

The MoHole: A Crustal Journey and Mantle Quest, Workshop in Kanazawa, Japan, 3–5 June 2010

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Introduction

Drilling an ultra-deep hole in an intact portion of oceanic lithosphere, through the crust to the Mohorovičić discontinuity (the ‘Moho’), and into the uppermost mantle is a long-standing ambition of scientific ocean drilling (Bascom, 1961; Shor, 1985; Ildefonse et al., 2007). It remains essential to answer fundamental questions about the dynamics of the Earth and global elemental cycles. The global system of mid-ocean ridges and the new oceanic lithosphere formed at these spreading centers are the principal pathways for energy and mass exchange between the Earth’s interior, hydrosphere, and biosphere. Bio-geochemical reactions between the oceans and oceanic crust continue from ridge to subduction zone, and the physical and chemical changes to the ocean lithosphere provide inventories of these thermal, chemical, and biological exchanges.

The 2010 MoHole workshop in Kanazawa, Japan followed from several recent scientific planning meetings on ocean lithosphere drilling, in particular the Mission Moho Workshop in 2006 (Christie et al., 2006; Ildefonse et al., 2007) and the “Melting, Magma, Fluids and Life” meeting in 2009 (Teagle et al., 2009). Those previous meetings reached a consensus that a deep hole through a complete section of fast-spread ocean crust is a renewed priority for the ocean lithosphere community. The scientific rationale for drilling a MoHole in fast-spread crust was developed in the workshop reports (available online) and most thoroughly articulated in the 2007 IODP Mission Moho drilling proposal (IODP Prop 719MP; www.missionmoho.org).

The 2010 MoHole workshop had two interconnected objectives, which have been discussed jointly between ocean lithosphere specialists, marine geophysicists, and engineers:

- to initiate a roadmap for technology development and the project implementation plan that are necessary to achieve the deep drilling objectives of the MoHole project,
- to identify potential MoHole sites in the Pacific (i.e., in fast-spread crust), where the scientific community will focus geophysical site survey efforts over the next few years.

Selecting drilling sites is essential to identify the range of water depths, drilling target depths, and temperatures that we anticipate, and to better define the technology required to be developed and implemented to drill, sample, and geophysically log the MoHole.

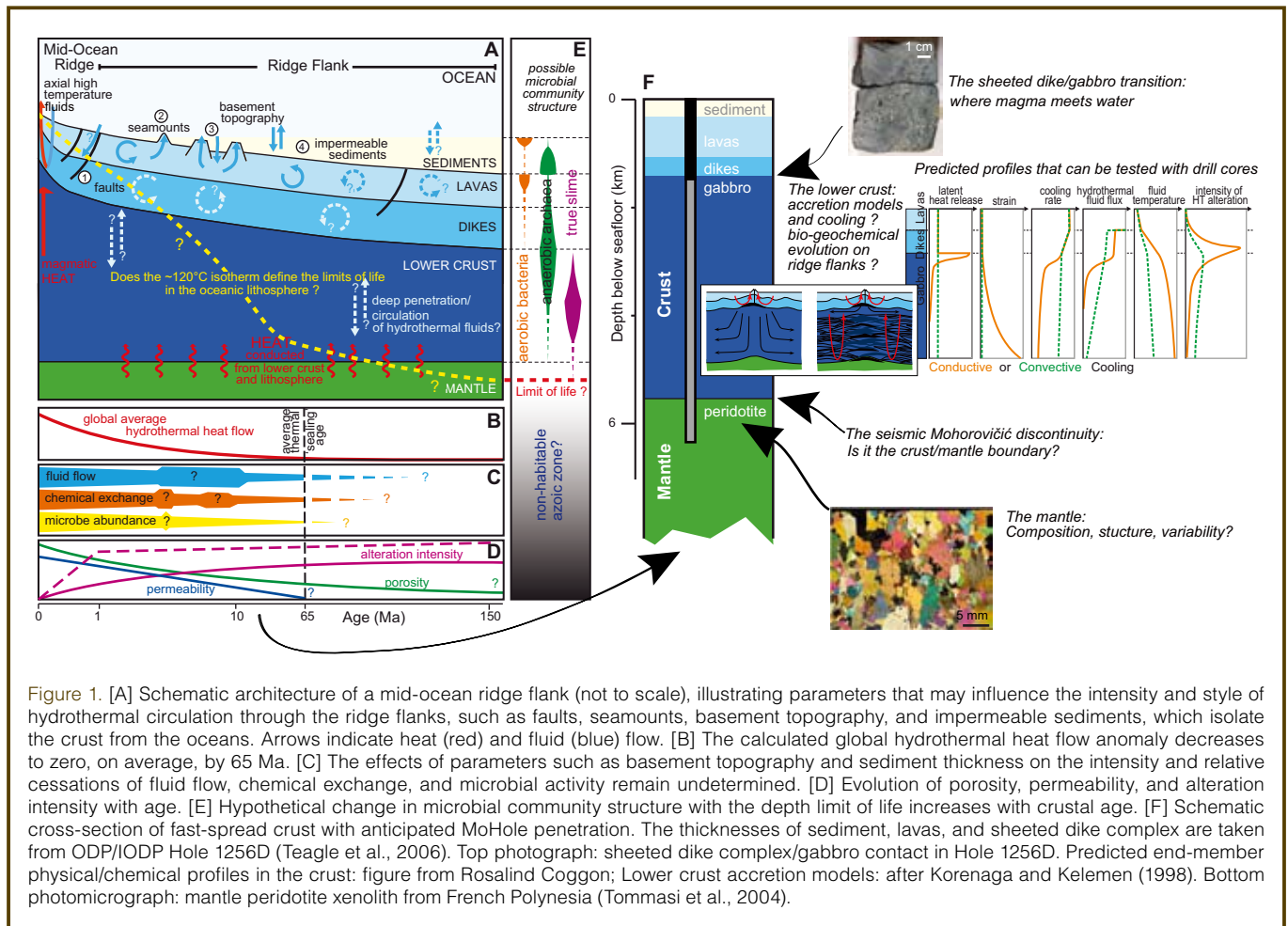
A Brief Summary of the Scientific Rationale for the MoHole

