

### MISSION MOHO WORKSHOP

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#### **Formation and Evolution of Oceanic Lithosphere**

The Mission Moho workshop, co-sponsored by IODP-MI, the Joint Oceanographic Institutions, Ridge 2000, and InterRidge, was held 7-9 September 2006 in Portland, Oregon, USA (full report online at [www.iodp.org](http://www.iodp.org)). It was convened to discuss and prioritize scientific objectives to be addressed by scientific ocean drilling, as part of our strategy to study the formation and evolution of the ocean lithosphere. It directly addressed InterRidge Deep Earth Sampling objectives to identify further the sub-seafloor biosphere, and to achieve total penetration of ocean crust, through international, collaborative, and multidisciplinary projects.

The potential for the Integrated Ocean Drilling Program (IODP, [www.iodp.org](http://www.iodp.org)) to contribute to an improved understanding of the composition, structure, and evolution of the ocean lithosphere is enormous and has been enunciated in planning documents since ocean drilling began. In April 1961, the first successful drilling and coring of oceanic basement was achieved offshore Guadalupe Island. A few meters of basalt were recovered, from about 3800m water depth. This remarkable breakthrough, beautifully reported by John Steinbeck in *Life* magazine, was intended to be the first stage of project Mohole, a much more ambitious project to drill through the ocean crust to the Mohorovičić discontinuity (Moho). Considerable progress has been made since the early days of scientific ocean drilling in our understanding of the architecture of the ocean crust and related mid-ocean ridge accretion and alteration processes. Yet, the number of completed ocean crust drilling expeditions at the present time remains relatively limited (45 holes deeper than 200 meters below sea floor started in basaltic crust or reached it below sediments; 37 holes deeper than 10 meters below sea floor in gabbros and serpentinitized peridotites). The fundamental goal of drilling a complete section through the oceanic crust and into the upper mantle has been reiterated through the last 45 years of scientific ocean drilling. IODP platforms are the only tools readily available for direct scientific sampling and measurements in hard rocks below the seafloor. It is highlighted in the IODP Initial Science Plan as the "21st Century Mohole" Initiative, one of eight high-priority scientific objectives. Inherent in this goal is the need for scientific and technical growth, for a clearly defined scientific strategy, and for parallel development of essential technology and operational experience.

The Mission Moho workshop set out to refine scientific objectives, to propose elements of a global strategy for understanding the formation and evolution of the oceanic lithosphere, and to begin the process of community prioritization for studies of these processes via ocean drilling. Since the early 1970's, the standard model of a uniformly layered ocean crust has evolved. Continuous investigations using ocean drilling and other marine geological tools have led to a more detailed and spatially variable picture of crustal architecture. Ocean crust produced at fast spreading ridges appears to be uniformly layered and relatively homogeneous, reflecting a relatively uniform mode of accretion. In contrast, crust created at slow and ultra-slow spreading ridges is spatially heterogeneous over distances as small as a few hundred meters, both along- and across-isochrons. For example, at some ridge segment centers in the northern Atlantic, magmatic processes dominate, and accretionary processes resemble those of fast spreading ridges. This similarity, however is limited in space, and crustal architecture typically varies along-axis, toward segment ends, where it is more heterogeneous and even discontinuous. In such areas, the ocean crust consists of a mixture of serpentinitized peridotite and gabbroic intrusions, locally capped by lavas ± sheeted dikes.

Although only 20% of modern ridges are spreading at fast spreading rates (>80 mm/yr), ~50% of present day ocean crust and ~30% of the Earth's surface was produced by fast spreading. The great majority of crust subducted back into the mantle during the last 200 Ma formed at fast spreading ridges. Hence, an understanding of accretion processes at one site might reasonably be extrapolated to describe a significant portion of the Earth's surface. Current working models include competing styles of magmatic accretion (e.g., gabbro glacier vs. sheeted sills), that can only be tested by sampling the ocean basement using scientific drilling.

In addition to the fundamental objective of drilling at least one hole through the entire crust, a thorough evaluation of lateral variability at multiple scales, and of correlations between seismic and lithological transitions will ultimately require multiple penetrations of the dike/gabbro transition, the lower crust, and the crust/mantle boundary in different tectonic settings. Therefore, in order to fully understand the architecture of the ocean crust, the slow-spreading end of the spectrum must be considered as well. Exploration of the nature of the Moho at slow-spreading ridges is an essential complement to the vision that we will gain from drilling in fast-spread crust. For example, serpentinitized mantle rocks are commonly incorporated into the crust (as

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defined seismically) at slow-spreading ridges. Drilling in this type of crust, down to fresh peridotite, will test competing hypotheses on the nature of the Moho. For example, is the Moho, (1) the boundary between the residual upper mantle and the igneous crust, or (2) a broader zone of layered ultramafic and mafic rocks, or (3) a serpentinization front, or, perhaps, some combination of these three.

