Received 25 March 2012

IODP Proposal Cover Sheet

805-MDP

☒ **New** ☐ **Revised** ☐ **Addendum**

Please fill out information in all gray boxes

Above For Official Use Only

Please check if this is Mission proposal ☐

Title:	MoHole to Mantle (M2M)		
Proponent(s):	Susumu Umino, Benoît Ildefonse, Peter B. Kelemen, Shuichi Kodaira, Katsuyoshi Michibayashi, Tomoaki Moroshita, Damon A.H. Teagle, and the MoHole proponents (full list inserted after the reference list)		
Keywords: *(5 or less)*	Mantle, Moho, oceanic lithosphere, oceanic crust, Mid-Ocean Ridge processes, hydrothermal cooling, carbon cycle, ultradeep drilling	Area:	Central/East Pacific

Contact Information:

Contact Person:	Katsuyoshi Michibayashi		
Department:	Institute of Geosciences		
Organization:	Shizuoka University		
Address	Ohya 836, Suruga-ku, Shizuoka, 422-8529, Japan		
Tel.:	+81 542384788	Fax:	+81 542380491
E-mail:	sekmich@ipc.shizuoka.ac.jp		

Permission to post abstract on IODP Web site: ■ Yes ☐ No

Abstract: (*400 words or less*)

The M2M project will sample for the first time upper mantle peridotites that in the near geological past resided in the convecting mantle, and recently (~20 to 100 Myrs) underwent partial melting at a fast-spreading mid-ocean ridge. This will be achieved by drilling through intact fast-spread oceanic crust, and ~500m into the mantle lithosphere. This first in-situ sampling of fresh upper mantle rocks will provide hitherto unattainable information on the chemical and isotopic composition (including fluid mobile elements K, U, C, S, H_2O, noble gases), physico-chemical conditions (e.g., fO_2, fS), seismic velocities and magnetic signatures, physical properties deformation and rheology, and the scales of chemical and physical heterogeneity of the uppermost mantle. This information is essential to understand the formation and evolution of Earth, its internal heat budget, planetary differentiation and reservoir mixing by mantle convection, mantle melting, and melt focusing and transport at mid-ocean ridges.

On the descent to the mantle, the ultradeep hole (MoHole) will sample fast spreading ocean crust, and make the first in situ observations of the geological nature of the Mohorovičić Discontinuity (Moho), the uppermost primary seismic boundary in the Earth, assumed to be the crust-mantle boundary. Fast spreading ocean crust is targeted because it exhibits relatively uniform bathymetry and seismic structure, and is the great majority of crust recycled back into the mantle by subduction during the past 200 Myrs. Sampling a section of intact oceanic crust will test models of magmatic accretion at mid-ocean ridges, quantify the geometry and vigor of hydrothermal cooling and geochemical exchanges with the oceans, identify the limits of life in the sub-seafloor biosphere and its functions, and ground-truth remote geophysical observations.

This proposal provides the scientific justification for drilling a >6000 m borehole to the mantle. The rationale has been developed by six workshops since 2006, and summarizes the scientific state-of-the-art, and the current vision for engineering and technology development, and operations. M2M directly addresses Challenges 6, 8, 9 and 10 of the 2013-2023 IODP Science Plan. A site for mantle drilling has yet to be selected, but three potential target regions await additional site surveys.

Drilling into the mantle will be the most ambitious undertaking ever achieved by the geoscience community and must engage the full spectrum of scientific expertise. Observations of pristine upper mantle will transform our understanding of the evolution of our planet and challenge the fundamental paradigms that are the foundations of Earth science.

Scientific Objectives: (*250 words or less*)

The M2M project echoes long-term goals of Earth scientists since the late 1950's, to understand the oceanic lithosphere. With a MoHole, we will address first-order questions about the composition and structure of the Earth's convecting mantle, the geological nature of the Moho, the formation and evolution of oceanic crust, and the deep limits of life. Specific objectives of M2M are to:

- Determine the in-situ composition, structure and physical properties of the uppermost mantle, and the physics and chemistry of mantle melting and melt migration processes,
- Determine the scales of physical and chemical heterogeneity of the uppermost mantle,
- Determine the geological meaning of the Moho in fast-spread lithosphere,
- Determine the bulk composition of the ocean crust to establish the relationship between lavas at the seafloor and the melts that separated from their mantle sources,
- Determine the mode of magmatic accretion at fast spreading ridges,
- Understand the extent and intensity of hydrothermal exchange between ocean crust and seawater, and estimate the chemical flux returned to the mantle by subduction,
- Determine the contribution of the lower ocean crust and upper mantle to global geochemical cycles, including carbon and water,
- Establish the limits, and controlling factors of life in the ocean lithosphere.
- Calibrate regional seismic measurements against core samples and borehole experiments, including long-term geophysical and microbiological monitoring,
- Understand the origin of marine magnetic anomalies and quantify the contribution of lower crustal rocks to the magnetic signature of the ocean crust.

Please describe below any non-standard measurements technology needed to achieve the proposed scientific objectives.

Continuous mud circulation (water depth > 3500 m); coring, logging, and fluid/gas sampling in a high temperature (≥ 200°C) environment; specialized drill bits for abrasive, hard, hot rocks; specialized drill string with high tensile strength; low weight, special drilling mud for use at high temperature; new casing and cementing materials and strategies; …

Proposed Sites:

Site Name	Position	Water Depth (m)	Penetration (m)			Brief Site-specific Objectives
			Sed	Bsm	Total	
Cocos Plate	6.7-8.7°N 89.5-91.9°W	3400-3650	250-300	>6000	>6000	
Off Southern/Baja California	20-33°N 120-127°W	Mostly 4000-4500	80-130	>6000	>6000	**MoHole site is yet to be determined, and other options may be considered**
NE Hawaiian Arch	22.9-23.9°N 154.5-155.8°W	4050-4500	~200	>6000	>6000	

MOHOLE TO THE MANTLE (M2M)

1. PRIMARY MOTIVATION FOR A MOHOLE TO THE MANTLE

This proposal presents the scientific justification for *in-situ* sampling and observations of the Earth's uppermost mantle by drilling an ultra-deep hole (MoHole) through intact oceanic crust formed at a fast spreading rate, penetrating the Mohorovičić Discontinuity (Moho), and hundreds of meters into fresh mantle peridotites. Target rocks include the uppermost oceanic mantle lithosphere that, in the past 20 to 100 Myr, was within the convecting mantle, and underwent partial melting at a mid-ocean ridge to form the overlying crust. Although deformed and recrystallized, these residual mantle peridotites have remained largely solid for more than 4 billion years. Thus the convective mantle (Fig. 1), fossilized in the oceanic lithosphere (Fig. 2), is intrinsically different from the igneous crust, crystallized from magma. During the descent to the upper mantle, the MoHole to the Mantle (M2M) project will provide hitherto unobtainable information on the magmatic accretion of the oceanic crust, the related frontier of deep seawater hydrothermal circulation, the limits of microbial life, and the first geological calibration of the Moho, the uppermost primary seismic boundary in our planet that separates the buoyant crust from the mantle.

To date, the elusive frontier at the Moho, and the enormous mantle domain beneath, have been symbolic, unattainable goals. However, with the riser-drilling vessel *Chikyu*, the aspirations of generations of Earth scientists to drill completely through the oceanic crust, and into the upper mantle, ~6 km below seafloor, have moved into the realm of technical feasibility.

1.1. Mantle composition and heterogeneity

The Mantle is the largest part of our differentiated planet, extending from the base of the crust (~5-70 km) to the outer core 2890 km below (Fig. 1). The Fe-Ni alloys that form the inner and outer core segregated from or passed through the mantle early in Earth's history (e.g., Rudge et al., 2010, Wood and Halliday, 2010; Wood, 2011). With the exception of late cosmic additions (e.g., Kimura et al., 1974; Chou, 1978), virtually all the materials that make up the oceanic and continental crust have been generated over the eons from the partial melting and degassing of the mantle through the dynamic interplay between the convecting mantle and the overlying tectonic plates.

The mantle regulates how the Earth looses its heat and how thermal energy is used to drive plate tectonics. How much of the heat released at the surface is primordial, produced in the mantle, or released from the core is an open debate (e.g., Korenaga, 2008). This question is directly tied to that of mantle heterogeneity. Chemical and isotopic measurements of ocean floor basalts have long been used as evidence for large-scale mantle heterogeneity. For example, ^{3}He anomalies suggest the preservation of primordial components within the mantle. However, there is no agreement on the nature and extent of compositional heterogeneity and its effect on mantle convection style (e.g., Nakagawa et al., 2004; Labrosse et al., 2007; Brandenburg et al. 2008; Simmons et al. 2009). The geochemical community was long satisfied by the concept of a well-mixed upper mantle depleted in crust-forming elements, and a deeper heterogeneous and more primitive lower mantle; textbook illustrations are commonly based on this view. However, while geochemical arguments (including new techniques; e.g., ^{142}Nd and ^{182}W anomalies), favor large-scale reservoirs that remain chemically isolated for long times, some possibly dating back to the formation of the Earth (e.g., Caro, 2011; Touboul et al., 2012), large-scale geophysical imaging (e.g., Kárason & van der Hilst, 2000; Ritsema et al., 2011; Fig. 1) and modeling provide strong evidence for a largely well-mixed mantle (summary in van Keken et al., 2002). Furthermore, the mechanisms for the addition of volatile elements to the Earth remain hotly debated (e.g., Albarède, 2009; Wood et al., 2010).

One of the principal reasons why the scale of mantle heterogeneity and the nature of mantle volatile contents are still debated is that we have no fresh, *in-situ* samples of the convecting mantle. This is not well known because peridotite samples are not rare. However, our mantle samples are limited to highly altered, tectonically exposed rocks on the seafloor, similarly altered peridotites in ophiolites (with an unknown genetic relationship to sub-oceanic mantle), xenoliths from the lithosphere (modified by host magmas), and continental peridotite massifs representative of material which has been long isolated from the convecting mantle. In addition to studies of these inadequate samples, the composition of the convecting mantle is estimated from the compositions of basaltic magmas, or inferred from cosmic abundances and assumptions regarding the partitioning of elements into the distant core. A few kilograms of fresh residual peridotite from beneath intact oceanic crust would provide a wealth of new information on the Earth's dynamics and evolution, comparable to the treasure trove obtained from the Apollo lunar samples. This is most apparent when considering the volatile element contents of the convecting mantle, which are completely obliterated by alteration processes in dredged abyssal peridotites, or by interaction with melt in xenoliths.

Water and carbon are two of the most important chemical species critical for life and the environment on Earth, but the contribution of the mantle, arguably the largest Earth's reservoir of these components, to the global water and carbon budgets remains totally unconstrained in the absence of samples (e.g., Hazen et al., 2012; Hirschmann and Kohlstedt, 2012). Water recycled into the mantle at subduction zones is hypothesized to reduce its viscosity, allowing continuous mantle convection and plate tectonics, providing the key reason why Earth is different from the other terrestrial planets in the solar system (e.g., Venus), and is an essential ingredient for the formation of arcs and continents. Primordial and surface derived carbon can form diamonds in the deep mantle, which may be brought back to the shallow mantle encapsulated in chrome spinel, as found in some ophiolites (Yang et al., 2007).

1.2. Mantle melting processes

Melt inclusions trapped in single minerals within extruded lavas show a remarkable variation in composition, suggesting a wide range of sources. Dredging of serpentinized peridotite at slow-spreading ridges provides hints of significant heterogeneity but the scale of these variations in isotopic composition remains unconstrained due to lack of context (e.g., Warren et al., 2009; Stracke et al., 2011), substantial alteration effects on key tracers such as $^{87}Sr/^{86}Sr$ and $^{3}He/^{4}He$ (e.g., Snow et al., 1994; Delacour et al., 2008), and complete resetting of stable sulfur, carbon, and oxygen isotope ratios (e.g., Barnes et al., 2009; Kelemen et al., 2011). To fully understand the processes that generate crust-forming magmas at mid-ocean ridges, we need to know the composition of the source mantle, together with the bulk composition of the overlying crust formed by these melts. Access to mantle material will also allow us to constrain models of partial melting, melt impregnation, and melt transport (e.g., how is it focused from a broad melting region to a narrow zone of crustal accretion beneath mid-ocean ridges?).