The Moho is the fundamental seismic boundary within the upper part of our planet, yet we have little knowledge of its geological meaning. New deep drilling technology now make it possible to fulfill scientists’ long-term aspirations to drill completely through intact oceanic crust, through the seismically defined Moho and then a significant distance (~500 m) into the upper mantle. Our scientific goals (Fig. 1; Christie et al., 2006; Ildefonse et al., 2007; Teagle et al., 2009) can be divided into the following principal tightly interconnected threads.

- What physical properties cause the Mohorovičić discontinuity, and what is the geological nature of this boundary zone?
- How is the (lower) oceanic crust formed at the mid-ocean ridges, and what processes influence its subsequent evolution? What are the geophysical signatures of these magmatic, tectonic, hydrothermal, biogeochemical, and chemical processes?
- What can we infer about the global composition of the oceanic crust, and what are the magnitudes of interactions with the oceans and biology and their influence on global chemical cycles?
- What are the limits of life, and the factors controlling these limits? How do the biological community compositions change with depth and the evolving physical and chemical environments through the oceanic crust?
- What is the physical and chemical nature of the uppermost mantle, and how does it relate to the overlying magmatic crust?

The Mohorovičić Discontinuity

In the oceans, the Moho is commonly a bright seismic reflector at 5–8 km depth, marking a step change to seismic



P-wave velocities (V_p) in excess of 8 km s^{-1} . It is generally assumed that the Moho also represents the boundary between mafic igneous rocks (crystallized from magmas that form the crust) and residual peridotites of the upper mantle. However, this interpretation has never been tested, and there are geologically valid scenarios where the Moho might delineate the boundary between mafic and ultramafic cumulate rocks within the crust, or exist below serpentinized peridotites that were previously part of the mantle. Observations and sampling of the Moho, the petrological crust-mantle boundary, and the rocks of the upper mantle are fundamental to understanding the geodynamics and chemical differentiation of our planet. A foremost goal is to reconcile geophysical imaging of the Moho with direct geological observations of cores and downhole measurements (e.g., is the Moho in our study region a sharp compositional boundary or a transition zone of significant thickness?).

