

# Executive Summary: “Mantle Frontier” Workshop

by Workshop Report Writing Group

doi:10.2204/iodp.sd.11.07.2011

## Introduction

The workshop on “Reaching the Mantle Frontier: Moho and Beyond” was held at the Broad Branch Road Campus of the Carnegie Institution of Washington on 9–11 September 2010. The workshop attracted seventy-four scientists and engineers from academia and industry in North America, Asia, and Europe.

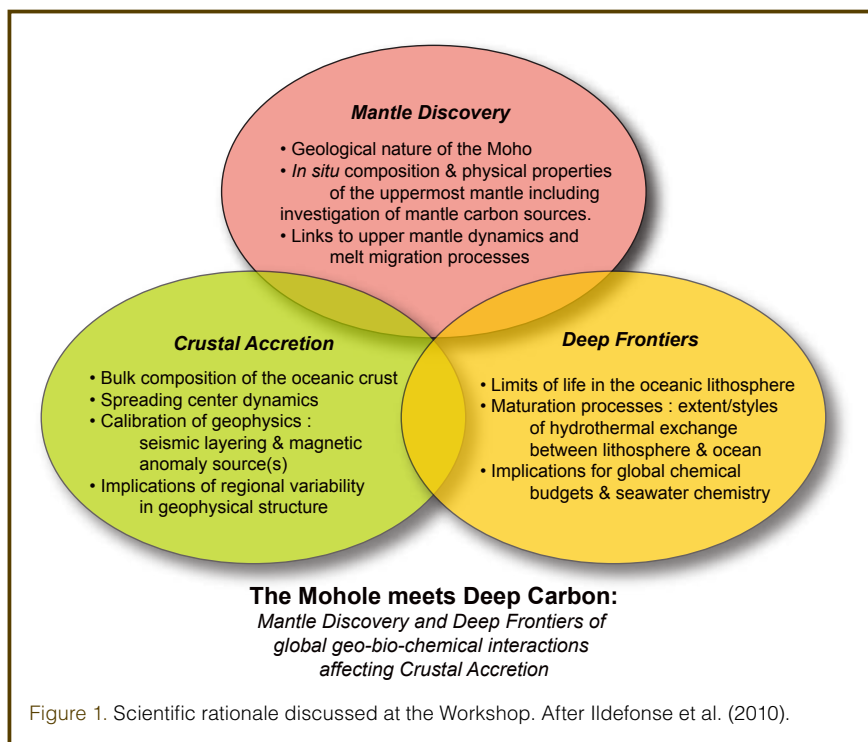
Reaching and sampling the mantle through penetration of the entire oceanic crust and the Mohorovičić discontinuity (Moho) has been a longstanding goal of the Earth science community. The Moho is a seismic transition, often sharp, from a region with compressional wave velocities ( $V_p$ ) less than  $7.5 \text{ km s}^{-1}$  to velocities  $\sim 8 \text{ km s}^{-1}$ . It is interpreted in many tectonic settings, and particularly in tectonic exposures of oceanic lower crust, as the transition from igneous crust to mantle rocks that are the residues of melt extraction. Revealing the *in situ* geological meaning of the Moho is the heart of the Mohole project. Documenting ocean-crust exchanges and the nature and extent of the seafloor biosphere have also become integral components of the endeavor. The purpose of the “Mantle Frontier” workshop was to identify key scientific objectives associated with inno-

vative technology solutions along with associated timelines and costs for developments and implementation of this grand challenge.