1.3. The Moho and the crust above it

The Moho is a seismically imaged, primary acoustic interface that represents the transition between the mantle and the overlying crust. Whereas oceanic crust is formed by a variety of igneous and metamorphic processes, and has a relatively low seismic velocity, the oceanic mantle is largely composed of residual peridotite with higher seismic velocity. However, questions about the relationship between the seismic boundary and the geological crust-mantle transition remain unanswered in the absence of *in-situ* samples. In addition to the mysteries surrounding the Moho, there are also major gaps in knowledge about the lower crust itself. How does it form, and how does it exchange heat and chemical components with seawater? The formation, evolution and recycling of oceanic lithosphere is the dominant process in the chemical differentiation and physical evolution of our planet. This process encompasses the transfer (from and to the Earth's mantle) of material (including water and CO_2) and energy, through interactions between the mantle and the crust, and between the crust, ocean, and atmosphere. Independent of sunlight, the evolving ocean crust supports life in unique subsurface and seafloor habitats that may resemble the conditions that enabled the origin of life. Upon its formation at mid-ocean ridges, the oceanic crust records geomagnetic field variability, providing the basis for geomagnetic polarity timescales, plate reconstructions, and estimates of plate motions.

2. Road to the Moho

Sampling a complete section of crust and shallow mantle was the original motivation for scientific ocean drilling. M2M will be the culmination of a decades-old quest by IODP, ODP and DSDP, since the "American Miscellaneous Society" first proposed "Project Mohole" in 1957 (e.g., Bascom, 1961; Crombie, 1964; Teagle and Ildefonse, 2011). The goal was and remains to understand the composition, structure, and evolution of the oceanic lithosphere through deep scientific drilling, as outlined in the IODP Science Plans for 2003-2013 and 2013-2023. This goal has been a core component of numerous planning documents since the inception of scientific ocean drilling (e.g., Murray et al., 2002; Teagle et al., 2004). The wide mantle dynamics, mid-ocean ridge and oceanic lithosphere community has discussed and articulated the scientific objectives and operational considerations presented herein via the IODP sponsored workshops "Mission Moho" (Portland, 2006; Christie et al., 2006; Ildefonse et al., 2007a), "Melting, Magma, Fluids and Life" (Southampton, 2009; Teagle et al., 2009), "INVEST" (Bremen, 2009; Bach et al., 2010; Ravelo et al., 2010), "The MoHole, A Crustal Journey and Mantle Quest" (Kanazawa, 2010; Ildefonse et al., 2010a, 2010b), and "Mantle Frontier" (Washington DC, 2010; Workshop Report Writing Group, 2011). A co-proponent meeting (mohole.org) was held in Tokyo in February 2012.

Since the early 70’s when the “Penrose” layered model for the ocean crust (Penrose Conference Participants, 1972) was widely accepted, investigations of the oceanic crust by scientific ocean drilling (Fig. 3), marine geological and geophysical techniques, complemented by ophiolite studies, have expanded our understanding of the architecture of the ocean crust (e.g., Teagle et al., 2004; Dick et al., 2006; Ildefonse et al., 2007b).

Away from transform faults, ocean crust formed at fast spreading rates exhibits relatively uniform bathymetry and seismic stratigraphy (e.g., Canales et al., 1998, 2003; Kodaira et al., 2010). At the ridge axis, continuous crustal seismic reflectors interpreted to be high level, axial melt lenses (e.g., Detrick et al., 1987) are imaged overlying axial low-velocity zones that extend down to sub-Moho levels (e.g., Harding et al., 1989; Sinton & Detrick, 1992; Dunn et al., 2000). This suggests that ocean crust formed at fast spreading rates (>80 mm/yr full rate) is layered and relatively homogeneous (Fig. 4). Although only 20% of modern ridges are fast-spreading, more than 50% of the present day seafloor (~30% of Earth's surface), and the great majority of crust subducted into the mantle during the past 200 Myr was produced at fast spreading ridges. Because of the relatively uniform architecture of fast-spread lithosphere, information at one drill site can be extrapolated to a significant portion of Earth's surface with some confidence. Importantly, we have well developed theoretical models of contrasting styles of magmatic accretion at intermediate to fast-spreading ridges, which can be tested using samples recovered from cored sections of ocean basement. Therefore, the goal of M2M is to sample, as continuously as feasible, the entire crust, Moho and shallow mantle, in oceanic lithosphere formed at a fast-spreading rate. Scientific and technological progress towards this goal will require additional site surveys, and effective scoping activity to organize the appropriate technical development and choices.

Ocean crust formed at slow to ultra-slow rates (<40 mm/yr) is heterogeneous, both along and across axis, particularly towards the end of ridge segments where the crust is composite (Fig. 4; e.g., Karson and Elthon, 1987; Dick, 1989; Cannat 1996; Canales et al., 2000; Ildefonse et al., 2007c; Blackman et al., 2011). The great variability of slow-spread lithosphere architecture is such that fully characterizing it is beyond the scope of this project. Tectonic windows through igneous crust to (altered) residual mantle peridotite are common at slow-spreading ridges, and these can be sampled using either conventional or riser technology. This has been done in the past, and will continue as a result of other, stand-alone drilling proposals.

3. Scientific Objectives

By drilling an intact section of ocean crust and upper mantle in fast-spread lithosphere, we will address first-order questions about the structure and composition of the Earth's convecting mantle, the nature of the Moho, and the formation and evolution of oceanic crust. Specific objectives include:

• Determine the *in-situ* composition, structure and physical properties of the uppermost mantle, and the physics and chemistry of mantle melting and melt migration processes,

• Determine the scales of physical and chemical heterogeneity within a ~500 meters long section of uppermost mantle,

• Determine the geological meaning of the Moho in fast-spread lithosphere,

• Determine the bulk, primary composition of ocean crust to establish the relationship between the lavas that erupt at the seafloor and the melts that separated from their mantle sources,

• Determine the mode of magmatic accretion at fast spreading mid-ocean ridges,

• Understand the extent and intensity of hydrothermal exchange between the ocean crust and seawater, and estimate the chemical flux returned to the mantle by subduction,

• Determine the contribution of the lower ocean crust and upper mantle to global geochemical cycles, including carbon and water,

• Establish the limits, and controlling factors of life in the ocean lithosphere.

• Calibrate regional seismic measurements against core samples and borehole experiments, including vertical seismic profiles, and long-term geophysical and microbiological monitoring,

• Understand the origin of marine magnetic anomalies and quantify the contribution of lower crustal rocks to the magnetic signature of the ocean crust.

Addressing these objectives requires sampling and logging in deep and so-far unexplored parts of the ocean lithosphere. Specific science questions and working hypotheses to be tested are summarized below.

3.1. Obtaining the first in-situ samples of Earth's mantle

Presently there are NO fresh samples of the convecting mantle, which comprises more than 98% of the mass and volume of the silicate Earth, and more than 68% of the mass of the entire planet, including the core. Xenoliths, brought to the surface in lavas, are (a) dominantly derived from old and stable continental lithosphere, rather than the recently convecting mantle (Fig. 2), and (b) modified by interaction with host lavas either in the source mantle, or during transportation (e.g., Demouchy et al., 2006). Mantle peridotites tectonically exhumed on the seafloor have undergone extensive hydrothermal alteration. As a result, hypotheses about oxygen fugacity, sulfide composition and proportion, CO_2, CH_4, graphite, H_2O, Li, B, He and other noble gas characteristics, and concentrations and isotopic ratios of "fluid mobile" elements such as Sr, in the mantle source of Mid-Ocean Ridge Basalts (MORB) are sustained largely by inferences and assertions. The residual mantle part of ocean lithosphere is directly derived from the convective mantle at the mid-ocean ridge axis (Fig. 2), and if sampled by deep drilling, will provide unique and invaluable information regarding the composition and structure of the Earth's interior.

Concentrations and isotope characteristics of volatile elements in Earth reservoirs are vital tracers for global chemical cycling and planetary evolution (e.g., Javoy, 1997; Marty, 2012). The volatile contents of pristine mantle are key information to better constrain the evolution of primitive Earth. Particularly interesting are the moderately volatile elements (S, Se, Te, …; Lorand et al., 2004; Lorand et Alard, 2010). They are basic components of the sulfides that also carry siderophile elements, which are used to quantitatively constrain the late veneer hypothesis (e.g., Kimura et al., 1974; Chou, 1978; Wanke and Gold, 1981; Albarède, 2009), but show a higher variability than previously thought (e.g., Alard et al., 2000). Other components, such as heat-producing elements U and Th, and geochemically similar Nb and La, may be concentrated on grain boundaries (Niu, 2004; Hiraga et al., 2004, 2007).

The nature and length scale of heterogeneity in the mantle source of MORBs are controversial because mantle source characteristics are largely inferred from lava compositions, and/or altered abyssal peridotites (e.g., Alard et al., 2005). Drill core from fresh, oceanic upper mantle will place constraints on the extent and scale of spatial variation in Sr, Nd, Pb, Hf, and Os isotopic ratios, which has fundamental implications for the most basic structure of mantle convection, and the formation and fate of the crust (e.g., Harvey et al., 2006; Stracke et al., 2011; Salters et al., 2011).

Also critical is the determination of the amount and chemical/structural form of carbon (hydrocarbons, polymorphs of native carbon) present in the MORB the upper convective mantle (e.g., Workshop Report Writing Group, 2011; Hazen et al., 2012). The influence of deep carbon reservoirs and fluxes on energy, environment, and climate (e.g., Sleep and Zahnle, 2001) remains speculative without direct measurements from the mantle.

The following example illustrates the extent of the unknown, and the potential impact of new discoveries when we obtain fresh samples from the mantle beneath oceanic crust. Figure 5 illustrates the variability of CO_2, Nb and La concentrations in mid-ocean ridge samples. The CO_2 and Nb contents of lavas (Fig. 5a) indicate that they behave similarly during mantle melting and melt transport, as does La (not shown). Figure 5b shows the range of variability of Nb and La concentrations in dredged mantle samples. A small part of this variability is due to heterogeneity of the mantle source of MORBs. Most of the variation is due to refertilization of peridotites by cooling melt crystallizing in the shallow mantle on the flanks of oceanic spreading centers, which adds variable amounts of Nb and La to highly depleted residues of melting and melt extraction (e.g., Niu et al., 2004; Godard et al., 2000, 2008; Brunelli et al., 2006). Nb and La are essentially immobile during hydrothermal alteration, hence their concentrations record the magmatic processes of melt extraction and refertilization. Probably, CO_2 is also added during refertilization processes, for example as fluid inclusions in olivine and other minerals, along with dissolved H within minerals, noble gases in fluid inclusions, S in sulfides, and other volatile elements. However, because dredged samples are highly altered due to hydrothermal interaction with seawater, the record of volatile element refertilization of the shallow mantle is not preserved in these samples. Therefore, drilling fresh mantle peridotite beneath intact Pacific ocean crust is essential to obtain unaltered samples of refertilized, residual mantle peridotites. Based on the Nb and La data shown in Figure 5b, together with the correlation of Nb and CO_2 in Figure 5a, there could be tens of ppm CO_2 in fresh, refertilized shallow mantle samples. If, for the sake of argument, there is a refertilized layer in residual oceanic, extending for 10 km beneath the base of the crust, and this layer contains 10 ppm CO_2, the resulting reservoir would contain ~100 trillion tons of CO_2, approximately the same mass as all the CO_2 in the ocean and atmosphere added together. How much CO_2 is actually present in the upper mantle beneath ocean crust? We simply do not know.

The grain size and microstructures of unaltered, *in-situ* residual mantle also remains unknown, although they are essential for understanding mantle seismic velocity (e.g., Faul and Jackson, 2005; Behn et al., 2009) and anisotropy (e.g, Kodaira et al., 2010), melt transport in the mantle (e.g., Spiegelman and Kenyon, 1992), or deformation at decreasing temperature caused by corner flow beneath the ridge. Textural and microstructural information from the MoHole mantle samples, together with their geochemical composition, will provide fundamental constraints on the rheology of shallow lithosphere, and by extension, on the nature of the lithosphere-asthenosphere boundary.