Formation of the Lower Crust

On the road to the Moho, we will make paradigm-testing observations of the lower oceanic crust and the deep magmatic, tectonic, and hydrothermal processes that occur at the mid-ocean ridges (Fig. 1). Our principal target will be intact ocean crust formed at a fast-spreading ridge, which should be relatively laterally uniform, and where we have

well-developed theoretical models of crustal accretion that can be tested by drilling. Is the lower oceanic crust formed from the subsidence of a high-level magma chamber, or are there multiple melt bodies at different levels within the oceanic crust (or upper mantle) at fast-spreading ridges?

Magnetic stripes document the history of ocean crust formation and are the very basis of plate tectonic theory, yet we have little information on what contribution the lower crust has to this fundamental signature. Similarly, seismic profiling remains the key tool for investigating the deep crust, but these regional scale measurements have never been calibrated against core or *in situ* measurements. It remains challenging to confidently develop geological interpretations from geophysical measurement of the oceanic crust.

Composition and Hydration of the Ocean Crust

A full penetration will provide the first direct estimate of the bulk composition of ocean crust critical for Earth differentiation models. How deeply do seawater-derived hydrothermal fluids penetrate, and how efficient is hydrothermal circulation at heat extraction and chemical alteration (Fig. 1)? Is fluid flow channeled by major faults, or is it more perva-

sive? The knowledge of modes of penetration of the hydrothermal fluids, and of the extent of their interactions with the lithosphere, is required to estimate chemical exchanges with the oceans, as well as to assess the volume and composition of materials transferred to the mantle via subduction.

Limits and Controlling Factors of Life

Understanding the limits of life (Fig. 1), and the factors controlling these limits, is one of the most fundamental goals of geo- and biosciences essential for understanding the origin, evolution, distribution, and future of life on Earth as well as celestial bodies. To date, the limits of life even on our own planet remain poorly defined. The MoHole project provides a unique opportunity to address these limits in the oceanic lithosphere that covers ~60% of our planet. Numerous factors may control the limits of life, such as temperature, water activity, salinity, pH, and energy and carbon sources. Among these, temperature plays a key role, because organisms cannot survive beyond as yet a poorly known temperature threshold (~110–120°C?). The ability of seawater to penetrate into the deep crust or mantle and be available for microorganisms (e.g., minimum pore space) will also have a strong impact on the distribution of living organisms.

Physical and Chemical Nature of the Upper Mantle

Direct observations of the mantle will document how magmas are focused from a broad melting region to a narrow zone of crustal accretion beneath mid-ocean ridges. Measurements across the Moho will quantify the tectonic coupling between the crust and mantle. We presently have little knowledge of the composition and physical state of *in situ* convecting mantle at the ridge axis. A few kilograms of fresh residual peridotite from beneath intact oceanic crust would provide a wealth of new information comparable to the treasure trove obtained from the Apollo lunar samples.

Geophysical Characteristics of the Mohole Project Area

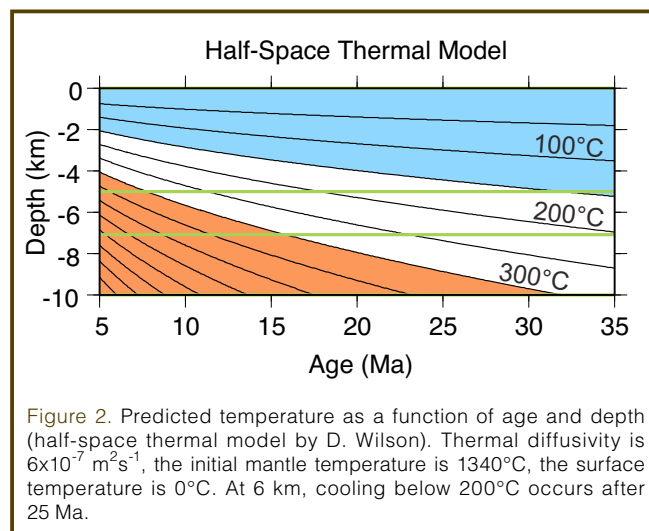
The criteria for best possible deep crustal penetration sites were reformulated during this workshop. The selected target would ideally meet all of the following scientific requirements:

- Crust formed at fast-spreading rate (>40 mm yr⁻¹ half rate).
- Simple tectonic setting with very low-relief seafloor and smooth basement relief; away from fracture zones, propagator pseudo-faults, relict overlapping spreading basins, seamounts, or other indicators of late-stage intraplate volcanism. Connection to the host plate active constructive and destructive boundaries would provide important scientific information.