## Background: Ocean Drilling and the Mantle Target

Scientific ocean drilling started from the first excitement of Mohole Phase I that penetrated 180 m in 3300 m water depth off Guadalupe Island (west of Baja California, Mexico) in April 1961 (Bascom, 1961; Steinbeck, 1961; Cromie, 1964), although the Mohole project was abandoned soon after (Greenberg, 1966). Fifty years after Mohole Phase I, the deepest hole into the oceanic crust is located on the Nazca Plate in the eastern equatorial Pacific (ODP Hole 504B) to 2111 m below the seafloor (mbsf) within the sheeted dikes. The second deepest hole in the Pacific, 1256D (1507 mbsf), is on the Cocos Plate northwest of 504B; it penetrates the transition zone between the upper and the lower crust, in the upper gabbroic rocks below the sheeted dike complex. Other significantly deep holes over 1000 m deep beneath the seafloor include ODP Hole 735B (1508 mbsf) in the Indian Ocean (Atlantis Bank) and IODP Hole U1309D (1415 mbsf) at the Atlantis Massif in the Atlantic Ocean. These achievements of relatively deep crustal penetration were made with the available riserless drilling technology. The deep holes outside the Pacific Ocean were drilled in uplifted fault blocks where lower crustal rocks are exhumed at shallow depths, in heterogeneous slow-spread ocean lithosphere.

In 2007, a riser-equipped drilling ship was introduced to IODP (D/V *Chikyu*, owned and operated by JAMSTEC). Riser technology significantly improves the deep drilling capability as proven by oil industry experience. The science plan of IODP thus includes 21<sup>st</sup> Century Mohole as one of its initiatives (IODP, 2001). We are in an era where drilling technology is rapidly advancing to realize deep drilling (>6 km below seafloor) in deep waters (industry drilling in >3000 m water depth in the Gulf of Mexico). Scientific and industry drilling



have come a long way, and we can now seriously consider scientific drilling to the mantle.

## **Deep Carbon Observatory and Carbon Reservoirs**

The Deep Carbon Observatory (DCO) is a multidisciplinary, international initiative dedicated to achieving a transformational understanding of Earth's deep carbon cycle. Key areas of study include the following:

- deep carbon mantle reservoirs and fluxes
- the nature and extent of the deep biosphere
- the physical and chemical behavior of carbon under extreme conditions
- the unexplored influences of the deep carbon cycle on energy, environment, and climate

The DCO's goal to advance understanding on these frontiers requires an integrated approach—incorporating field-based global sampling efforts, laboratory experiments, analytical methodology, and theoretical modeling, as well as establishing new research partnerships. Much of the DCO's work will be experimental, but much will also depend on deep Earth samples recovered using the framework of established programs like IODP and the International Continental Scientific Drilling Program (ICDP).

The present IODP and the current vision for the future International Ocean Discovery Program share numerous similar goals for understanding Earth processes and systems. Discoveries of microbial life deep in the crust beneath the oceans and continents indicate a rich subsurface biota that by some estimates may rival all surface life in total biomass. Much work also remains to understand how life adapts to deep environments, what novel biochemical pathways sustain life at high pressure and temperature, and what the extreme limits of life are. How does biological carbon link to the slower deep physical and chemical cycles? Is biologically processed carbon represented in deep Earth reservoirs? The nature and full extent of carbon reservoirs and fluxes in Earth's deep interior are not well known. The subduction of tectonic plates and volcanic outgassing are primary vehicles for carbon fluxes to and from deep in the Earth, but the processes and rates of these fluxes—as well as their variation throughout Earth's history—remain poorly understood. Likewise, there is evidence for abiogenic hydrocarbons in some deep crustal and mantle environments, but the nature and extent of deep organic synthesis is unknown. Last but not least, what are the impacts of deep carbon on energy and the surface carbon cycle?

The DCO recognizes a longstanding goal in the ocean drilling community to reach and sample *in situ* pristine mantle and—in the process—penetrate the entire ocean crust and the Moho. Samples obtained en route to and across the Moho will complement the DCO's other research efforts and

may address some of the DCO questions above. Such samples and their subsequent study may also ground truth existing hypotheses and, perhaps the findings will inspire entirely new hypotheses and studies regarding the nature of Earth's upper mantle and lithosphere. Undoubtedly, the interest and participation of portions of the DCO community in such a monumental drilling project will expand the scope of the ocean drilling community with its own scientific goals related to carbon cycling deep in the Earth.