One of the least constrained, fundamental problems in geodynamics is the focusing of mantle melt beneath spreading ridges. Melt is produced in tiny pores along grain boundaries (e.g., Zhu et al., 2011) within a region of the upper mantle extending to more than 100 km depth and laterally for 100's of km on either side of spreading ridges (e.g., Forsyth et al., 1998). How is this melt extracted and crystallized to form oceanic crust within a few km wide region, as seismically imaged along the East Pacific Rise (e.g., Dunn and Forsyth, 2003)? No consensus will emerge without the direct evidence that would be provided by drilling *in situ* upper mantle. For example, the upwelling path of partially molten mantle is modeled as either passive, plate-driven flow (e.g., McKenzie, 1967; Sleep, 1975) or active, buoyancy-driven flow (e.g., Rabinowicz et al., 1984; Buck and Su, 1989). Away from the ridge axis, both models predict flow trajectories nearly horizontal and approximately perpendicular to the ridge. However, active upwelling models predict that outward horizontal flow in the upper mantle is faster than plate velocity, resulting in an inversion of shear senses (recorded by olivine crystallographic preferred orientations) on a vertical section beneath the mantle-crust boundary, as has been mapped in the Oman ophiolite (e.g., Nicolas et al., 1994; Ildefonse et al., 1995, Michibayashi et al., 2000). If present, this shear sense inversion could be detected in drill cores if they are azimuthally oriented (e.g., using core-log integration techniques). Another possible indication of active flow would be ridge-ward dipping shear zones, one of the possible interpretations of ridge-ward lower crustal dipping reflectors documented in the northwest (Reston et al., 1999; Kodaira et al., 2010) and central (Eittreim et al., 1994) Pacific.

Equally important is to understand the transport of melt through the mantle peridotite. Transport may be by diffuse porous flow (e.g., Phipps Morgan, 1987; Spiegelman and McKenzie, 1987), by focused flow in high porosity dissolution channels marked by dunites (e.g., Kelemen et al., 1995, 1997a), by focused flow in high porosity decompaction channels overlain by a permeability barrier at the base of the cold, overlying lithosphere (e.g., Sparks and Parmentier, 1991; Rabinowicz and Ceuleneer, 2005), by focused flow in high porosity shear zones (e.g., Kelemen & Dick, 1995; Holtzman et al., 2003), via passive transport within low permeability, partially molten, buoyant diapirs (e.g., Rabinowicz et al., 1984; Buck and Su, 1989), and/or in fractures initiated as a result of overpressure in an interconnected column of buoyant melt overlain by a permeability barrier (e.g., Nicolas 1986). All of these processes form distinctive geological features, and should be evident in drill core sampling melt transport features in mantle peridotites below the Moho.

3.2. What is the geological meaning of the Moho and seismic layers in the crust?

Understanding the seismic structure of ocean lithosphere requires calibration of remotely obtained regional geophysical data against physical properties and petrological measurements of geological samples. There is a well-established terminology for seismic layering in fast-spread oceanic crust (Fig. 6). Layer 1 is locally absent, but present where sediment thickness exceeds a few tens of meters, and has Vp <3 km/s. Layer 2 is a band with a high gradient in Vp with depth, ranging from ~3-5 to ~6.7 km/s, and Layer 3 has nearly uniform Vp ranging from ~6.7 to ~7.1 km/s. The Layer 2/3 boundary is an inflection point, between seismic velocities that increase with depth through Layer 2 and nearly uniform seismic velocity through Layer 3. Below Layer 3, in typical Pacific seismic profiles, a sharp transition from ~7 to ~ 8 km/s occurs within <500 m. By analogy with ophiolites and sparse samples from the Pacific, these layers are commonly interpreted as pelagic sediment (Layer 1), lavas and fractured, sheeted dikes (Layer 2), intact, sheeted dikes and plutonic rocks (Layer 3), and residual mantle peridotite ± ultramafic plutonic rocks (below Layer 3).

In contrast to the classical interpretation of the Moho as the crust-mantle boundary, Hess (1960, 1962) posited that the Moho represents a serpentinization front, i.e., a boundary between fresh peridotite and serpentinite. Partially serpentinized peridotites can have densities and velocities very similar to (or even lower than) those of fresh gabbros (e.g., Horen et al., 1996; Carlson and Miller, 1997). At fast-spreading ridges, the depth to the Moho is nearly constant along flow lines, making the Hess hypothesis unlikely, as a serpentinization front would result in increasing Moho depth with age. The Moho is commonly sharp (Fig. 6), which is thought to indicate that it is a lithological contact between gabbro and ultramafic rock. However, the Moho may alternatively be more diffuse, with multiple reflectors (e.g., Nedimovic et al., 2005), which may account for a more complex transition zone between the mantle and the crust, such as seen in parts of the Oman ophiolite (e.g., Arai, 2009). Recent active source seismic data in the western Pacific (Kodaira et al., 2010) show high Vp (8.6 km/s) and strong anisotropy (7%) in the uppermost mantle immediately below sharply imaged Moho. However, Vp beneath the oceanic Moho is commonly slightly lower than predicted for unaltered peridotite (Shipboard scientific party, 2004). This could indicate ~10% serpentinization, small proportions of gabbroic lenses intruding residual peridotite, or the presence of ultramafic plutonic rocks below the Moho. Until we drill through the Moho beneath fast-spread crust, its petrophysical significance will remain unresolved.

Seismic velocities in the lower oceanic crust are systematically lower than predicted for gabbros (Korenaga et al., 2001; Behn and Kelemen, 2003). This could be related to the presence of cracks and/or alteration phases, and/or to our poor knowledge of lower crustal composition. Direct sampling of Layer 3 will resolve this issue, and restore our ability to interpret Layer 3 velocities in terms of geologically significant rock properties.

The only site where geological samples have been recovered from intact oceanic crust at the depth of the Layer 2/3 seismic boundary is DSDP Hole 504B, where the inflection in seismic velocity gradient occurs within the sheeted dikes (Detrick et al., 1994; Alt et al., 1996; Carlson, 2010) and appears to be controlled by alteration and/or the nature and density of cracks in the formation, rather than rock type or grain size. In ODP Hole 1256D, data suggest that the layer 2/3 transition has not been yet reached, but is close to the bottom of the hole (Carlson, 2010; Gilbert and Salisbury, 2011), even though the hole extends below the first appearance of gabbros at the base of the sheeted dikes (Teagle et al., 2006, 2012).

Recent high quality seismic surveys in the western Pacific using air-gun, multi-channel streamers, and ocean-bottom seismometers indicate some variability of the structure of ocean crust and uppermost mantle (Kodaira et al., 2010). The calibration of regional seismic measurements against core samples and borehole experiments at a single MoHole site will be essential to properly interpret spatial variations of seismic velocities and anisotropy, and/or style of Moho reflection. Hence, to fully connect laboratory-derived velocities of discrete samples and large-scale structures within the oceanic lithosphere, integration of seismic reflection/refraction and drilling data will require detailed wireline sonic logging coupled with vertical and multi-ship offset seismic experiments.

3.3. Bulk composition, and mode(s) of accretion of fast spread crust

Much of what we know about the composition and temperature of the upper mantle, and their global variability, comes from MORB chemistry, which is used to infer the composition of the primitive mantle melts (e.g., Klein and Langmuir, 1987, McKenzie and Bickle, 1988). The majority of MORBs have Mg# << 70 (where Mg# = 100 x Mg/(Mg + Fe) atomic ratio) whereas primitive melts in equilibrium with mantle peridotites should have Mg# ranging from ~70 to 78 (O'Hara, 1968; Langmuir et al., 1982). Thus, we know that melts undergo partial crystallization to produce primitive cumulates, with Mg# ≤ ~90 (equivalent to that of the mantle residues of MORB formation) before the remaining melt is extracted as MORB. On average, erupted MORBs record about 50% crystallization (e.g., Kelemen et al., 2007). Primitive cumulate rocks have only rarely been sampled in the oceans, whereas they should be at least as abundant as erupted lavas and sheeted dikes. They must comprise much of seismic Layer 3 in fast-spread crust, but their nature, hence the composition of unfractionated melts is undetermined in the absence of *in-situ* samples. Whether fractionation is solely responsible for MORB chemistry also remains unquantified. Recent results from fast- and slow-spreading ridges (e.g., Rubin and Sinton, 2007; Lissenberg and Dick, 2008; Suhr et al., 2008; Godard et al., 2009; Drouin et al., 2009, 2010) indicate that significant reactions can occur between melts and lower crustal cumulates or mantle rocks. The extent to which melt-rock interactions bias our current understanding of mantle melting processes cannot be assessed without studying the genetically conjugate source mantle rocks, cumulate rocks, and extrusive lavas.

The nature of the process to form plutonic rocks from subsurface crystallization of melt is hotly debated. Our understanding has been limited by the difficulties of geophysically imaging and directly sampling the gabbroic lower crust. Consequently, the nature of magma chambers beneath mid-ocean ridges and the formation of the lower crust are virtually unconstrained. How is melt transported from the mantle through the crust? Where do melts fractionate and crystallize? How, and how fast is heat extracted? These fundamental questions remain unresolved.

Multi-channel seismic (MCS) profiles across active intermediate and fast spreading ridges commonly reveal bright, low velocity reflectors ~1-2 km below the ridge axis, interpreted to be thin (20-100 m thick) axial magma lens (e.g., Morton and Sleep, 1985a; Detrick et al., 1987; Harding et al., 1989; Singh et al., 1998; Kent et al., 2000). Melt lenses have also been imaged within the lower crust and at Moho depth (Nedimovic et al., 2005; Canales et al., 2009, 2012), and there is ample geophysical evidence for melt accumulation at or near the Moho (e.g., Garmany, 1989; Dunn et al., 2000, 2001; Crawford and Webb, 2002; Singh et al., 2006). These observations, combined with geological and petrological evidence from the Oman ophiolite, have led to two competing models of lower crustal accretion at fast-spreading mid-ocean ridges:

1. All of the crystallization occurs in a shallow melt lens, and the accumulated crystal residues subside in a "gabbro-glacier" to build the lower crust (e.g., Henstock et al., 1993; Phipps Morgan and Chen, 1993; Quick and Denlinger, 1993; Fig. 7a).

2. Crystallization of lower crustal gabbros occurs partly (Boudier et al., 1996) or completely *in situ* (Kelemen et al., 1997b; MacLeod and Yaouancq, 2000) via injection of sills. In the end-member "sheeted sill" model (Kelemen et al., 1997b; Fig. 7b), there is no material from the upper melt lens in the lower crust.

The two end-member models have profoundly different implications for the properties of the lower crust, including its composition, the distribution of melt, the extent of deformation, thermal history, and the geometry, temperature and intensity of hydrothermal fluid-rock exchange. Criteria for distinguishing between the two contrasting models are outlined below, following tests developed from ophiolite and limited drill core studies. Samples from an intact crustal section are essential to test these competing models directly, through systematic measurements of compositions, textures, structures, and igneous contacts as a function of depth in the lower crustal gabbro section (Fig. 7).

The igneous stratigraphy and the nature of igneous contacts will be determined, to evaluate whether or not the lower crust comprises individual magma bodies that were intruded into the lower crust, and fractionated and crystallized *in situ*. In the sheeted sill model, the bulk crustal composition will be either more evolved upwards or randomly variable, and sub-Moho sills (Boudier et al., 1996; Kelemen et al., 1997b; Korenaga and Kelemen, 1997) are predicted. In contrast, in the gabbro glacier model there will be no change in bulk crustal composition with depth, and sub-Moho sills are not expected. In addition to modal layering, vertical chemical variation is observed in ophiolite gabbros (e.g., Pallister and Hopson, 1981; Malpas et al., 1989; Bédard, 1991; Schouten and Kelemen, 2002), and in plutonic rock sections drilled along slow-spreading mid-ocean ridges (e.g., Dick et al. 1991, 2000; Cannat et al., 1995; Pedersen et al., 1996; Natland and Dick, 1996; Kelemen et al., 2004, 2007; Blackman et al., 2006, 2011). The nature of this chemical layering can be used to constrain the size of individual crystallization units (Browning, 1984). Magma lenses ≤ 10 m thick crystallized layered gabbros in the Troodos ophiolite lower crust (Browning et al., 1989), and in the crust-mantle transition zone of the Oman ophiolite (Boudier et al., 1996; Korenaga and Kelemen, 1997).