- Crustal seismic velocity structure should not be anomalous relative to current understanding of “normal” fast-spread Pacific crust, indicative of layered structure.
- A sharp, strong, single-reflection Moho imaged with Multi-Channel Seismic (MCS) techniques.
- A strong wide-angle Moho reflection (PmP), as observed in seismic refraction data, with distinct and clearly identifiable sub-Moho refractions (Pn).
- A clear upper mantle seismic anisotropy.
- A crust formed at an original latitude greater than ±15°.
- A location with relatively high upper crustal seismic velocities indicative of massive volcanic formations to enable the initiation of a deep drill hole.

Satisfying requirements for points a–e is essential for success. More flexibility is allowed in meeting points f–h, which are highly desirable but not essential. Several technological constraints limit the range of potential sites:

- Technology for re-circulating drilling mud (riser or alternative; see next section) is currently untested at water depths greater than 3000 m.
- Prior scientific ocean drilling experience is mostly limited to temperatures less than 200°C. Temperatures higher than ~250°C will may limit choices of drill bits and logging tools, may decrease core recovery, and may increase risk of hole failure, or require substantial re-design of drilling equipment. Based on plate cooling models, crust older than ~15–20 Ma should meet this requirement at Moho depths (Fig. 2).
- Thickness of the crustal section above Moho must be at least a few hundred meters less than the maximum penetration/logging/recovery depth of the drilling system to allow significant penetration in mantle peridotites.
- Target area should be in a region with good weather conditions at least eight months out of the year, with calm seas and gentle ocean bottom currents.



- Sediment thickness should be greater than 50 m to support possible riser hardware and other seafloor infrastructure (re-entry cones/uppermost casing strings).
- Targeted area should be close (less than ~1000 km) to major port facilities for logistical practicalities.

Potential Sites

Based on the scientific requirements and technological constraints described above, the workshop participants focused discussions on three areas in the Pacific Basin: Cocos Plate, off Southern and Baja California, and off Hawaii (Table 1; Fig. 3). One of the most important issues to take into consideration is the trade-off between seafloor depth and temperature at Moho depths. Most ocean seafloor subsides below 4000 m by ~25 Ma, whereas at Moho depths of 5–7 km temperatures of 200°C or less are expected for crustal ages of 17–35 Ma (Fig. 2). The respective advantages and disadvantages of the three selected areas are listed in the full workshop report (available online at <http://campaign.iodp.org/MoHole/>).

The *Cocos Plate region* (Site 1256 area, Fig. 3A) encompasses a section of the Cocos Plate off Central America (from Guatemala to northern Costa Rica) with lithospheric ages between 15 Ma and 25 Ma. At its western limit on 15-Ma crust, this area includes the Ocean Drilling Program (ODP) Hole 1256D (Wilson et al., 2006; Teagle et al., 2006), a site of ongoing Integrated Ocean Drilling Program (IODP) deep

drilling into intact ocean crust. MCS (Hallenborg et al., 2003; Wilson et al., 2003) and wide-angle ocean bottom seismometer (OBS) data exist for the 15–17 Ma area in the vicinity of Site 1256. This region sits in superfast crust (half-spreading rate 110 m yr⁻¹), within a corridor that includes a complete tectonic plate life cycle, making it an excellent candidate for understanding ocean crust evolution from a spreading center to subduction. Structure of the crust within this area can be directly related to processes occurring at the modern East Pacific Rise and the Central American subduction zone.