## **In Relation to Previous Workshops**

The ocean drilling science community has met in numerous workshops over the course of Deep Sea Drilling Project (DSDP), Ocean Drilling Program (ODP), and IODP (Ildefonse et al., 2007; Teagle et al., 2009; Ildefonse et al., 2010). An international workshop on “The Mohle: a Crustal Journey and Mantle Quest” was held in Kanazawa, Japan in June 2010; it reaffirmed the scientific rationale, considered technological realities and opportunities, and identified potential drilling sites for site surveys planning (Ildefonse et al., 2010).

The “Mantle Frontier” workshop was planned to make a natural step forward in technological discussion, but the emphasis of the scientific discussion was to expand the scope irrespective of specific sites, to emphasize the mantle portion of the targeted section, and to ask the general and fundamental questions of interest to the broader scientific community, such as the DCO.

## **Scientific Presentations**

The DCO overview was given by Robert Hazen from a program-wide perspective, by Constance Bertka from a program management perspective, and by Erik Hauri from the carbon reservoirs and fluxes viewpoint (in his presentation “REFLEX: Deep Carbon Reservoirs, Fluxes and Experiments”). We are accustomed to thinking about the carbon cycle near the Earth's surface, but we know so little about Earth's deep carbon that we lack estimates of carbon quantity or chemical structure, and the effects of carbon on mantle (or core) behavior. The nature and extent of the deep microbial biosphere also need to be investigated.

REFLEX's interests in deep carbon include 1) the pathways and fluxes of carbon exchange between the surface and deep Earth; 2) the nature and variability of carbon compounds in the deep Earth; 3) the interactions between carbon concentration and the dynamics of the Earth's interior; and 4) the ultimate origins of mantle carbon. From these perspectives, REFLEX can use the IODP database to inventory carbonate and organic carbon content in deep-sea sediment cores; analyze a complete ocean crustal section for full understanding of CaCO<sub>3</sub> addition to the mantle at subduction zones; and determine carbon flux from pore fluid release in subduction zones.

An illuminating keynote address was given by Donald Beattie, who oversaw the Apollo lunar rock sampling project (Beattie, 2001). A proper project management system to manage a project of this scope from the beginning to end is the key and challenge to success.

Benoit Ildefonse gave a summary of Mohle history and outlined the scientific rationale for the Mohle in three categories (based on the outcome of the previous recent workshops, and as summarized in the Kanazawa workshop report): mantle discovery, crustal accretion, and deep frontiers (Ildefonse et al., 2010). An anticipated timetable for the new Mohle project will enable complete preparations by 2017 and reach the mantle by 2022. Three candidate sites are being considered for reaching the mantle: Cocos Plate site (including Site 1256), off southern Baja California, and north of Hawaii. Site surveys are being planned to gather data to make the final selection.

Shuichi Kodaira presented recent high-resolution seismic profiles of oceanic Moho and mantle from active source seismic studies in the western Pacific that can help extrapolate drilling observations to mantle dynamics from ridges to trenches. Seismic images of the Moho can vary from sharp to diffuse boundaries, which may correspond to the geologic variety found at the crust/mantle transition in ophiolites. Strong seismic azimuthal anisotropy can be expected to start immediately beneath the Moho, such as measured in the NW Pacific (Oikawa et al., 2010). Lower crustal dipping reflectors matching fast  $V_p$  directions may be manifestations of basal shear near the Moho.

Donna Blackman showed how grain-scale deformation due to mantle asthenospheric flow, with melt and recrystallization overprints, may be linked to seismological observations. So far, such inferences have been made without *in situ* knowledge of crystallographic fabric. Mantle samples will document structures and ground truth petrophysical properties. Borehole experiments will provide high-resolution information to be extrapolated to kilometers beyond the hole.