The nature of chemical layering can also be used to constrain the mode of melt migration from the mantle through the lower crust, to form shallow gabbros, sheeted dikes, and lavas. Korenaga and Kelemen (1998) showed how reactive porous flow of melt through chemically layered gabbros would disrupt correlations between mineral compositions formed during crystal fractionation, and gradually smooth vertical chemical variation via diffusion. The scale of measurements undertaken in drill cores is ideal to document such chemical variations.

If the lower crust is built by the subsidence of material from a high level melt lens in a gabbro glacier, increasing strain with depth is predicted (Fig. 7). In contrast, crustal construction by successive sill injections will not produce systematic gradients in strain with depth. Published data from the Oman ophiolite are too limited to be conclusive, and show either no significant downward trend (Yaouancq and MacLeod, 2000), or increasing strain in the uppermost part of the upper, foliated gabbro section (Nicolas et al., 2009). The intensity of deformation, manifested by crystal shape and lattice preferred orientations, and to some extent by magnetic fabrics (Gee et al., 2004) can be readily assessed in drill core samples.

As magmas cool and crystallize, both the latent heat of crystallization, and the specific heat of cooling must be removed. Heat is transferred through the crust by conduction, or the advection of melt, solid material and seawater-derived hydrothermal fluids. Hydrothermal convection removes heat more rapidly than conduction. The distinct distributions of melt intrusion and crystallization with depth implicit in the two end-member models yield different distributions of latent heat removal with depth (Fig. 7). Computer simulations that balance the input of magmatic heat from the mantle to the crust with heat sinks provided by conduction, advection, and hydrothermal circulation have been used to test crustal accretion models, by constraining the input parameters to yield the best fits to geophysical or geological observations (Sleep, 1975; Morton and Sleep, 1985b; Henstock et al., 1993; Phipps Morgan and Chen, 1993; Maclennan et al., 2004). The gabbro glacier model provides the most efficient geometry for hydrothermal heat extraction, as the latent heat and specific heat of cooling can be readily advected from the lid of the melt lens (Henstock et al., 1993; Phipps Morgan and Chen, 1993). Very slow, deep cooling could be predominantly by conduction in gabbro glacier scenarios, but rapid deep cooling via hydrothermal convection cannot be ruled out. The sheeted sill model (Fig. 7b) can also be successfully simulated, provided that vigorous deep hydrothermal circulation occurs near the ridge axis and there is some crystal subsidence from the axial magma lens (Maclennan et al., 2004, 2005).

The vigor of hydrothermal convection in the lower crust depends on how close to the ridge axis hydrothermal fluids are able to penetrate deeply in the crust, and on permeability. Small changes in permeability may have a huge effect on the resulting thermal structure (e.g., Cherkaoui et al., 2003; Fontaine and Wilcock, 2007), and we do not know the permeability of *in-situ* lower crust, rendering thermal models highly uncertain and non-unique until tested by data in drill cores. If hydrothermal fluids penetrate sufficiently deep close enough to the ridge axis, they may lower the melting point of newly crystallized gabbro or gabbroic mush and generate more felsic melts (e.g., Koepke et al., 2007), resulting in the intrusion of silicic veins and plutons with distinctive isotope and compositional characteristics. Silicic veins, produced via crystal fractionation or partial melting, are essential to understanding the crustal budget of many geochemically important elements such as U, Th and Pb (e.g., Hart et al., 1999).

The cooling rate of the lower crust, as a function of depth, can be estimated (i) using "geospeedometers" that exploit elemental (Fe, Ca, Li) diffusion rates in olivine, clinopyroxene, and plagioclase (Ozawa, 1986; Coogan et al., 2002, 2005a, 2005b; VanTongeren et al. 2008), or (ii) by analysis of plagioclase crystal size distributions in gabbros (Garrido et al., 2001). Given the potential for small-scale variability in cooling rates, due to fracture-controlled heterogeneous fluid circulation (Coogan et al., 2006), drill core provides the ideal samples for such studies. In addition, the locking of the Earth's geomagnetic field polarity in oceanic gabbros at ~500°C can provide strong constraints on cooling rate. Encountering a series of polarity reversals with increasing depth would reveal the record of the blocking isotherm moving deeper in the crust, with time intervals known separately from calibrating the polarity time scale (e.g., Kidd, 1977). The depth over which polarity remains uniform is expected to increase with increasing cooling rate.

3.4. Lithosphere aging, chemical fluxes, and limits and controlling factors of life

The chemical evolution of the oceanic basement does not stop after the crust crystallizes. There is a discernable deficit in conductive heat flow out to 65 Ma on average (e.g., Stein & Stein, 1994) and some seawater-rock exchange probably occurs in ocean crust of all ages (Fig. 8). Well-established petrologic and geochemical techniques can be used to characterize the nature and relative timing of hydrothermal exchange between seawater and the lithosphere, the flux of fluid through the crust, and the depth to which fluid penetrates. Mineral geothermometers and cross-cutting vein mineral sequences, coupled with trace element, Sr isotope, and stable isotope compositions of whole rock samples and mineral separates can be used to establish the temperature- and chemical-evolution of the fluids in the crust and upper lithospheric mantle (e.g., Gregory and Taylor, 1981; Manning et al., 1996; Teagle et al., 1998a, 1998b; Bach et al., 2004; Coggon et al., 2004; Gillis et al., 2005), the extent of fluid channeling along fractures and veins (Manning et al., 1996; Banerjee and Gillis, 2001; Bosch et al., 2004; Coogan et al., 2006), and time integrated fluid fluxes (Bickle, 1992; Bickle and Teagle, 1992; Teagle et al., 2003; Gillis et al., 2005). These will provide essential information on chemical and thermal exchange between the lithosphere and the oceans, key to global geochemical budgets. Stein and Stein (1994) inferred from heat flow data that 33% of the convective cooling of oceanic lithosphere occurs in crust more than ten million years old, although isothermal basement temperatures and modeling suggest that much of the hydrothermal fluid flow may be restricted to the uppermost few hundred meters of the crust. Common, albeit volumetrically minor, veins of low temperature hydrothermal phases such as prehnite, laumontite and zeolites in dikes and gabbros of the Troodos ophiolite (e.g., Vibetti et al., 1989) are evidence that there can be deep penetration of seawater-derived hydrothermal fluids. Deep drilling may actually sample active, low temperature off-axis hydrothermal fluid flow driven by the conductive cooling of the lithosphere. Drilling in mature crust where significant fluid-rock (±microbial) exchange has ceased will provide improved constraints on the role of hydrothermal alteration in influencing the chemical evolution of seawater (e.g., Davis et al., 2003; Nielsen et al., 2006), and the bulk composition of the igneous crust recycled into the mantle in subduction zones. Understanding hydrothermal interactions preserved in altered rocks and vein suites, geochemical exchanges, and the calculation of time integrated fluid fluxes (e.g., Gregory and Taylor, 1981; Bickle and

Teagle, 1992; Teagle et al., 2003; Gillis et al., 2005; Coogan, 2008) requires knowledge of ancient seawater chemical and isotopic compositions. Recent evidence indicates that the major element concentrations and ratios (e.g., Mg/Ca and Sr/Ca) of seawater have changed markedly during the Neogene (e.g., Horita et al., 2002; Coggon et al., 2010), although this remains controversial (Broeker and Yu, 2011; Coggon et al., 2011). Hence, to avoid complications in interpreting hydrothermal alteration due to past changes in ocean chemistry, coring the youngest possible crust could be advantageous. Changes in the concentration of the main divalent cations in seawater (Ca, Mg, Sr) as well as oceanic pCO_2 has led to the repeated switching throughout the Phanerozoic of aragonite and calcite as the dominant carbonate mineral precipitated from the oceans (Wilkinson and Algeo, 1989; Hardie, 1996; Horita et al., 2002). The last change from a "calcite sea" to the modern "aragonite sea" occurred ~60 Ma ago. Ocean crust altered before the Tertiary exchanged elements and isotopes with seawater significantly different from today's oceans. This is also reflected in the much greater proportion of carbonate minerals preserved within Mesozoic ocean crust compared with younger rocks (Alt and Teagle, 1999; Gillis and Coogan, 2011).

While being altered by hydrothermal fluids, the upper oceanic crust becomes an extensive habitat for microorganisms. Endolithic microbes colonize fractures in glassy basaltic rocks, extracting energy and nutrients from the glass by dissolving it, and leaving behind biomarkers that reveal their former presence (e.g., Fisk et al., 1998; Furnes et al., 2001; Thorseth et al., 2001; Bach and Edwards, 2003; Banerjee and Muehlenbachs, 2003; Kimura et al., 2003; Staudigel et al., 2006; McLoughlin et al., 2009; Schrenk et al., 2010; Edwards et al., 2011; Orcutt et al., 2011). Hydrogen and simple organic compounds can be produced abiotically where water interacts with olivine and ultramafic rocks (e.g., McCollom and Seewald, 2001; McCollom et al. 2010) in a variety of geotectonic settings, and are described at slow-spreading mid-ocean ridges where serpentinized ultramafic rocks commonly occur at the seafloor (e.g., Schrenk et al., 2004; Kelley et al., 2005). In IODP Hole U1309D (Blackman et al., 2006) at the slow-spreading Mid-Atlantic ridge, evidence for a microbial community that can degrade hydrocarbons and fix carbon and nitrogen has been documented to 1313 mbsf in the recovered gabbroic section (Mason et al., 2010). Evidence for microbial activity in the oceanic crust has been growing in the past decade with an increasing number of dedicated studies and improving technology (e.g., Schrenk et al., 2010; Edwards et al., 2011; Orcutt et al., 2011). Microbial activity in the sub seafloor biosphere may have a profound impact on processes and chemical fluxes during water-rock reactions but the depth limits, as well as the controlling factors of microbiological activity in the oceanic basement have yet to be fully explored (Fig. 8).

Exploring and characterizing the sub seafloor biosphere in the ocean crust will be pursued in the MoHole. Deep drilling will cross chemical and physical boundaries, involving energy, carbon, nutrients and porosity/permeability, which define our current understanding of habitability and may shed light on deep energy sources for microbial communities. Studies of high temperature and high-pressure microbial ecosystems have pushed the boundaries of microbial physiology (Kashefi and Lovley, 2003; Takai, 2008; Picard et al., 2011), and have revealed novel adaptations to extreme conditions. Deep drilling will provide access to rocky habitats at the "biotic fringe" (Fig. 8; e.g., Bach et al., 2006) to search for novel microorganisms and potentially lead to the discovery of new compounds with biotechnological and industrial applications. These environments may also be key in the search for primordial microbial, deep-seated microbial communities that may be relicts of the earliest life forms on Earth (e.g., Furnes et al., 2004; Banerjee et al., 2006).

4. M2M Project Area, and Technology Developments

Drilling the MoHole will be a challenging enterprise requiring space mission-levels of detailed planning and engineering. The depth of the required borehole (~ 6000m) is far beyond depths reached so far in ocean crust using conventional non-riser drilling (Fig. 3), but industry commonly drills deeper (10 km or more). However, the required water depth, the hardness of the formations encountered, and the temperature for the MoHole exceed current industry thresholds. The characteristics and location of the potential MoHole sites, as well as the needs for technological developments have been extensively discussed during the "MoHole" and "Mantle Frontier" workshops in 2010 (Ildefonse et al., 2010a, 2010b; Workshop Report Writing Group, 2011), with outcomes and recommendations summarized below. At the end of 2010, the IODP-MI Board of Governors gave its approval to IODP-MI (BoG Motion 1012-03) for a technical feasibility and cost analysis study of a MoHole, conducted by an independent company (Blade Energy Partners, 2011). Beyond the details of the various studied drilling scenarios, this report states that "drilling to the mantle is certainly feasible and that there are existing industry solutions to many of the technological challenges associated with drilling this type of borehole".