Alteration of the oceanic crust encompasses a wide range of water-rock reactions that change the physical properties of the crust on a variety of temporal and spatial scales. One strategy for studying the aging of oceanic crust is to drill multi-hole transects along seafloor spreading flow lines to examine the time-integrated changes in physical and chemical properties. To date, drilling has been concentrated either relatively close to the mid-ocean ridge axes or close to subduction zones; very few holes have been drilled in crust between ~20-80 Myr old. There are no sites in the vicinity of ~60-65 Myr old which, based on heat flow measurements, is the average age at which the crust becomes sealed and the heat flux from the mantle becomes solely conductive. An additional important aspect of alteration is its spatial heterogeneity and variability in style. Although drilling cannot address this on a global scale, sampling and logging of closely spaced holes, in conjunction with cross-hole experiments, would provide important information on the length scales of variability.

The sub-seafloor biosphere also plays an important role in the chemical evolution of oceanic crust. The spatial distribution of microbes in the crust is not known but is likely influenced by host rock composition, temperature and permeability. Progress in understanding subseafloor microbial distribution, and its interactions with geochemical alteration processes, will proceed hand-in-hand with determination of the distribution of rock type, temperature and permeability as a function of depth and crustal age, and of how these relationships influence the distribution of microbial activity.

Finally, the technological requirements for achieving our objectives were discussed by a special panel that included several drilling engineers. In addition to deep drilling (see below), desired developments include improved core recovery, higher temperature tolerances for drilling and especially logging tools (> 150-200°C), and the ability to obtain oriented cores.

Mission Moho workshop was also aimed to develop guidance on the scientific and operational framework of a future "Mission Moho" within IODP.

The Moho is a seismic boundary assumed to represent the interface between the crust and the pristine mantle. Mission Moho will provide the scientific framework and encourage the technical development that will ultimately allow us to drill to and beyond this "last frontier". The primary goal of Mission Moho is to determine the nature of the Moho by in situ sampling and data collection. The road to the Moho will be a long one. Progressively deeper and more technically challenging drillholes will probe and sample the ocean crust, examining the primal architecture of the ocean crust

and ultimately sampling Earth's uppermost mantle.

A clear consensus emerged at the end of the workshop that drilling a deep, full crustal penetration hole through fast-spread (high magma flux) crust, through the Moho and into the uppermost mantle, at a single site, is the community first priority, and that a future Mission Moho should be articulated around achieving this goal as soon as feasible. Only by drilling and sampling such a complete section we will be able to estimate the bulk composition of the crust, establish the chemical connections between the lavas erupted and melts coming from the mantle, test competing models of lower crustal magmatic accretion, understand the extent and intensity of hydrothermal exchange between the ocean crust and seawater, calibrate regional seismic measurements, understand the origin of magnetic anomalies, and make estimates of the chemical fluxes returned to the mantle by the subduction of oceanic lithosphere. With samples of the upper mantle we can define, at least in one place, the geological meaning of the Moho and address fundamental questions about the nature of melt migration in the mantle, mantle deformation, cooling rates of the lithosphere, and the composition of the uppermost mantle.

The workshop participants also recognized that the primary Mission Moho objective of full crustal penetration must be supplemented by studies of spatial and temporal variability if a comprehensive understanding of the formation of the ocean lithosphere is to be achieved. Sampling crust and upper mantle produced at low spreading rates (i.e., low magma flux), in order to at least partially address the variability of lithospheric architecture and potentially of the nature of the Moho, is also an important goal of Mission Moho. However, the extent to which current or planned drilling projects in slow-spread crust should be included in Mission Moho was not discussed. Criteria for inclusion of such projects will have to be defined by a mission proponent team. One particularly important mission objective is an assessment of the role of serpentinization in modifying the seismic signature of the crust and the transition to typical mantle velocities, because seismic studies are and will remain one of our primary tools for investigation of the subsurface over wide areas. The relationship between lithologic variability and subsurface seismic images can only be investigated by deep drilling one or more complete sections through non-layered, slow-spread crust.

Finally, the evolution of the oceanic crust, i.e., understanding the alteration, thermal, and fluid-flow history in the crust while recognized as a fundamental scientific goal for IODP, was not perceived as an essential element of Mission Moho.

