, C Bertka, R Hazen, R Hemley, G Myers, K Suyehiro

Program Committee: C Bertka, B Ildefonse, G Myers, A Shahar, Y Tatsumi

September 9 – 11, 2010
Carnegie Institution of Washington
5251 Broad Branch Road NW, Washington, DC, USA

IODP
INTEGRATED OCEAN DRILLING PROGRAM

Deep Carbon Observatory

CONTENTS

[1] Go to http://campanian.iodp.org/MantleFrontier/ or http://www.iodp.org and click on Mantle Frontier Workshop Reports.

Conference Aims

The Integrated Ocean Drilling Program (IODP) is a well-established international partnership of scientists and research institutions organized to explore Earth's structure and history through scientific ocean drilling. Its efforts are now complemented by the recently formed Deep Carbon Observatory (DCO) which is a multi-disciplinary, international initiative dedicated to achieving a transformational understanding of Earth's deep carbon cycle—including deep carbon mantle reservoirs and fluxes, the role of deep biology, and the influences of the deep carbon cycle on critical societal concerns related to energy, environment and climate.

Both the IODP and DCO recognize that a longstanding goal of the ocean drilling community—to reach the mantle and in the process penetrate the entire ocean crust and the Mohorovicic discontinuity—will benefit from an opportunity for a broad scientific community to consider the opportunities and challenges of this goal in the context of both scientific and technical perspectives. The DCO would like to help engage this broader community and invites them to consider the likely impacts of reaching the mantle on the scientific goals and strategies being identified by the growing DCO community. Important questions to address are: (1) What is the most reasonable and feasible pathway to reach the pristine mantle rock? (2) What novel methods can extract completely new information about our planet? (3) How might reaching the mantle complement and contribute to DCO scientific goals? To this end the IODP and DCO are co-sponsoring a three-day workshop.

The workshop attendees included key scientists and engineers from academia and industries that aspire reaching the mantle in a timeframe of 15-20 years. The purpose of this workshop is to identify key scientific objectives associated with innovative technology specifications along with associated timelines and costs for developments and implementation. The workshop's ultimate goal is to produce a realistic roadmap for penetrating the Moho and reaching the mantle portion of Earth. Such a project will require the concerted efforts of the international scientific and engineering communities who share aspirations in direct exploration of the deep interior of Earth.

Consensus at the Workshop

(1) IODP and DCO

The presentations and discussions at the Mantle Frontier workshop enlighted obvious potential points of synergy between DCO and IODP, which may allow close collaboration between the two programs, towards a comprehensive understanding of carbon-water cycle in the Earth system.

(2) Scientific rationale of MoHole

The workshop participants endorse the following outline of the MoHole project scientific rationale, based on earlier meeting reports (Mission Moho, 2006[2], MMFL, 2009[3], MoHole workshop, 2010[4]), the Mission Moho proposal (IODP proposal # 719-MP[5]), and discussions at this meeting:

- Geological nature of the Moho
- Formation of oceanic crust, and processes that influence its subsequent evolution
- Evolution of oceanic crust: Interactions with oceans and biosphere, and influence on global chemical cycles, including Carbon cycle
- Limits of life and controlling factors; evolution of biomass with depth and changing crustal conditions
- Physical and chemical nature of the uppermost mantle, incuding investigation of mantle Carbon source(s).

(3) Messages to IWG+ and SPWC of IODP

Workshop participants will receive draft messages on implementation of the MoHole project and will be asked to send them back to the organizing committee of this meeting with comments. The organizing committee will pass these messages to the IWG+, and to the Science Plan Writing Committee of IODP.