Yoshiyuki Tatsumi showed how drilling could contribute to the understanding of mantle dynamics and geochemical cycles. He emphasized the important roles of water and carbon in creation-destruction cycles in the ocean lithosphere, including arc and continental crust genesis. Deep

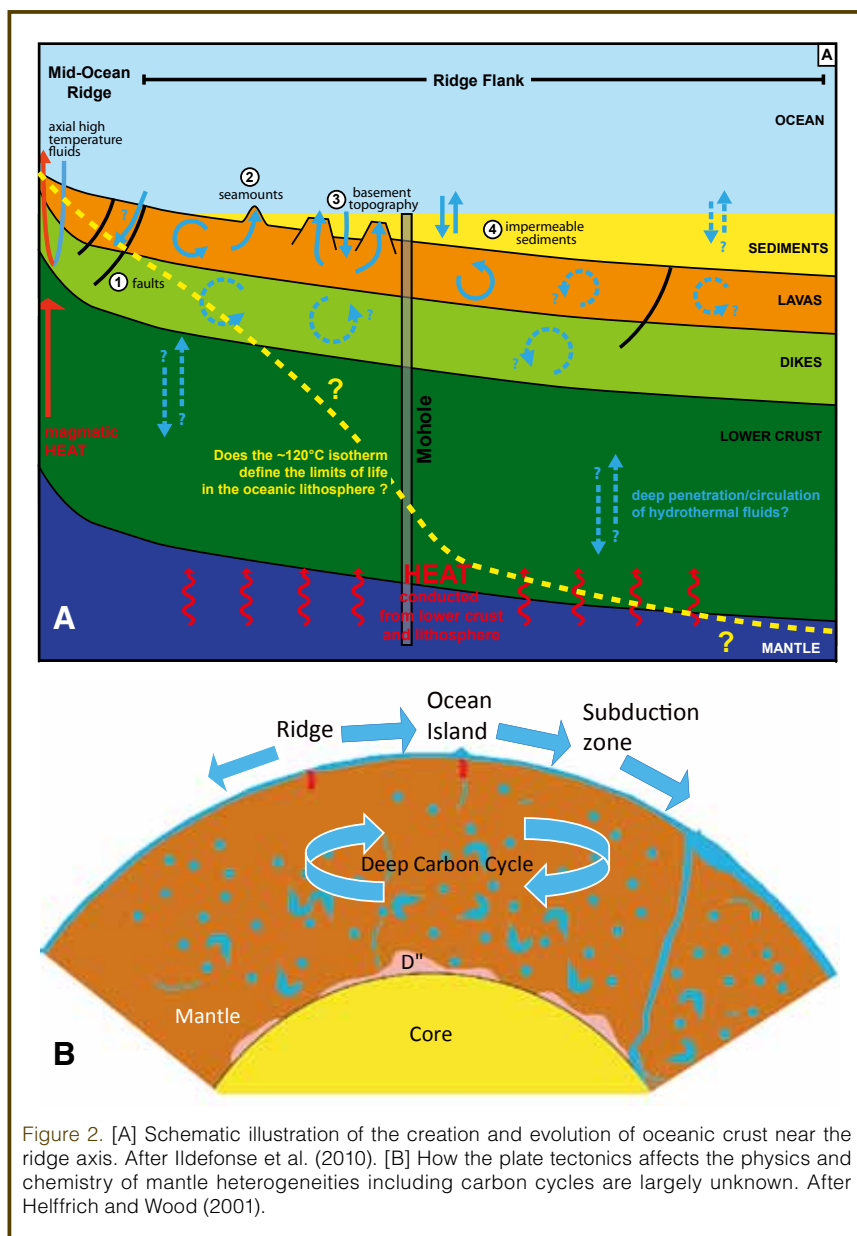


Figure 2. [A] Schematic illustration of the creation and evolution of oceanic crust near the ridge axis. After Ildefonse et al. (2010). [B] How the plate tectonics affects the physics and chemistry of mantle heterogeneities including carbon cycles are largely unknown. After Helffrich and Wood (2001).

drilling at key sites along the ocean lithosphere pathway will contribute to a better constrained global geochemical model including the explanation of mantle geochemical heterogeneities.