The *off Southern/Baja California region* (Fig. 3B) encompasses a section of the eastern Pacific Plate at ~20°–33°N and ~130°–118°W. Crustal ages are ~20–35 Ma. Very little

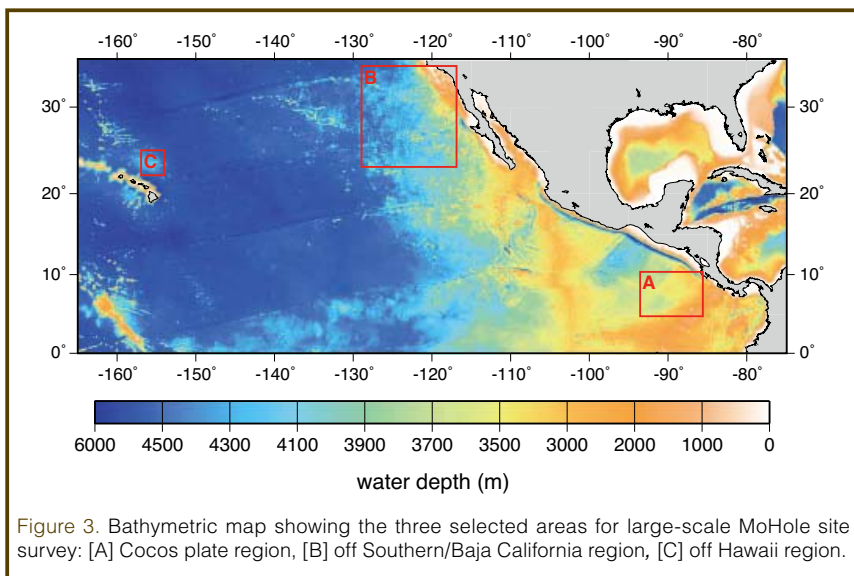


Figure 3. Bathymetric map showing the three selected areas for large-scale MoHole site survey: [A] Cocos plate region, [B] off Southern/Baja California region, [C] off Hawaii region.

Table 1. Principal characteristics of possible candidate sites for the MoHole project.

Candidate Site	Location	Half-Spreading Rate (mm yr ⁻¹)	Crustal Age (Ma)	Inferred Moho-T (°C)	Water Depth (m)	Sediment Thickness (m)	Crustal Thickness (km)	Total Length to the Moho (km)	Original Latitude
Cocos (Site 1256)	6.7°N, 91.9°W	110	15	>250	3646	250	5.5	8.7–9.2	Near equator
Cocos (Site 844)	8°N, 90.5°W	100	17	>250	3414	290	5.5?	8.7–9.2?	Near equator
Cocos	8.7°N, 89.5°W	100	19	~250	~3400	~300	5.5?	8.7–9.2?	Near equator
off S/Baja California (Deep Tow Site)	31°–33°N, 125°–127°W	60	30–27	<200	4300–4500	~100	~5.5?	~10?	~30–33
off S/Baja California	28°–29°N, 123°–125°W	50	27–22	~200	4200–4400	~100	?	?	~28
off S/Baja California	25°–26°N, 120°–122°W	60	27–22	~200	3900–4300	~80	?	?	~30
off S/Baja California	30.5°–31°N, 121°W	45	20–22	~250	2700–4100	~130	?	?	~25
Hawaii	22.9°–23.7°N, 154.9°–155.8°W	35–40	79–81	~150	4050–4300	~200	~6?	10–10.5?	Near equator
Hawaii	23.5°–23.9°W, 154.5°–154.8°W	35–40	78	~150	4300–4500	~200	~6?	10–10.5?	Near equator

modern geophysical information exists from this region. The best-studied area is in the northernmost part off San Diego, the “Deep Tow” site at $32^{\circ}25'N$, $125^{\circ}45'W$ (31–32 Ma; Luyendyk, 1970). Historical data there include deep-tow sidescan and bathymetry, 3.5 kHz profiler, magnetics, and single-channel seismics.

The *off Hawaii region* is located north of Oahu in the flexural arch, where water depths are 4000–4300 m. The crust is ~80 Ma and was formed at an intermediate half-spreading rate of 35–40 mm yr⁻¹. This site offers the lowest temperature at Moho depth (~100°C–150°C), but crustal structure is potentially affected by hotspot volcanism (underplating and/or crustal intrusions), and its significantly older age makes it difficult to relate geochemical changes to modern ocean chemistry or conditions.