(4) Scoping Group

The workshop participants propose to establish a MoHole Scoping Group (MHSG) by the end of year 2010. The mandate of the Scoping Group should include:

1. Review and refine the science goals (High Level Objectives) and project leader
2. Identify technology to meet the science goals
3. Evaluate technology, prioritize science goals and recommend a technical plan
4. Establish a management structure
5. Estimate the total cost of the project (for various technologies, logistics, etc)
6. Initiate outreach and communication activities
7. Seek funding opportunities
8. Refine the project timeline

The following colleagues were identified (on a voluntary basis) as members of a nomination committee, in charge of proposing nominees for the MHSG to IODP, after taking inputs from the community: Donna Blackman, Jonathan Snow, Marguerite Godard, Shoji Arai, and Wataru Azuma from Ctr for Deep Earth eXploration and Joerg Geldmacher from Texas A&M U, representing Japan and US Implementing Organizations, respectively.

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[2] Mission Moho, 2006 Workshop Report: http://www.iodp.org/index.php?option=com_docman&task=doc_download&gid=1309

[3] Melting, Magma, Fluids and Life, 2009 workshop report: http://www.interridge.org/WG/DeepEarthSampling/workshop2009

[4] Ildefonse, B., Abe, N., Blackman, D., et al., 2010. The MoHole: a crustal journey and mantle quest, workshop in Kanazawa, Japan, 3-5 June 2010. *Scientific Drilling*, 10:56-63.

[5] Mission Moho Proposal: http://www.missionmoho.org

Program

Day one – September 9 13:00-17:00
Introduction/Opening remarks/Meeting goals (Kiyoshi Suyehiro, Russell Hemley and Jesse Ausubel)
Deep Carbon Observatory overview (Robert Hazen, Connie Bertka and Erik Hauri)
Oceanic Moho and Mantle - what we learned from recent active source seismic studies (Shuichi Kodaira)
Kanazawa Mohole meeting summary and Mohole history (Benoit Ildefonse)
Keynote address - Drilling the MOHOLE - More Difficult than Landing Men on the Moon?" (Donald Beattie)

Day two – September 10 08:45-17:00
Linking in-situ information to global and planetary scale processes. Uses and limitations and why is in-situ sampling useful (Donna Blackman)
Global chemical cycles and relation to mantle dynamics/petrological processes (Yoshiuki Tatsumi)
Microbiology – extent of life (Matt Schrenk)
Deep energy, environment and climate (Peter Kelemen)
Breakout sessions
1- Mantle and global chemical cycles (chairs: Erik Hauri and Katherine Kelley)
2- Mantle dynamics, from petrophysics to large scale imaging (chairs: Jason Phipps Morgan and Donna Blackman)
3- Deep energy and life (Chair: Matt Schrenk)
Plenary Session – Results of breakout
Discussion on outcome of previous MoHole planning workshops- Science and Sites (Chairs: Benoit Ildefonse and Eric Hellebrand, Rapporteur Jessica Warren)

Day three – September 11 08:45-16:30
Present technological capabilities and limitations and discussion (Greg Myers: Ocean Leadership)
Drilling Fluid technology (Michael Freeman: MI-SWACO)
Riserless Mud Recovery technology for deep holes in deep water (John Cohen: AGR Drilling Services)
Self-sinking capsules to investigate Earth's interior (Michael I. Ojovan: Sheffield University)
Sub-sea equipment manipulation (Larry Karl: Oceaneering)
Blow out preventors and sea floor isolation devices (John Kotrla: Cameron)
Managing the project- cost, timeline, resources (John Thorogood: Drilling Global Consultants LLC)
Breakout sessions
1- Funding (chair: Brian Taylor)
2- Technical operations and engineering, milestones and road mapping (chair: Greg Myers)
Plenary Session - Capture consensus items (chair: Yoshiuki Tatsumi)

Breakout Sessions Summary Notes

1- Mantle and global chemical cycles (Chairs: Erik Hauri and Katherine Kelley)

Main Questions

- What are the most important geochemical & petrological questions that can be addressed by an in situ Moho drill hole?
- Which of these problems are best addressed by complete coring vs spot coring vs logging?
- What potential contamination issues are deal killers?
- Do any of these science topics require time-series borehole observations?