Matt Schrenk presented how drilling can be used to discover the extent of microbial life in the deep biosphere. The subsurface biosphere may host one-third to one-half of all prokaryotic cells on Earth, and contain biomass equivalent to that of all plant life at the Earth's surface. Furthermore, the deep biosphere is dependent upon energy in the form of chemical disequilibria and not directly coupled to photosynthesis; it is sometimes referred to as the dark energy biosphere (DEB). However, the absolute extent, the nature, and controls upon the subsurface biosphere are not completely known. Fluid circulation (hydrology) is considered a key to nourishing the DEB; drilling and associated hydrological experiments can provide direct observations of cell density,

together with quantitative measurements of permeability and time-integrated fluid/rock ratios. Drilling through the ocean crust means penetrating from the life to the non-life regime, and it provides an opportunity to explore the connectivity and flow between deep and surface chemical reservoirs. Developing technologies to overcome contamination-by-drilling as well as distinguishing signal from “noise” introduced by drilling fluids is crucial to interpreting the results of this portion of the project.

Peter Kelemen made a presentation on deep energy, environment, and climate. Carbon is present in the mantle as a result of hydrothermal interaction followed by subduction, and perhaps as a primordial component. Shallow interaction yields fluids containing hydrogen and methane as well as more complex hydrocarbons similar to those stable at greater depth, and these could be a future fuel source. ODP data yield an average of 0.6 wt% CO<sub>2</sub> in altered peridotites, extrapolated to ~0.3 wt% CO<sub>2</sub> over a 7-km depth where mantle peridotite is exposed at the seafloor. A mass equivalent to all dissolved CO<sub>2</sub> in the oceans is added to altered mantle peridotite every ten million years. Optimizing this near-surface weathering holds great potential for carbon storage. Each ton of mantle peridotite can permanently store up to 600 kg of CO<sub>2</sub> in the form of inert, non-toxic solid carbonates. Kinetic data show that a rate of one billion tons CO<sub>2</sub> per km<sup>3</sup> of rock per year can be achieved under optimal conditions (Kelemen and Matter, 2008; Kelemen et al., 2011). There are tens of thousands of cubic kilometers of peridotite near the surface on land, and millions near the seafloor along slow spreading ridges. A Mohle would provide crucial data on the depth of natural CO<sub>2</sub> uptake.

## Engineering Presentations

Greg Myers gave a comprehensive presentation on current technological capabilities and limitations. The uniqueness of mantle drilling is the water depth/hole depth combination and the rocks (not sediments) to be drilled. The oil and gas industry already drills deeper holes, yet in water depths less than 3300 m. An integrated approach utilizing all available IODP platforms will reduce the overall cost. Engineered mud must be circulated continuously as part of a comprehensive plan to drill and core effectively. Improved borehole pressure control for deep drilling can be achieved by utilizing dual gradient drilling, which applies mud pressure from the seafloor rather than the platform or vessel. Discussions of continuous coring vs. spot coring and down-hole equipment (drilling/coring/logging) are necessary. Myers emphasized the definition of success must be clear and understood by all.

Randy Normann supplied a presentation introducing electronics, batteries, and tools that withstand very high temperatures continuously (>250°C). Michael Freeman lectured on drilling fluid and making deep holes. John Cohen introduced a riserless mud recovery (RMR) method as an applica-

tion of the dual gradient drilling concept. At present, there is technology qualified for 1500 m water depth.

Michael Ojovan introduced a totally different approach to investigating Earth’s interior with the use of self-sinking capsules. The capsule melts the rocks and creates acoustic signals to be detected at the surface, thus yielding information about the nature of the rocks through which the capsule and the signals pass (Ojovan et al., 2005). In their design the probe reaches the Moho in about five months (100 km depth in 35 years).

Larry Karl introduced Remotely Operated Vehicles (ROV) for deep-water applications (depth rated to 10,000 ft) used in offshore oil and gas fields. Also presented were unique and robust techniques for resupply at sea. John Kotrla made a presentation on blow-out preventers (BOP) and seafloor isolation devices. The standing water depth record well is at 3051 m in the Gulf of Mexico (Transocean “Discoverer Deep Seas”). In order to go deeper, utilizing a surface BOP and an environmental safe guard (ESG) on the seafloor was introduced.

John Thorogood presented the management aspect of mantle drilling. There are multiple technology and operational options available to achieve project goals, and yet new technologies may arrive to alter the direction of the project. Subsurface conditions may differ profoundly from the prognosis. Effective operations will involve multiple contingencies, defined rules, and protocols for changing the rules. These indicate the project is not a “normal” project, but will require skillful management from project scoping to execution.