Penetrating the entire ocean crust will require riser drilling technology. The world's only scientific riser drilling vessel "Chikyu" ("Earth" in Japanese; [www.jamstec.go.jp/chikyu/eng](http://www.jamstec.go.jp/chikyu/eng)) is currently undergoing System Integration Tests. Chikyu's first multiple platform IODP project involving both riser and riserless drilling is scheduled in the Nankai Trough beginning in September 2007. For eventual penetration of the oceanic fast-spread crust, a technically challenging,

phased modification of the riser from the current 2500-meter maximum depth to 4000-4500 meters will be required. The construction of such deep-water riser capability was recently included as one of five domestic science and technology high priorities by the Japanese Government. Even with this depth capability being available sometime after 2010, the journey to Moho will be long. The number of potential deep drilling sites, on fast-spread seafloor that is old enough, and therefore cold enough (>15 million years) but still shallow enough for riser capability is limited.

It is imperative that any site chosen for a deep penetration hole is thoroughly investigated and characterized geophysically, geologically, geochemically and petrologically. Boreholes are spatially limited, and they need to be understood in their broader context. Spatial context for ODP and IODP drillholes is primarily provided before and after drilling occurs through appropriate site surveys, and can be complemented by field studies in ophiolites, in particular the Oman ophiolite, and by drilling in tectonic windows (e.g., Hess Deep) that provide direct access to the lower crust and rocks that once formed the uppermost mantle. These windows of opportunity provide important short cuts to test models of lower crustal accretion, hydrothermal alteration and physical properties. The knowledge

gained will enable model refinements and better experimental designs for progressively deeper penetration of intact oceanic crust.

IODP has recently established deep holes at two complementary sites. Hole U1309D (1415 m below sea floor) has recovered a complex series of gabbroic rocks from slow-spread Atlantic Ocean crust. Hole 1256D (1507 m below seafloor) has, for the first time, penetrated the entire pillow basalt and sheeted dike sequence in superfast-spread crust of the eastern Pacific Ocean, terminating in the transition between sheeted dikes and underlying gabbros. A lot of experience about drilling deep in the ocean crust was gained with these two holes, and with earlier deep ODP Holes 504B and 735B. Holes 1256D and U1309D remain open and will very likely be deepened in coming years. Site 1256 is a potential location for a deep penetration crustal hole and much can be learned from continued drilling at this site. At the same time, potential alternative sites need to be identified and evaluated before a final full crustal penetration site is selected. In the near term, riserless drilling should be used to penetrate the crust in Hole 1256D as deeply as possible, and to prepare a cased hole for subsequent riser drilling at the selected deep penetration site.

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## **INTERRIDGE OUTSTANDING STUDENT AWARD 2006**

This year's InterRidge outstanding student award went to Anna Cipriani, a PhD student at Columbia University (Lamont-Doherty Earth Observatory), for her presentation at the Polar Ridges Meeting and Workshop in Sestri Levante, Italy.

Here is a short description of how she came to this award for the presentation:

"From magma-engorged to magma starved "constipated" lithosphere: the mid atlantic ridge from 40°N to the equator" (A. Cipriani, D. Brunelli, M. Ligi and E. Bonatti)



Since an early age I have been fascinated with rocks, fossils, and minerals. Therefore, at the end of high school I enrolled at the University of Padua (Italy) to study Geology. Early in my undergraduate years, I developed a strong interest in learning about the structure of mid-ocean ridges and the formation of the oceanic basins. Since 1996, I have participated to a number of major marine geology/geophysics expeditions in the central Atlantic, in the Peri-Antarctic Ocean and in the Red Sea, including an ODP leg. I will defend my PhD thesis next week ("Pulsating generation of the oceanic lithosphere and isotopic fingerprints of its mantle source"). During my thesis research at Columbia University (Lamont-Doherty Earth Observatory), I have been investigating the variations through time of the processes of creation of lithosphere at a single ridge segment, by studying a section of oceanic lithosphere exposed near the Vema Transform (Central Atlantic). I have been particularly interested in understanding the genetic relationship between the peridotitic upper mantle and the basaltic oceanic crust through Sr, Nd and Pb isotope systematics. In particular, there is much debate about whether source composition is a strong control on the degree of mantle melting or, instead, that source enrichment is correlated with relatively high mantle temperature. Resolving the question of whether source composition or temperature is more important, will give earth scientists a more fundamental understanding of the genesis of mid-ocean ridge basalts worldwide. After my defense, I will continue to work at LDEO as a Post-