Crust Questions

• Bulk composition of the oceanic crust? Primary igneous vs. secondary alteration
• Alteration/carbon addition history of the crust
• Permeability structure of crust w/ depth
• Lithology w/ depth, relationship to seismic observations

Mantle Questions

• Petrologic nature of the Moho? Composition, grain size, alteration, etc.
• How altered is the mantle?
• Mantle sample in situ vs. exhumed
• Mantle/crustal cycling of C, He

Contamination Issues

• Samples/tracers in drilling fluid
• Site 801 micro-bio used PFC, fluorescent microbeads to test for microbial contamination
• 13C doped diamonds?

In-Situ Measurements?

YES--this will be a legacy site

2- Mantle dynamics, from petrophysics to large scale imaging (Chairs: Jason Phipps Morgan and Donna Blackman)

How much mantle to be sampled?

1 km beneath the Moho to capture lithologic variation w/depth.
4 km beneath the Moho to capture gradients on top of lithologic variation.

Ridge processes

Sample origin of Moho, distinguish cause of different seismic signatures.
Is there a sub-Moho decoupling zone active at spreading centers?
Measure fabric & strain history, does mantle actively flow relative to crust?
What is responsible for strong anisotropy measured? (layering? deformation?)
Permeability of seawater circulation system(s), including mantle section.
How deep is hydrothermal circulation at ridges? Off-axis? What limits depth?

Mantle properties

Does Moho mark transition to fresh peridotite?
[What are the radionuclide concentrations introduced by alteration?]
What replenishes mantle at subduction zones, in terms of fluxes of water/seds/crust/depleted mantle that flux thru system
How much erupts in arc volcanoes
In-situ measurements of near-Moho mantle & shallower crustal properties

Slab behavior

How does hydration influence slab bending & chemical transformations in subducting slab? Is this major factor in enabling plate tectonics to operate now and in past on Earth?

Issues responding to Science/field area criteria in Kanazawa Report.

(1) Hydrothermal circulation at ridges is deep (through crust) — this means that the Moho is at ~200° very near the ridge axis EXCEPT in places where hydrothermal circulation has been sealed by relatively impermeable near-ridge sediments (e.g. except in Equatorial High Productivity Zone, for example — sediment thickness, continuity, and heatflow can be easily measured in pre-site survey.

(2) Bend-faulting at subduction zones is very likely to be an important geologic process that has major implications for the composition/fluxes of water&carbonates into subduction zones. Bend-faults have been shown to be seismically linked to sub-Moho velocity reductions that are most simply interpreted as being linked to significant mantle serpentinization (including mantle hydration and carbonation that have important consequences for the dynamics of subduction zones and the refertilization of the mantle. Note that Central America has ~3700m sites that could drill to the Moho in a region of active bend-faulting and associated geophysical changes in the sub-Moho mantle.

3- Deep energy and life (Chair: Matt Schrenk)

How to engage the microbiological community?

- Contamination is a deterrent, can be overcome with more ground-truthing pubs! (cf. **Santelli, C.M.,** Banerjee, N.R., Bach, W., and Edwards, K.J., 2010. Tapping the

subsurface ocean crust biosphere: low biomass and drilling-related contamination calls for improved quality controls. *Geomicrobiology Journal*, vol. 27, no. 2, pp. 158-169.)

- Intimidating IODP/ICDP structure
- Make good use of open borehole and post-drilling experiments

Sampling Considerations

Contamination
- Sidewall coring
- New tracers
- Signal: noise

Collection and archiving without artifacts
- Cryogenic preservation
- Pressure sub-sampling

Better communication about needed technologies
- In situ monitoring

Connections between the DCO and MoHole project (and drilling in general)

Ongoing short-term initiatives (sequencing, instrumentation)
What suite of samples and technological developments would inform us about the drilling to the Moho?
(Existing samples, other boreholes, potential contaminants)

What biological analyses are most relevant to the problem?