4.1. Geophysical Characteristics of the M2M Project Area

The target for deep crustal penetration will ideally meet the following requirements. Satisfying requirements for points a to e is essential for success. More flexibility is allowed in meeting Points f to h, which are highly desirable but not essential.

a. Crust formed at fast spreading rate (>80 mm/yr),
b. Simple tectonic setting with low-relief seafloor and smooth basement; away from fracture zones, propagator pseudo faults, overlapping spreading basins, seamounts, or other indicators of late-stage intraplate volcanism,
c. Crustal seismic velocity structure that fits our current understanding of "normal" fast-spread Pacific crust, indicative of layered structure,
d. A sharp Moho imaged with MCS techniques,
e. A strong wide-angle Moho reflection (PmP), as observed in seismic refraction data, with clearly identifiable sub-Moho refractions (Pn),
f. A clear upper mantle seismic anisotropy,
g. Crust formed at a palaeo-latitude greater than ±15° to maximize utility of core magnetic data,
h. A location with relatively high upper crustal seismic velocities indicative of massive volcanic formations to enable the initiation of a deep dill hole.

Several technological constraints limit the range of potential sites:

• Technology for re-circulating drilling mud (riser or alternative) is needed for ultra-deep drilling, but is currently untested at water depths greater than ~3000 m. Depths greater than 4000 or 4500 m may exceed the capabilities of a reliable and affordable system, although it is difficult to anticipate on technology improvements over the next decade, as the hydrocarbon exploration ventures into progressively deeper frontiers.

• Prior scientific ocean drilling experience is mostly limited to wall-rock temperatures less than 200°C. Temperatures higher than ~250°C may limit choices of drill bits and logging tools, decrease core recovery, and increase risk of hole failure, or require substantial re-design of drilling equipment. Based on basic plate cooling models, crust older than ~15-20 Ma should meet this requirement at Moho depths (Fig. 9).

• 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 8 (preferably 12) months/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 (~1000 km or less) to major port facilities.

4.2. Potential sites

Based on the scientific requirements and technological constraints outlined in section 4.1, three regions have been identified as potential M2M project areas (Ildefonse et al., 2010a, 2010b; Fig. 10, Table 1). No region anywhere satisfies all of the desirable criteria. The key trade off is between the shallowest possible water depth (see section 5) found in younger crust, and lowest possible Moho temperatures (<~250°C; Fig. 9) found in older crust underlying >~4000 m seafloor.

Region A (Fig. 10, Table 1) encompasses part of the Cocos Plate off Central America with lithospheric ages between 15 and 25 Ma. At its western limit on 15 Ma crust, this area includes ODP Hole 1256D (Wilson et al., 2006; Teagle et al., 2012), a site of on-going conventional drilling into intact ocean crust. MCS (Hallenborg et al., 2003; Wilson et al., 2003) and wide-angle OBS data exist for the 15-17 Ma area in the vicinity of Site 1256. A significant advantage of the Cocos Plate area is that it is located within a corridor that spans the complete life cycle of a tectonic plate. This makes it the only candidate where results from MoHole drilling can be placed within the context of the full ocean crustal evolution, from a modern spreading center (East Pacific Rise) to an active subduction zone (Central America). The major disadvantage of Site 1256 is the relatively high Moho temperature; this problem might be overcome in areas of older crust to the east (17-24 Ma).

The region off Southern/Baja California (Fig. 10B, Table1) encompasses a section of the eastern Pacific Plate off Southern and Baja California, between ~20-33°N, and ~127-120°W. Crustal ages are ~20-35 Ma. Very little modern geophysical information exists from this region. A long, EW MCS transect ~300 km north of the Clipperton fracture zone (Eittreim et al, 1994) shows Moho reflections over most of the profile, bright and generally continuous for crustal ages 18-32 Ma, with uniform (~6 km) crustal thickness. The best-studied area is the "Deep Tow" site at 32°25'N, 125°45'W near San Diego (31-32 Ma; Luyendyk, 1970). Geophysical data on this site include deep-tow sidescan and bathymetry, 3.5 kHz profiler, magnetics, and single channel seismic profiles. No modern seismic data are available to evaluate crustal structure and Moho characteristics.

The Hawaii region (Fig. 10C, table 1) is located north of Oahu in the flexural arch, where water depths are shallower than in the surrounding Cretaceous Pacific plate. The crust is ~80

Ma, and was formed at a half spreading rate of 35-40 mm/yr. Older crust appears more appealing for the search of the deepest limit of life. This region offers the lowest temperature at the Moho, but its general geological setting counterbalances this strong advantage. The contribution of the abundant arch volcanism northwest of the proposed site area (Clague et al., 1990, 2002), and of the Hawaiian hot spot south of the proposed site area (e.g., Leahy et al., 2010) to the crustal architecture remains to be established.

4.3. Large-scale surveys: finding the right project area

The existing geophysical data at the three potential sites are not sufficient to identify a clear M2M Project target area. The short-term priority should be conducting large-scale seismic surveys in the three regions to identify a MoHole target that meets the requirements listed in section 4.1. These surveys, which will necessarily require international collaboration and funding, should collect spatially coincident MCS data, wide-angle OBS data, multi-beam bathymetry, gravity, and magnetics. Heat flow data would also be useful. The characteristics of the required seismic surveys are listed in Ildefonse et al. (2010a).

JAMSTEC (Japanese Agency for Marine-Earth Science and Technology) is planning a 2 months survey cruise in Japanese FY 2013. Although region B (Fig. 10) was prioritized at the Kanazawa workshop for the short-term (because so little is known about this area, where depth/age/logistical criteria are viable), the available ship time is not long enough to allow for transit from Japan, and completion of the desired seismic profiles in the Eastern Pacific. Hence the cruise will survey the NE Hawaiian Arch region; this will be coordinated with the project submitted by Greg Moore (University of Hawaii) et al. to NSF (US National Science Foundation) in 2011. The planned MCS and OBS surveys are designed to characterize the crustal structure and Moho reflectivity in the Hawaiian Arch north of Oahu, and north of the Arch in deeper waters. New reconnaissance profiling in region A was considered a lower immediate priority in Kanazawa since EW9903 data provides some good-quality information in that region (Wilson et al., 2003; Hallenborg et al., 2003). However, conducting a small survey in this area with state of the art seismic capabilities for comparison with the EW9903 data will be crucial to assess the reason(s) for the low apparent Moho reflectivity, and to image the areas east and north of Site 1256. A proposal to re-analyze the EW9903 MCS dataset and compare it to similar datasets from other regions where Moho reflectivity is strong is currently under review. This will determine whether the EW9903 weak reflectivity of the Moho is a natural consequence of crust formed at super-fast rates; or alternatively that

EW9903 data may not be of optimal quality for Moho imaging due to experimental parameters, warranting new surveys in the area.

The choice of the appropriate MoHole site, and subsequent start of operations are likely still several years ahead, and some site characteristics (such as water depth) that are now perceived as major drawbacks may become less problematic in the future, as drilling technology improves. At this stage, we remain open to other possible areas of interest, possibly in deeper water (i.e., in colder lithosphere), pending on technological development. After an appropriate drilling target has been selected, additional, detailed seismic surveys will be needed in the vicinity of the target. Details of the recommended experiments, including 3D MCS and OBS surveys for accurate imaging of intracrustal and Moho reflectors, assessing crustal structure and thickness, and characterizing upper mantle velocity structure/anisotropy, are listed in Ildefonse et al. (2010a).

4.4 Technology and Engineering Developments for M2M

Drilling into the uppermost mantle will require a drill hole at least 6000 m deep, in water depths between 3500 and 4500 m. M2M is arguably at the point where the framework for the operations can be constructed, since it is now technologically feasible to drill such a hole (Blade Energy Partners, 2011). Technology selection and engineering development will be key components of the scientific success of the project. It is important to identify potential issues in drilling and coring engineering from the past and ongoing ocean drilling expeditions (see "Deep drilling of intact ocean crust: harnessing past lessons to inform future endeavors" in Teagle et al., 2012), and to find solutions to overcome the problems encountered. *Technology selection process and planning for key engineering developments should be launched as soon as possible in conjunction with site-survey efforts. To do this, establishing a realistic roadmap, including project scoping, development and testing, all within a unified project management structure, is imperative.* To drill an ultra-deep borehole, the provision for continuous mud circulation is a top priority technical requirement. Other major areas requiring engineering development include logging and coring in a high-temperature environment, specialized drill bits for abrasive, hard, hot rocks, specialized drill string with high tensile strength, low-weight drilling mud for use at high temperature, and new casing and cementing materials and strategies. In sampling the rock-hosted biosphere in the MoHole we will also confront unprecedented challenges, such as precisely discerning living and dead cells, and discriminating native microflora from contaminants, which will require creative and innovative technological solutions. Specific issues to be considered include the use of highresolution next-generation DNA sequencing approaches, highly sensitive biomarker analyses, and considering pressure as an experimental variable in microbiological studies. High temperatures can be directly estimated from novel RNA analysis (Kimura et al., 2010).

A promising candidate technology for drilling the MoHole is riser drilling. The DV Chikyu is currently equipped with a riser system with a maximum rated water depth of 2500 m. Significant engineering development would be required to prepare Chikyu for riser drilling in water depths ≥4000 m. Several other technologies are also being considered to drill safely and efficiently to the target depth, such as a Surface Blow Out Preventer (BOP) combined with a slim riser pipe (casing pipe) and a Subsea Isolation Device (SID), or Riserless Mud Recovery (Myers, 2008) with a seafloor mud circulation pump and return line. The lithologies intersected by the borehole drilled to Moho depths will be free from overpressures, hydrocarbons, or other geohazards. However, although a BOP will probably not be needed for well control, the use of a BOP might be required by safety regulations.

Operationally, major challenges will be associated with collecting the cored material, making *in-situ* measurements, installing casing, and keeping the borehole open for successive deepening in a multiyear, multiphase operation. To prepare for this, 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 (see key elements listed in Ildefonse et al., 2010a). The feasibility study (Blade Energy Partners, 2011) is encouraging. The report concludes that there are existing solutions to both the riser design and drill-string design issues. The key issues identified are the development of 1) downhole tools capable of withstanding the high downhole temperatures, and 2) bits with improved bit life, which will reduce operation cost and improve coring techniques.

After completion of drilling, coring, and logging, the MoHole should be used for experiments, including vertical seismic profiles, and long-term geophysical, geochemical (fluid, gases), and microbiological monitoring. Instrumenting the MoHole will eventually be a key, last-stage goal of M2M. Hence, the sub-sea equipment and borehole should be constructed to accommodate observatory science (fluid monitoring, microbiology incubation experiments). This implies ROV access to the wellhead and the ability to access the borehole through a BOP or SID.

5. Keys for Success

The keys for the M2M project include considerations on sampling strategy, technology development, industry engagement, and public support. M2M would be one of the largest scientific endeavors in Earth science history, and this challenge should provide precious opportunities to a diversity of Earth and Life scientists, engineers and technologists (Ildefonse et al., 2010a, 2010b). The timeline for M2M is difficult to predict precisely as it depends strongly on the time and money invested to move ahead. It will likely last 10 years or more. The estimated cost of the operational part of the project is also difficult to predict, depending on the choices that will be made regarding location (in particular water depth; the shallower the better), and coring all or only part of the drilled section (Blade Energy Partners, 2011).

Achieving our primary scientific goals ideally requires continuous core to the bottom of the hole (Fig. 11a). If technically and/or financially not feasible, it will require a minimum amount of continuous core samples. To be regarded as successful, M2M must at least return all of the following (Fig. 11):

- Continuous coring of 500 m of peridotites and associated lithologies in the uppermost mantle below the Moho,
- Continuous coring, including samples of all boundaries, across the region identified by seismic imaging as the Moho, and the lithologic transition from cumulate 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,
- 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 (Layer 2-3 boundary, Moho) throughout the ocean crust and into the upper mantle.