Geophysical Surveys: Finding the Right Project Area

The existing geophysical data at all potential sites are not sufficient to identify a clear MoHole Project target area. Consensus at the workshop was that the priority of the community should be directed toward conducting large-scale seismic surveys in the three selected regions, which will lead to the identification of a MoHole target that best satisfies the requirements stated above. These surveys should collect spatially coincident MCS data, wide-angle OBS data, multi-beam bathymetry and gravity. Heat flow and magnetic anomaly data will be useful and should be collected. The characteristics of the required seismic surveys are listed in the full workshop report. JAMSTEC will dedicate three months of science ship time in 2011 for large-scale surveys. There was a consensus that the first survey should be in the off Southern/Baja California region, because so little is known in this area (where depth/age/logistical criteria are viable). Baseline reconnaissance seismic data are urgently required to assess whether this area can possibly meet the scientific requirements. Two additional factors contributed to the choice of this region as short-term priority for initial reconnaissance: crustal ages are greater than near Site 1256 (so temperatures are expected to be cooler), and the existing data suggest that Moho in the Site 1256 area may not be associated with a simple, continuous, strong reflector.

After an appropriate drilling target has been identified, the community should conduct detailed seismic surveys in the vicinity of the specific target, including 3-D multi-streamer MCS and OBS surveys for accurate and geometrically correct imaging of intracrustal reflectors (faults, sills, etc.) and Moho, and to assess crustal structure and thickness variability, and upper mantle velocity structure/anisotropy.

The scope and costs of the surveys required for this project are too large to be undertaken by a single nation or funding agency, hence international collaboration is essential.

Technology Development and Operations

The MoHole initiative is arguably at the point where the framework for the operations can be constructed, since the technology to drill such a hole exists or at least has been shown to be feasible. The technology selection and required engineering development will be key components for the success of the MoHole project. It is important to identify potential issues in drilling and coring engineering from the past and ongoing ocean drilling expeditions, and to find solutions to overcome the problems encountered. The engineering efforts must be directed to ensure that the scientific goals of the MoHole project are achieved. Technology selection process and planning for the key engineering developments should be launched as soon as possible in conjunction with site-survey efforts. To do so, establishing a realistic road-map, which includes project scoping, development and testing elements all controlled by proper project management, is imperative. All MoHole target sites are located in ultra-deep water of ~4000-m water depth or beyond, and the drilling depth to achieve the MoHole objectives is estimated to extend more than 6000 m below the seafloor. To drill such an ultra-deep borehole, the provision for continuous mud circulation is a top priority technology requirement. Other major areas requiring engineering consideration include logging and coring in high temperature environment, drill bits (specifically designed for abrasive, hard rocks) and drill string (high tensile strength), drilling mud (developed for high temperature environment), and casing/cementing materials and strategies (specifically designed, ideally to the bottom of the hole).

A promising candidate technology for drilling the MoHole is riser drilling, which provides a conduit for the mud to be returned to the vessel for cleaning, evaluation, and recirculation. The D/V *Chikyu* is currently equipped with a deep riser system with a maximum rated water depth of 2500 m. Significant engineering development is required to prepare the D/V *Chikyu* for riser service in water depths ≥ 4000 m. In addition to riser drilling, several other technologies are being considered to drill safely and efficiently to the target depth, including Surface Blow Out Preventer (BOP) with slim riser pipe (casing pipe) and Shut In Device (SID), or Riserless Mud Recovery (RMR; Myers, 2008) with mud circulation pump and mud return line. The lithologies intersected by the borehole drilled to Moho depths are unequivocally expected to be free from overpressures, hydrocarbons, or other geohazards. However, future regulatory changes may require the use of blow-out prevention in mud circulation systems. Hence, although a BOP will likely not be needed for well control, the use of a BOP will be considered by the MoHole planning group.

Drilling the MoHole will be a challenging enterprise requiring years of detailed preparation, planning, and engineering. Operationally, major challenges will be associated

with collecting the cored material, making the *in situ* measurements, installing casing, and keeping the borehole open for successive episodes of deepening in a multiyear, multiphase operation. To gear up for the operations, all issues related to drilling, casing, coring, and logging must be adequately explored and included in a comprehensive and complete operation plan, as soon as the site characteristics are known. Key elements of the drilling/coring/downhole measurements were listed during the workshop (see full workshop report). The well design of the primary site may

require data from a pilot hole, to properly evaluate parameters such as mud weights and casing set points. A pilot hole may be either a separate hole or simply a pilot section of the main hole. Drilling engineering data from a pilot section will be critical in managing the pressure, temperatures, and stress within the borehole.