## Outcome of the Workshop

The participants agreed on the following:

1. IODP and DCO recognize the potential for synergy towards a comprehensive understanding of carbon-water cycle in the deep Earth system, including consequences of microbial activities.
2. The workshop participants endorse the following outline of the Mohle project scientific rationale (Figs. 1 and 2).
3. The participants agree that the scale of mantle drilling—which is not just drilling but requires long-term commitment before and after the drilling—needs to be recognized by the wider IODP entities from the decision making level.
4. The workshop participants propose to establish a Mohle scoping group. The group will review and refine the science goals, identify technology, and review plans to meet the science goals. Also recognized was the need to establish a management structure, estimate the total cost of the project, and seek funding

along with outreach and communication activities within a broad IODP umbrella.

## Acknowledgements

The Integrated Ocean Drilling Program (IODP) and the Deep Carbon Observatory (DCO) initiative jointly supported the workshop with primary financial support from the Alfred P. Sloan Foundation.

## References

- Bascom, W., 1961. A Hole in the Bottom of the Sea, *The Story of the Mohle Project*: New York (Doubleday & Co.).
- Beattie, D.A., 2001. *Taking Science to the Moon: Lunar Experiments and the Apollo Program*: Baltimore MD (The Johns Hopkins University Press).
- Cromie, W.J., 1964. *Why the Mohle: Adventures in Inner Space*: Boston (Little, Brown and Co.).
- Greenberg, D.S., 1966. News and Comment. *Science*, 152:895–896, doi:10.1126/science.152.3724.895.
- Helfrich, G.R., and Wood, B.J., 2001. The Earth's mantle. *Nature*, 412:501–507.
- Ildefonse, B., Christie, D.M., and Mission Moho Workshop Steering Committee, 2007. Mission Moho workshop: drilling through the oceanic crust to mantle. *Sci. Drill.*, 4:11–18, doi:10.2204/iodp.sd.4.02.2007.
- Ildefonse, B., Abe, N., Blackman, D., Canales, J.P., Isozaki, Y., Kodaira, S., Myers, G., Nakamura, K., Nedimovic, M., Skinner, A.C., Seama, N., Takazawa, E., Teagle, D.A.H., Tominaga, M., Umino, S., Wilson, D.S., and Yamao, M., 2010. The MoHole: a crustal journey and mantle quest, workshop in Kanazawa, Japan, 3–5 June 2010. *Sci. Drill.*, 10:56–63.
- IODP, 2001. *Earth, Oceans and Life, Initial Science Plan*, 2003-2013, IODP Planning Subcommittee, pp. 110.
- Kelemen, P.B., and Matter, J., 2008. *In situ* carbonation of peridotite for CO<sub>2</sub> storage. *Proc. Natl. Acad. Sci.*, 105:17295–17300, doi/10.1073/pnas.0805794105.
- Kelemen, P.B., Matter, J., Streit, E.E., Rudge, J.F., Curry, W.B., and Blusztajn, J., 2011. Rates and mechanisms of mineral carbonation in peridotite: natural processes and recipes for enhanced, *in situ* CO<sub>2</sub> capture and storage. *Ann. Rev. Earth Planet. Sci.*, in press.
- Oikawa, M., Kaneda, K., and Nishizawa, A., 2010. Seismic structure of the 154–160 Ma oceanic crust and uppermost mantle in the Northwest Pacific Basin. *Earth Planets Space*, 62:e13–e16, doi:10.5047/eps.2010.02.011.
- Ojovan, M.I., Gibb, F.G.F., Poluetkov, P.P., and Emets, E.P., 2005. Probing the interior layers of the Earth with self-sinking capsules. *Atomic Energy*, 99:556–562, doi:10.1007/s10512-005-0246-y.
- Steinbeck, J., 1961. High drama of bold thrust through ocean floor. *Life*, 50(15):111–122.
- Teagle, D., Ildefonse, B., Blackman, D., Edwards, K., Bach, W., Abe, N., Coggon, R., and Dick, H., 2009. Melting, magma, fluids and life: challenges for the next generation of scientific ocean drilling into the oceanic lithosphere. [Workshop Report, National Oceanographic Center, Southampton,

27–29 July 2009], [http://www.interridge.org/files/interridge/MMFL\\_wkshp\\_rpt\\_2009\\_final.pdf](http://www.interridge.org/files/interridge/MMFL_wkshp_rpt_2009_final.pdf).