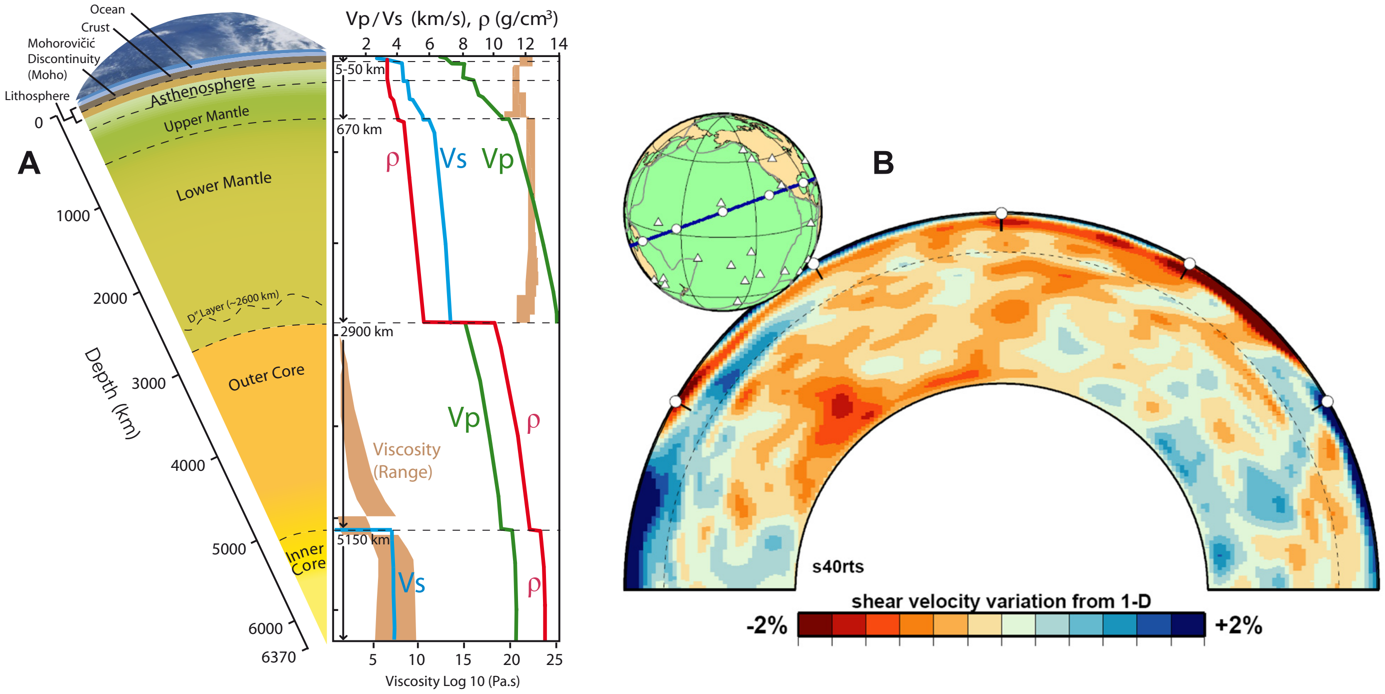

Figure 1. A) Solid layers of the Earth, and variation of seismic velocities, density, and viscosity with depth. Seismic velocities and densities: Kennett (1991); crust and mantle viscosity profile: Steinberger and Holme (2002); core viscosity profile: Burmin (2008). Figure by Christopher Smith-Duque. B) Tomographic model of the whole mantle (Ritsema et al., 2011); the section is centered on the Pacific ocean, and shows to the East a fast (cold) region down to the core, inferred to be the subducting Farallon plate into the deep mantle, and to the West some possible upwellings from the core-mantle boundary below the Pacific. This model is one of the many possible illustrations of the whole mantle convective dynamics.

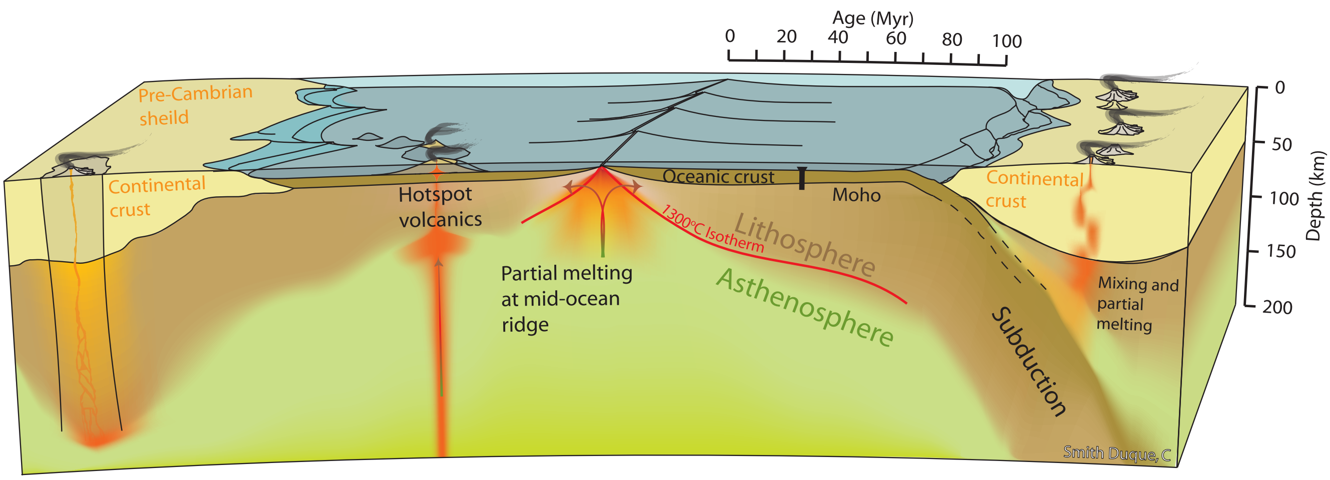

Figure 2. Sketch of the plate tectonic cycle showing the upwelling and partial melting of asthenospheric mantle to form new ocean crust at a mid-ocean ridge and the progressive growth of the lithospheric mantle as the plate conductively cools away from the ridge until it is subducted back into the mantle. Beneath the continental shields there is commonly a deep keel of continental lithospheric mantle that has been isolated from mantle convection since the Pre-Cambrian. The MoHole (thick black line) will sample the upper part of the oceanic mantle lithosphere, which is eventually recycled at subduction zones. Figure by Christopher Smith-Duque.

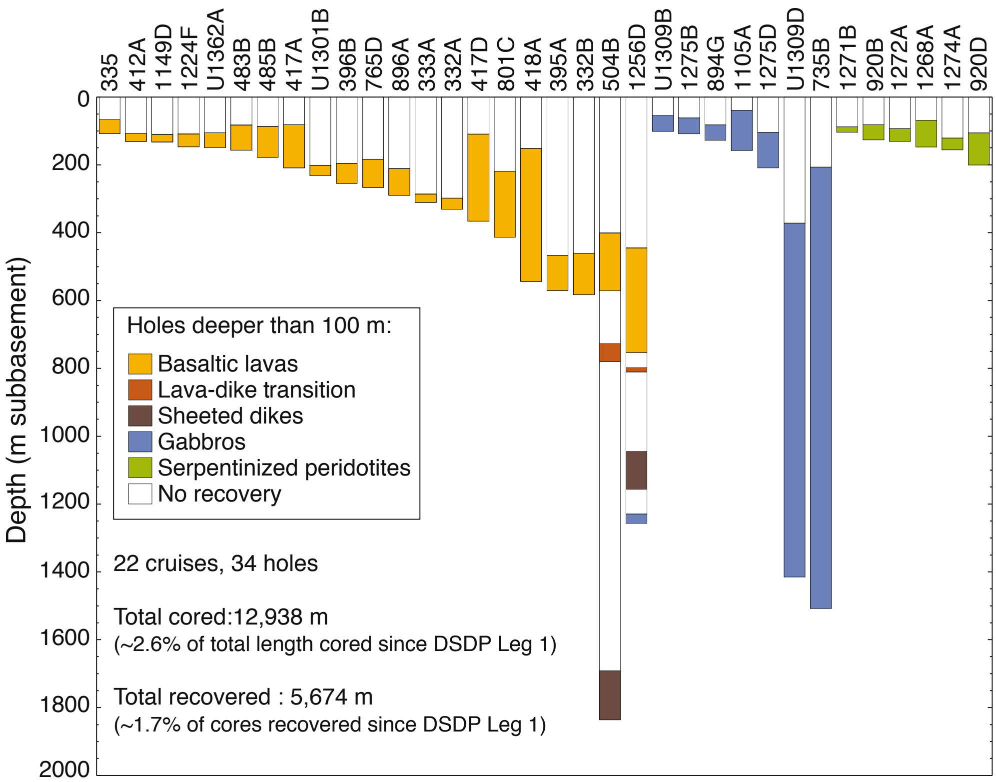

Figure 3. Compilation chart showing holes drilled >100m in intact crust and tectonically exposed lower crust and upper mantle from 1974 to 2010 (Teagle et al., 2012; localization in Fig. F3 therein). This compilation does not include "hard rock" drill holes in oceanic plateaus, arc basement, hydrothermal mounds, or passive margins.

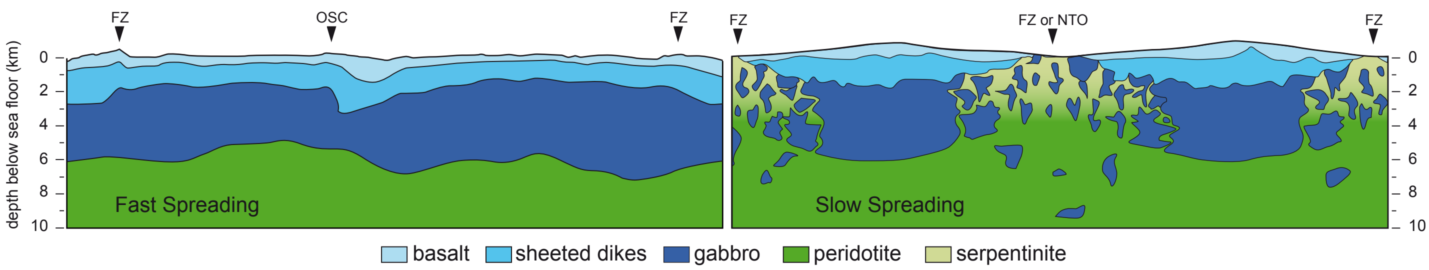

Figure 4. Schematic along-axis cross-sections of fast spread (left) and slow spread (right) crust. FZ: fracture zone; OSC: overlapping spreading center; NTO: non-transform offset. Sections are approximately 200 km long. Modified from Ildefonse et al. (2007a), Canales et al. (2003), and Cannat et al., (1995).