DNA -> RNA -> protein -> metabolites <- stable isotope probing/geochem.
Biology, carbon phases, and carbon mobility
Fixation of inorganic carbon
Diamonds, graphite, carbonates
Alkanes, CO, CO2, etc.
Diagenesis of subsurface biosphere biomass

Feedbacks between geophysical process and biology

Fracture opening and closing
Solid Earth processes (capacitors)
Isolation and evolution (impacts upon biodiversity and evolution)
Topics biologists get excited about

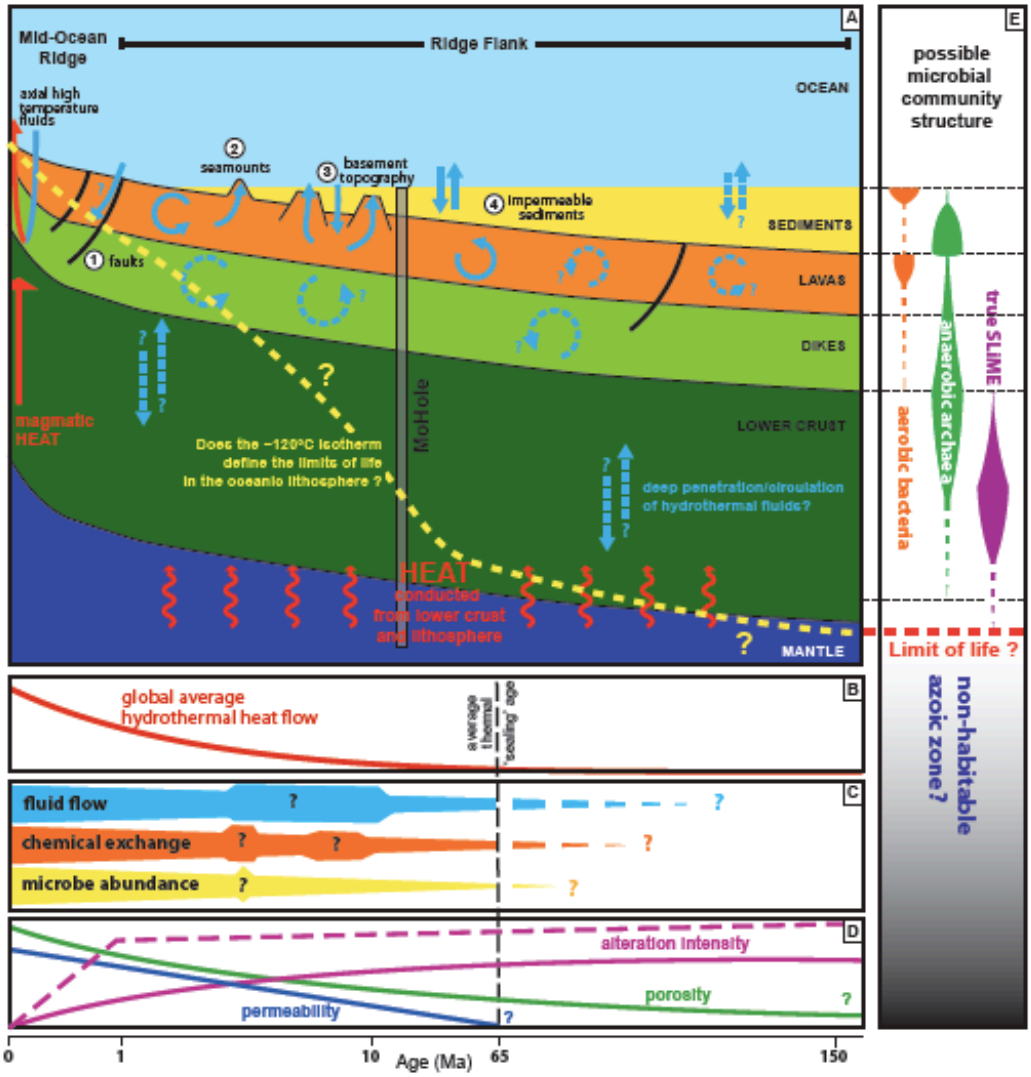

Figure: A: Schematic architecture of a mid-ocean ridge flank (not to scale) illustrating parameters that may influence the intensity and style of hydrothermal circulation through the ridge flanks such as faults, seamounts, basement topography and impermeable sediments, which isolate the crust from the oceans. Arrows indicate heat (red) and fluid (blue) flow. The yellow dashed line is a hypothetical trajectory of the ~120°C isotherm as ocean crust moves away from the ridge crest. B: The calculated global geothermal heat flow anomaly decreases to zero, on average, by 65Ma. C: The effects of parameters such as basement topography and sediment thickness on the intensity and relative cessations of fluid flow, chemical exchange, and microbial activity remain undetermined. D: Evolution of porosity, permeability, and alteration with age. E: Hypothetical change in microbial community structure with; the depth limit of life increases with crustal age. F: Schematic cross-section of fast-spread crust with anticipated MoHole penetration. (Figure by Coggon, Teagle, and Nakamura after The MoHole Workshop Report, June 2010.) This figure was deemed an exemplary figure (after appropriate modifications and improvements) for the MoHole goal at the Workshop.

Plenary Session: Discussion of Sites, Science and Program (Chairs B Ildefonse and E Hellebrand; Rapporteur J Warren)

Participants discussed the following items:

Drilling the outer rise
We discussed the opportunity of drilling on the Cocos plate where it bends as it goes into the trench, to be able to look at alteration of a plate when it starts to subduct, and document the serpentinization of the upper mantle hypothesized from geophysical data (e.g., Ranero and Sallares, 2004; doi:10.1130/G20379.1). Drilling this area also presents the advantage of being in shallower waters. This objective, with a distinct scientific rationale, is exciting, but has also two major drawbacks :

- We would miss the state (degree of serpentinization) of the mantle before the subduction-realted bending.
- Fractured rock is worse to drill, as shown by experience in drilling hard rocks so far; we probably want to avoid fractured environments for a first ultradeep lithospheric hole.

Diamonds