## Workshop Report Writing Group (in alphabetical order)

**Constance Bertka**, Deep Carbon Observatory, Senior Consultant, Geophysical Laboratory, 5251 Broad Branch Road NW, Washington, DC 20015, U.S.A., e-mail: [cbertka@ciw.edu](mailto:cbertka@ciw.edu).

**Donna K. Blackman**, IGPP, Scripps Institution of Oceanography, University of California San Diego, 9500 Gilman Drive, La Jolla, CA 92093-0225, U.S.A., e-mail: [dblackman@ucsd.edu](mailto:dblackman@ucsd.edu).

**Benoit Ildefonse**, CNRS, Géosciences Montpellier, Université Montpellier 2, CC 60, 34095 Montpellier Cédex 05, France, e-mail: [benoit.ildefonse@univ-montp2.fr](mailto:benoit.ildefonse@univ-montp2.fr).

**Peter B. Kelemen**, 211 Comer, 61 Route 9W – P.O. Box 1000, Palisades, NY 10964-8000, U.S.A., e-mail: [peterk@ideo.columbia.edu](mailto:peterk@ideo.columbia.edu).

**Andrea Johnson Mangum**, Deep Carbon Observatory, Program Associate, Geophysical Laboratory, 5251 Broad Branch Road NW, Washington, DC 20015, U.S.A., e-mail: [amangum@ciw.edu](mailto:amangum@ciw.edu).

**Greg Myers**, Senior Technical Expert: Engineering and Technology, Department: Ocean Drilling, Consortium for Ocean Leadership, 1201 New York Avenue NW, 4th Floor, Washington, DC 20005, U.S.A., e-mail: [gmyers@oceanleadership.org](mailto:gmyers@oceanleadership.org).

**Jason Phipps-Morgan**, Professor, Earth and Atmospheric Sciences, Cornell University, Snee Hall, Room 2122, Ithaca, NY 14853, U.S.A., e-mail: [jp369@cornell.edu](mailto:jp369@cornell.edu).

**Matthew Schrenk**, Assistant Professor, Howell Science S301B, Department of Biology, East Carolina University, Greenville, NC 27858, U.S.A., e-mail: [schrenkm@ecu.edu](mailto:schrenkm@ecu.edu).

**Kiyoshi Suyehiro (corresponding author)**, President & CEO, IODP-MI, Tokyo University of Marine Science and Technology, Office of Liaison and Cooperative Research 3rd Floor, 2-1-6, Etchujima, Koto-ku, Tokyo 135-8533, Japan, e-mail: [ksuyehiro@iodp.org](mailto:ksuyehiro@iodp.org).

**Yoshiyuki Tatsumi**, Institute for Research on Earth Evolution (IFREE), Japan Agency for Marine-Earth Science and Technology, 2-15 Natsushima-cho, Yokosuka-city, Kanagawa 237-0061, Japan, e-mail: [tatsumi@jamstec.go.jp](mailto:tatsumi@jamstec.go.jp).

**Jessica Warren**, Assistant Professor, School of Earth Sciences, Department of Geological and Environmental Sciences, Stanford University, 450 Serra Mall, Stanford, CA 94305, U.S.A., e-mail: [warrenj@stanford.edu](mailto:warrenj@stanford.edu).

## Related Web Links

Integrated Ocean Drilling Program: <http://www.iodp.org>  
Deep Carbon Observatory Initiative: <http://dco.gl.ciw.edu/>  
Mission Moho Proposal: <http://www.missionmoho.org>  
Kanazawa MoHole Workshop Report: <http://www.mohole.org>