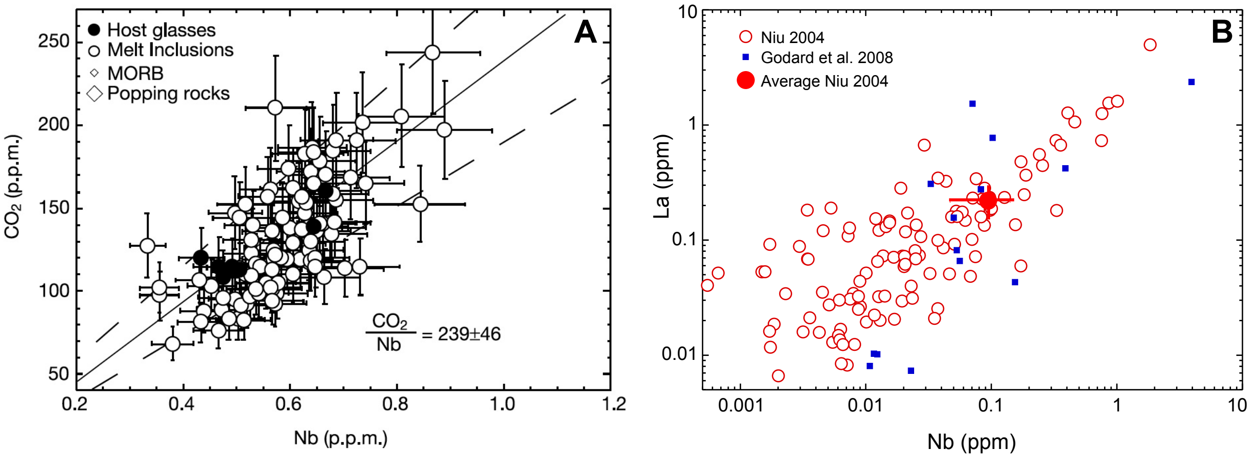

Figure 5. A) Graph from Saal et al. (2002), showing that CO2 and Niobium (Nb) concentrations are correlated in mid-ocean ridge lavas. B) ICP-MS trace element data on ~ 130 peridotite samples dredged from the mid-ocean ridges (Niu, 2004; Godard et al., 2008), showing that Nb and La concentrations are high and vary over three orders of magnitude. The average concentration (red circle, with error bars for one standard error of the mean) is about 20% of the average concentration in mid-ocean ridge lavas. Samples in Godard et al. (2008) with low La contents and ~constant Nb about 0.01 ppm are omitted in this graph.

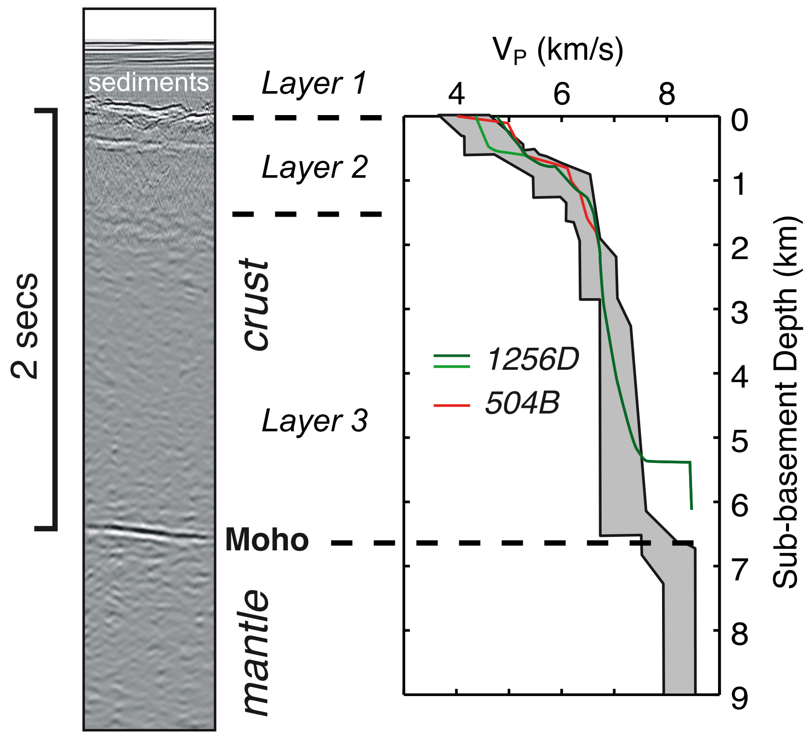

Figure 6. Left: Example of multichannel seismic reflection image showing a crustal column over a sharp, strong single Moho reflection (from Nedimovic et al., 2005). Right: Seismic structure (one-dimensional Vp models) of Pacific crust (Grey: Bounds of average "normal" crust older than 29 Ma (after White et al., 1992); Green: ODP site 1256 (Teagle et al., 2006); Red: DSDP site 504 (Swift et al., 2008).

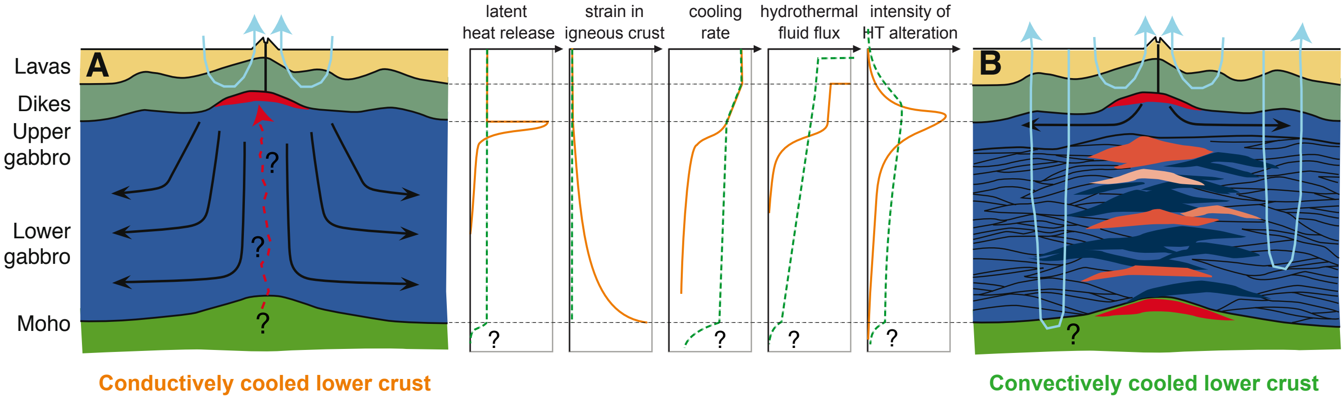

Figure 7. Sketches of end-member crustal accretion models (after Korenaga and Kelemen, 1998). Black arrows show the movement of the solid lower crust; blue arrows show the dominant zones where hydrothermal circulation will remove latent and sensible heat; the red arrow in A shows the movement of magma (unknown in all models). A) Gabbro glacier ductile flow model (e.g., Henstock et al., 1993; Quick and Denlinger, 1993). B) "Sheeted" or "stacked" sill model of in situ formation of the lower crust by on-axis sill intrusions (e.g., Kelemen et al., 1997b). The middle panel shows schematic relative variations in the general trends of latent heat release, strain rate, cooling rate, hydrothermal fluid flux, and intensity of high temperature alteration with depth predicted by the end-member "gabbro glacier" with mainly conductive cooling of the lower crust (orange), and the "sheeted sill" model, which requires convective cooling of the lower crust (Original figure by R. Coggon).

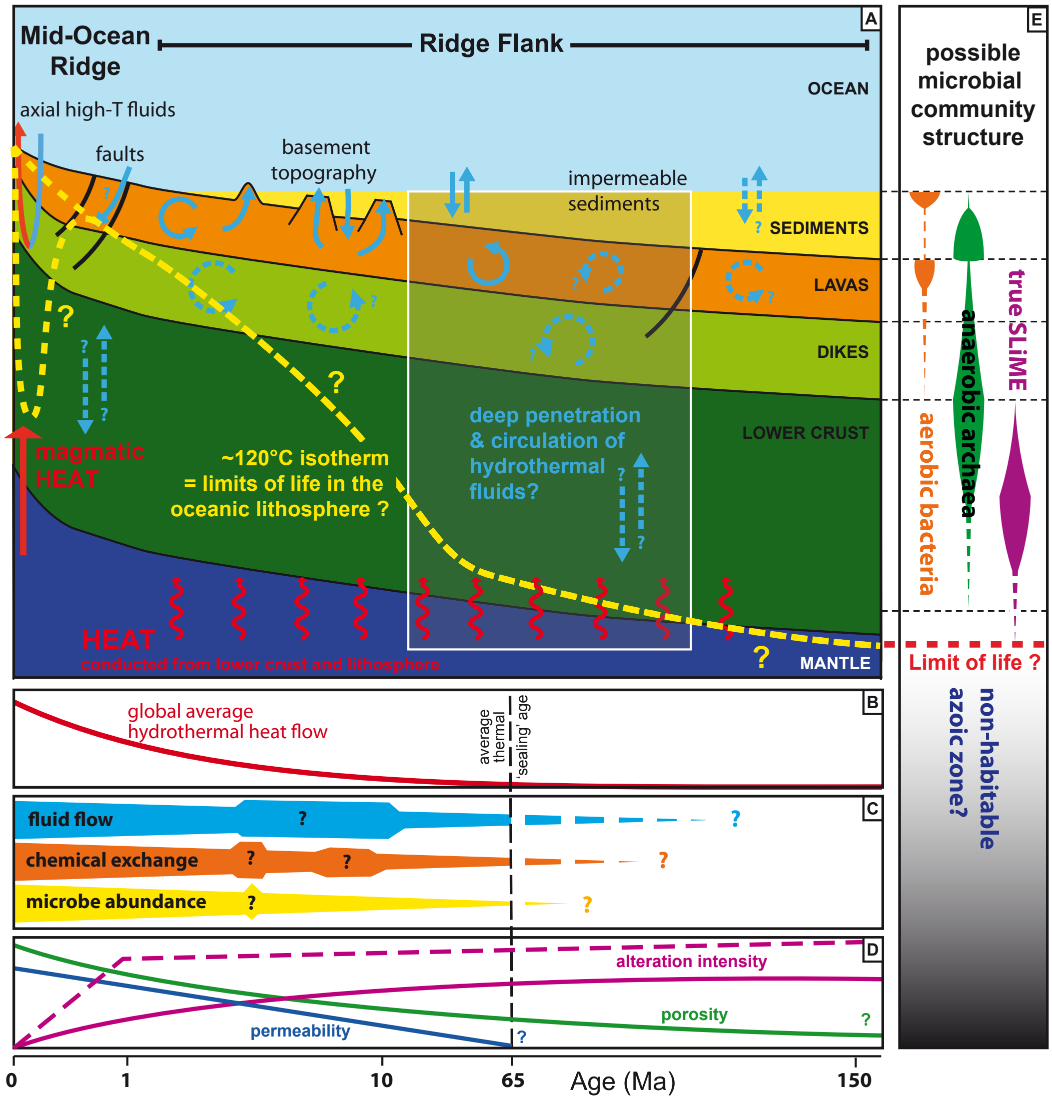

Figure 8. A) Parameters that influence the intensity and style of hydrothermal circulation, such as faults, seamounts, basement topography, and impermeable sediments. Arrows indicate heat (red) and fluid (blue) flow. Yellow dashed line is the ~120°C isotherm (note the rapid cooling close to the axis in case of deep penetration of hydrothermal fluids, e.g., Spinelli and Harris, 2011). B) Calculated global hydrothermal heat flow anomaly decreases to zero by ~65 Ma. C) The effects of basement topography and sediment thickness on the intensity and relative locations of fluid flow, chemical exchange, and microbial activity remain undetermined. D) Evolution of porosity, permeability, and alteration intensity with age. E) Hypothetical change in microbial community structure with; the depth limit of life increases with crustal age (from K. Nakamura). After Ildefonse et al. (2010b), and Coggon and Teagle (2011). The grey box show the age range covered by the regions of interest considered so far for the MoHole.

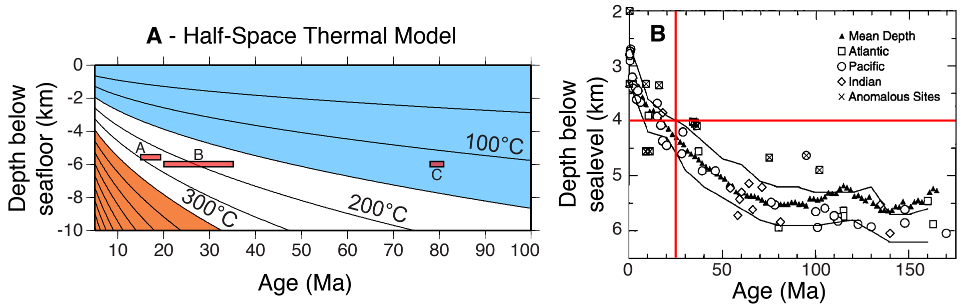

Figure 9. A) Predicted temperature as a function of age and depth below seafloor (half-space thermal model; Davis and Lister, 1974; Turcotte and Schubert, 1982), with thermal diffusivity of 6x10-7 m2s-1, initial mantle temperature of 1340°C, and surface temperature of 0°C. At 6 km, cooling below 250°C occurs after ~18 Ma. The red bars A, B and C show the approximate temperature at the presumed Moho depth in the considered regions of interest (see section 4.2). B) Seafloor depth Vs age (Carlson and Johnson, 1994). Most of ocean crust subsides to > 4000 m depth by ~25 Ma. These two diagrams illustrate the inherent difficulty for any site to be "ideal", i.e. both shallow and cold.