Identification of diamonds in the upper mantle was mentioned again (see also Kanazawa workshop report) as a potential goal for the moHole. This objective does not reach consensus; some participants clearly stated that it should not be a major goal of the project.

First Moho penetration
Several participants proposed drilling first through the Moho at sites 735 (SouthWest Indian Ridge, Atlantis Bank) and/or U1309 (Mid-Atlantic ridge, Atlantis Massif), where basaltic crust is absent, then drilling through the Moho in the Pacific. This has been extensively discussed in the past (e.g., Mission Moho Workshop report and Proposal), and it is recalled that the community priority for the MoHole is deep drilling in intact, fast-spread crust (see Mission Moho, MMFL, and Kanazawa workshop reports). This, however, is not incompatible with proposing, and conducting deep drilling in other geodynamic settings, independent of (in parallel to) the MoHole project.
An alternative option is to first drill in Oman. The cost is relatively limited (~5 million US$) and the project is technologically straightforward. However, it won't address the objectives outlined for the oceanic lithosphere. Results from Oman could be used to guide future drilling strategy, and to test equipment (e.g., getting technology to calibrate for magnetic north in a serpentinized peridotite hole). We could also drill immediately offshore in Oman to test drilling technology.

Engineering considerations
Engineering considerations are particularly important to get to target quickly, especially as keeping the hole open for a while can be difficult. See Kanazawa workshop report for further discussion on this topic.

Planning and scheduling

Drilling will take many expeditions, with a program running over several years (>10?). Therefore, the MoHole project needs a different system for planning and scheduling, including long-term commitment to continually return to the site. The claim for a dedicated planning entity was a major conclusion of the Kanazawa workshop. Should the organization be conducted in parallel to IODP, instead of as part of it? To proceed, the project needs a managing body, which in turn requires funding. Can this be funded within the next generation of IODP?

The need for a bigger program than just for drilling was also pointed out. This will include a lot of science research both before and after drilling; and will require a long-term community commitment beyond drilling alone.

As IODP is currently changing its planning structure, a new proposal should be submitted as soon as feasible.

Concerns were expressed with current Chikyu availability/funding for only ~ 5 months/year. To get more months, the project will need outside funding. Other options, such as using a different ship during the first part of the project, should also be examined.