After completion of drilling, coring, and borehole logging, the MoHole should be used for further experiments, including vertical seismic profiles (VSP), and long-term monitoring. Given the extreme borehole depth to be drilled, at least two offset VSPs are ideally required, one at the estimated halfway point of the well and perhaps one at final depth. Instrumenting the MoHole will eventually become a key, second-stage goal. Hence, the sub-sea equipment and borehole must be constructed to accommodate observatory science (e.g., fluid monitoring, microbiology incubation experiments). This implies ROV access to the wellhead and the ability to access the borehole through a BOP or SID.

Keys for Success

The keys for a successful MoHole project, as identified during the workshop, include scientific (essentially sampling strategy) considerations, as well as technology development, industry engagement, and public engagement through outreach activities and education. The MoHole project will be one of the largest scientific endeavors in Earth science history, and this challenge should provide precious opportunities to a diversity of scientists, engineers and technologists. One of the keys to success will be the sharing of the opportunities and achievements across a broad spectrum of Earth and life scientists.

The size and duration (ten years or more) of the MoHole project will require an appropriately supported, centralized science operations and engineering management group to oversee the successful initiation and completion of the project. This international group will be key to success and should be created as early as feasible. The envisioned, ideal timeline for the MoHole project is to complete prospective 2-D site survey (including data analysis) in ~2014, choose the MoHole site and conduct 3-D site survey in ~2015, start preparing operations in ~2015-2016, start drilling in ~2018, and reach the mantle in ~2022.

Scientific Coring, Sampling, and Measurements

Many of our primary scientific goals will require continuous core samples. To be regarded as successful, the MoHole project must at least return the following (see also Fig. 4):

- Continuous core, including samples of all boundaries, across the region identified by seismic imaging as the Moho, and the lithologic transition from cumulate