Breakout Session: Funding the MoHole Project

(Chair B Taylor, Rapporteur: K Suyehiro)

Participants of the discussion agreed on the following:

- The goal of penetrating the oceanic crust and Moho to reach the mantle stands out among other scientific objectives of the IODP's new science plan for 2013-2023 in terms of its technical requirements, potential cost, and need for integration and outreach.

- The Mohole Project requires a serious feasibility assessment. The Project has to be clearly defined with cost vs. risk assessments and engineering/logistics analyses of the options. The scoping activity requires setup of an international advisory body composed of engineers (including industry), scientists and platform providers (Implementing Organizations of IODP).

- A successful Mohole Project will require a formal Project Management system and a Project Office.

- The level of effort, including engineering developments, site surveys, drilling, observatories, science and education/outreach, will likely require augmentation (and/or additional partnerships) beyond the present IODP funding level. Strategies should be formulated to obtain such.

- The international framework under IODP umbrella should be maintained for such activities, while coordinating with other relevant engineering and scientific communities such as InterRidge and the Deep Carbon Initiative.

- The initial Project Office provided through IODP-MI to support these activities may require 5 FTEs (lead scientist, lead engineer, project manager, administrator, outreach and communications).

Breakout/Plenary Session: Operations and engineering, milestones and road mapping (Chair G Myers; Rapporteur J Kotrla)

Following the technology presentation session provided by the engineering participants, this breakout session attempted to begin identifying the key planning steps needed to move mantle drilling forward from a concept to an achievable endeavor with logical, systematic steps. The discussion began with identifying the near-term steps, such as generating the meeting report and understanding where convergence or consensus was needed in the science and engineering goals. The discussion then transitioned to longer term steps such as establishing conceptual management frameworks needed to scope and then eventually manage a future mantle drilling effort.

The group agreed that before substantive progress could be made, the significant science and technology questions encompassing the where and how Mohole could be drilled must begin to be answered. To this end, the science community has narrowed the possible Mohole sites to three in the pacific. The engineering community has identified numerous technological pathways that can be utilized all with wide ranging cost, time and science delivery constraints. Thus the need for a scoping effort was identified as a key step in moving from this point with many options to a more refined and quantified position for a future Mohole project. The importance of the scoping effort could not be overstated and therefore professional well planners and engineers with experience with ultra-deepwater and ultra-deep holes must be retained to achieve the desired high-quality, unbiased scoping result. The areas of focus for the scoping effort could be:

1. Identify science goals (High Level Objectives) and Project Champion
2. Identify technology to meet science goals including long term observatories
3. Evaluate Technology, Prioritize Science Goals and Recommend Technical Plan
4. Establish management structure for execution

While the scoping effort would be overseen by IODP-MI, and using industry experts, the standing IODP committees on engineering and technology have created relevant and applicable technology roadmaps that can be used to bridge the gap between the academic and oil and gas drilling communities. Both science and engineering communities would be required to advise the scoping process and have equal representation and to support the scoping effort. The output of the scoping effort would be final report that would serve as a basis for an implementation plan to be used by the scientific ocean drilling stakeholders.

Lastly, the group thought that writing a letter to the IODP structure representing consensus of this meeting- to drill MoHole would help strengthen the support to engaging on this ambitious endeavor. A suggestion was made to send a letter to the IODP Science Plan Writing Committee

The above proceedings were discussed with the workshop participants in the following plenary session.

Special thanks to Johnnie Kotrla of Cameron who graciously took notes

Participants List

Participant		Expertise/Affiliation
Natsue	Abe	Mantle petrologist & geochem, MoHole project/JAMSTEC
James	Allan	Program Director, ODP at NSF
Jesse	Ausubel	Sloan Foundation
Wataru	Azuma	JAMSTEC
Rodey	Batiza	NSF
Donald	Beattie	Keynote speaker, moon landing
Connie	Bertka	Geophysical Lab - CIW
Donna	Blackman	Mantle and crust geophysics/Scripps Inst. Oceanography
Taras	Bryndzia	Oxidation state of Earth's upper mantle
Mike	Cheadle	Univ of Wyoming
Anna	Cipriani	Mantle geochemistry/Lamont Doherty Earth Observatory
John	Cohen	R&D Technologhy Manager/AGR
Marco	Coolen	Paleomicrobiology, ancient biomolecules/Woods Hole Oceanogr. Inst.
Rajdeep	Dasgupta	C-O-H volatiles in mantle melting processes/Rice Univ
Henry	Dick	Mantle/crust petrology & geochemistry/Woods Hole Oceanogr. Inst.
Tom	Duffy	Princeton Univ
Yingwei	Fei	Mantle evolution, core & mantle differentiation/Geophys. Lab-CIW
Michael	Freeman	High performance drilling mud
Joerg	Geldmacher	IODP - USIO
Marguerite	Godard	Mantle geochemistry, CO2 capture/Univ. Montpellier
Uli	Harms	ICDP
Yumiko	Harigane	Kanazawa University
Chris	Harrison	University of Miami
Erik	Hauri	Chemical evolution of the mantel, mantle plume modeling/CIW
Robert	Hazen	Origins of life, pre-biotic chemical complexity
Eric	Hellebrand	Mantle petrology/geochemistry (Gakkel Ridge)
George	Helffrich	U. Bristol Earth Sciences UK
Russell	Hemley	Material properties at high pressure/CIW
Susan	Humphris	Woods Hole Oceanographic Inst

Benoit	Ildefonse	Mantle and Crust Geology, MoHole project
Yoshio	Isozaki	Riser drilling technology expert
Kevin	Johnson	Mantle petrology and CCS
Takero	Kasaya	JAMSTEC
Larry	Karl	Oceaneering
Yoshihisa	Kawamura	IODP-MI
Peter	Kelemen	Mantle Geodynamics, CO2 capture
Katherine	Kelley	Magmatic volatile budgets and H2O effects on mantle
Shuichi	Kodaira	Seismic structure of Crust and upper mantle
John	Kotria	Riser and Riserless BOP
Shin'ichi	Kuramoto	CDEX/JAMSTEC
Hans Christian	Larsen	IODP - MI
Murli	Manghnani	University of Hawaii
Catherine	Mevel	ECORD
Katsuyoshi	Michibayashi	Structural geology, mantle xenolith petrophysics
Jason Phipps	Morgan	Mantle and crust geophysics
Tomoaki	Morishita	Petrology geochemistry
Suyoy	Mukhopadhyay	Harvard Univ.
Greg	Myers	Engineering/COL
Bjorn	Mysen	Geophysical Lab - CIW
Takashi	Nakagawa	JAMSTEC
Jim	Natland	Petrology of ocean crust and upper mantle
Wendy	Nelson	Carnegie Institute of Washington
Eiji	Ohtani	Effect of water on mantle dynamics
M.I.	Ozhovan	Self Sinking Capsule
Hani	Sadek	DeepStar director
Matthew	Schrenk	Deep biosphere
Anat	Shahar	Geophysical Lab - CIW
Shingo	Shibata	Ministry of Education, Culture, Sports, Science & Technology, Japan
Steve	Shimonek	Cameron Drilling Engineer
Alister	Skinner	Coring expert
Deborah	Smith	National Science Foundation
Johnathan	Snow	Univ. of Houston
Nikolai	Sobolev	Russian Academy of Science
Sergie	Stishov	Phase transitions, high pressure minerals
Kiyoshi	Suyehiro	IODP-MI

Eiichi	Takazawa	Mantle petrology/geochemistry
Yoshiyuki	Tatsumi	Mantle and crust petrology
Brian	Taylor	SOEST Univ Hawaii
John	Thorogood	Deep Drilling Project Management
Masako	Tominaga	Oceanographic Institute
Vladimir	Trofimov	Geometric theory
Bill	Ussler	Monterey Bay Aquarium Research Inst
Jessica	Warren	Mantle geochemistry
John	Weare	UCSD