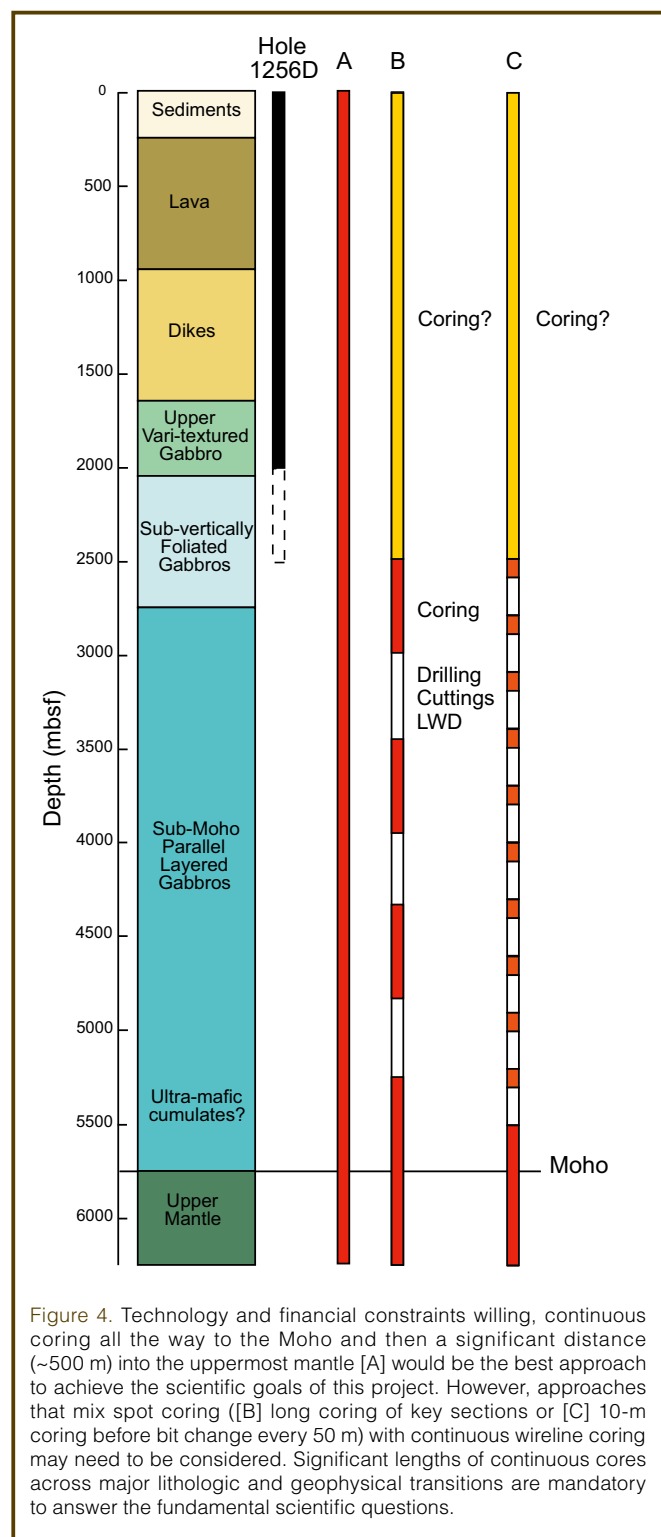


Figure 4. Technology and financial constraints willing, continuous coring all the way to the Moho and then a significant distance (~500 m) into the uppermost mantle [A] would be the best approach to achieve the scientific goals of this project. However, approaches that mix spot coring ([B]) long coring of key sections or [C] 10-m coring before bit change every 50 m) with continuous wireline coring may need to be considered. Significant lengths of continuous cores across major lithologic and geophysical transitions are mandatory to answer the fundamental scientific questions.

magmatic rocks to residual peridotites (these may or may not be the same target)

- Continuous coring of the lower 500 m of the mafic and ultramafic cumulate rocks in the oceanic crust
- Continuous coring of 500 m of peridotites and associated lithologies in the uppermost mantle below the Moho
- Sufficient cores from intervals of the lower oceanic crust to test models of crustal accretion and melt movement, to resolve the geometry and intensity of hydrothermal circulation, and to document the limits and activity of the deep microbial biosphere
- A continuous, comprehensive suite of geophysical logs (wireline, Logging While Drilling/Coring) and borehole experiments to measure *in situ* physical properties, to acquire borehole images, and to identify key geophysical and lithologic regions and transitions (e.g., Layer 2-3 boundary, the Moho) throughout the ocean crust and into the upper mantle.

Due to the expected relatively coarse grain size of the rocks to be encountered in the MoHole and the fine scales of expected lithologic/geochemical variation, it is anticipated that lithological records provided by mud/chip logging will be insufficient to address the scientific questions posed. However, a continuous series of mud, cuttings, and gas logs will provide useful supplementary information in areas of poor or no core recovery, and should be routine throughout the experiment. In addition to sampling and analyzing rocks, measurements of temperature and chemical compositions of fluids are required, together with biological analyses such as cell counting and DNA/RNA analyses.

Drilling Technology and Industry Engagement

Technologies that are applicable to the MoHole project are now being developed within the oil and gas industry. These were presented at the workshop by industry representatives. Conversely, some of the required technologies are very specific to scientific drilling, such as logging and coring at high temperatures (e.g., the IDDP project, Skinner et al., 2010) or drilling the hard crustal and mantle rocks. Development of such technologies will be a primary key for success, but to achieve this it may be necessary to complement IODP financial support with external funding.

As the oil and gas industry conducts operations in increasingly deep water, important keys for success will be continuous collaboration with industry and introduction of new technologies to the MoHole project where applicable. It will be necessary to establish a strategy to engage the industry in the project, exchange personnel, and plan joint development work. This can occur at several levels, including i) continuing *ad hoc* collaboration, through inviting oil and gas industry representatives to participate in planning activities and community workshops, ii) contracting services

from planning to execution, and iii) participation of engineers and scientists engaged in the MoHole project to industry workshops, symposiums, and technology development forums.

Public Engagement, Outreach, and Education

Another key component of the success of a Mohole project will be to improve public support and understanding of the scientific goals and excitement of the project. Engaging the public through outreach and education activities, as well as being pro-active in advertising the project to the wider scientific community and engaging new groups of scientists, should be integral parts of the activities carried out by the MoHole project scoping group, under the umbrella of IODP and future international collaboration for scientific ocean drilling. One tool to be implemented rapidly, as soon as scoping activities commence, is a dedicated, dynamic and engaging MoHole web page.

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