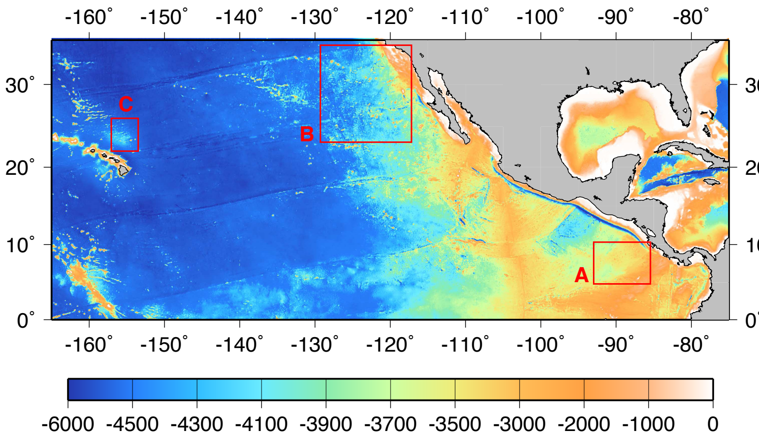

Figure 10. Bathymetric map showing the three selected areas for large-scale MoHole site survey. A) Cocos plate region; B) off Southern/Baja California region; C) NE Hawaiian Arch region.

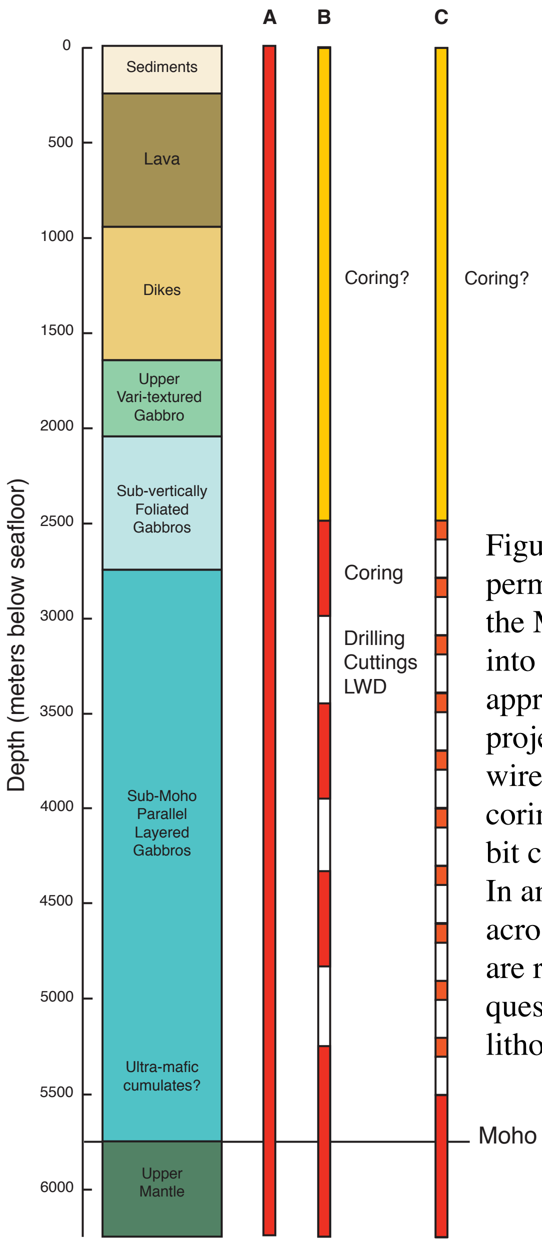

Figure 11. Technology and financial constraints permitting, continuous coring all the way to the Moho and then a significant distance (~500 m) into the uppermost mantle (A) would be the best approach to achieve the scientific goals of this project. However, approaches that mix continuous wireline coring with spot coring (e.g., (B) long coring of key sections or (C) 10-m coring before bit change every 50 m) may need to be considered. In any case, significant lengths of continuous cores across major lithologic and geophysical transitions are required to answer the fundamental scientific questions. The left column shows the anticipated lithology, based on ophiolite observations.

Candidate Project Area	A - Cocos Plate	B - Off Southern/Baja California	C - Hawaii
Location	6.7-8.7°N 89.5-91.9°W	20-33°N 120-127°W	22.9-23.9°N 154.5-155.8°W
Half Spreading Rate (mm/yr)	100-110	45-60	35-40
Crustal Age (Ma)	~15-19	~20-35	~78-81
Inferred Moho T (°C)	≥ 250	≤ 250	~150
Water Depth (m)	3400-3650	Mostly 4000-4500, some shallower area	4050-4500
Sediment Thickness (m)	250-300	80-130	~200
Crustal Thickness (m)	5500 (?)	?	5500-6000
Total Length to the Moho (m)	8700-9200 (?).	?	9500-10000
Original Latitude	near equator	25-33	near equator
Advantages	- Shallowest depth - Modest crustal thickness - Sits within a corridor that includes a complete tectonic plate life cycle - 12 month weather window, 3 m swell rare	- Large range of depth - Modest Moho T - Higher latitude - Portions of region are close enough for shore logistics base	- Lowest T - Nearby major port - 12-month weather window (consistent trade winds but only episodic storms) - Deepest limit of life
Disadvantages	- Highest Moho T - Poor Moho reflection in existing data - Faster than present-day fastest spreading rate - Near equator - 1.0-1.5 knots whole-water-column tidal currents	- Few data available - Off-ridge volcanism	- Deepest water - Crustal structure is potentially affected by hotspot volcanism - Close to arch volcanism; many seafloor volcanic fileds - Near equator - Lowest end of fast-spreading rates

Table 1. Candidate areas for the MoHole project, with principal characteristics, advantages and disadvantages (see Ildefonse et al., 2010a, 2010b, for further details on candidate regions)

References

Alard, O., Griffin, W.L., Lorand, J.P., Jackson, S.E., O'Reilly, S.Y., **2000**. Non-chondritic distribution of the highly siderophile elements in mantle sulphides. Nature 407, 891-894. doi:10.1038/35038049

Alard, O., Luguet, A., Pearson, N.J., Griffin, W.L., Lorand, J.P., Gannoun, A., Burton, K.W., and O'Reilly, S.Y., **2005**. In situ Os isotopes in abyssal peridotites bridge the isotopic gap between MORBs and their source mantle. Nature, 436, 1005-1008. doi:10.1038/nature03902

Albarède, F., **2009**. Volatile accretion history of the terrestrial planets and dynamic implications. Nature 461, 1227-1233. doi:10.1038/nature08477

Alt, J.C., Laverne, C., Vanko, D.A., Tartarotti,, P., Teagle, D.A.H., Bach, W., Zuleger, E., Erzinger, J., Honnorez, J., Pezard, P.A., Becker, K., Salisbury, M.H., and Wilkens, R.H., **1996**. Hydrothermal alteration of a section of upper oceanic crust in the eastern equatorial Pacific: a synthesis of results from Site 504 (DSDP Legs 69, 70, and 83, and ODP Legs 111, 137, 140, and 148.). In: J.C. Alt, H. Kinoshita, L.B. Stokking and P. Michael (Eds), Proc. ODP, Sci. Results, 148. College Station, TX (Ocean Drilling Program), 417-434.

Alt, J.C., and Teagle, D.A.H., **1999**. The uptake of carbon during alteration of ocean crust. Geoch. Cosmoch. Acta 63, 1527-1535. doi:10.1016/s0016-7037(99)00123-4

Arai, S., **2009**. Petrological nature of the oceanic Moho. White Paper for the INVEST meeting, Bremen (http://www.marum.de/Binaries/Binary42200/Arai_MoHole.pdf).

Bach, W., and Edwards., K.J., **2003**. Iron and sulfide oxidation within the basaltic ocean crust: extent, processes, timing, and implications for chemolithoautotrophic primary biomass production. Geochim. Cosmochim. Acta, 67: 3871-3887.

Bach, W., Edwards, K.J., Hayes, J.M., Huber, J.A., Sievert, S.M., and Sogin, M.L., **2006**. Energy in the dark: Fuel for life in the deep ocean and beyond. Eos, Trans., AGU, 87, 73-78.

Bach, W., Garrido, C.J., Paulick, H., Harvey, J. and Rosner, M., **2004**. Seawater-peridotite interactions: First insights from ODP Leg 209, MAR 15 degrees N. Geochem. Geophys. Geosys., 5: Q09F26 SEP 10 2004.

Bach, W., Ravelo, C., Behrmann, J., Camoin, G., Duncan, R., Edwards, K., Gulick, S., Inagaki, S., Pälike, H., and Tada, R., **2010**. IODP New Ventures in Exploring Scientific Targets (INVEST) : Defining the New Goals of an International Drilling Program. Sci. Drill., 9, 54-64. doi:10.2204/iodp.sd.9.12.2010

Banerjee, N.R., Furnes, H., Muehlenbachs, K., Staudigel, H., and de Wit, M., **2006**. Preservation of biosignatures in 3.5 Ga pillow lavas from the Barberton Greenstone Belt, South Africa. Earth Planet. Sci. Lett., 241, 707-722.

Banerjee, N. R., and K. M. Gillis, **2001**, Hydrothermal alteration in a modern suprasubduction zone: The Tonga forearc crust, J. Geophys. Res., 106(B10), 21,737–21,750.

Banerjee, N. R. and Muehlenbachs, K., **2003**, Tuff life: bioalteration in volcaniclastic rocks from the Ontong Java Plateau, Geochem. Geophys. Geosys., 4, 1037, doi:10.1029/2002GC000470.

Barnes, J.D., Paulick, H., Sharp, Z.D., Bach, W., and Beaudoin, G., **2009**. Stable isotope (delta(18)O, delta D, delta(37)Cl) evidence for multiple fluid histories in mid-Atlantic abyssal peridotites (ODP Leg 209). Lithos 110, 83-94. doi:10.1016/j.lithos.2008.12.004

Bascom, W.N., **1961**. A Hole in the Bottom of the Sea: The Story of the Mohole Project. Garden City, New York (Doubleday and Company, Inc.): 352 pp.

Bédard, J.H., **1991**. Cumulate Recycling and Crustal Evolution in the Bay of Islands Ophiolite. J. Geol., 99(2): 225-249.

Behn, M.D., Hirth, G., Elsenbeck, J.R., **2009**. Implications of grain size evolution on the seismic structure of the oceanic upper mantle. Earth Planet. Sci. Lett. 282, 178-189. doi:10.1016/j.epsl.2009.03.014

Behn, M.D. and Kelemen, P.B., **2003**. Relationship between seismic P-wave velocity and the composition of anhydrous igneous and meta-igneous rocks. Geochem. Geophys. Geosyst., 4(5), 1041. doi:10.1029/2002GC000393

Bickle, M.J., **1992**. Transport mechanisms by fluid-flow in metamorphic rocks: oxygen and strontium decoupling in the Trois Seigneurs Massif - a consequence of Kinetic dispersion. Am. Jour. Sci., 292: 289-316.

Bickle, M.J. and Teagle, D.A.H., **1992**. Strontium alteration in the Troodos ophiolite: implications for fluid fluxes and geochemical transport in mid-ocean ridge hydrothermal systems. Earth Planet. Sci. Lett., 113: 219-237.

Blackman, D.K., Ildefonse, B., John, B.E., Ohara, Y., Miller, D.J., MacLeod, C.J., and the Expedition 304/305 Scientists, **2006**. Proc. IODP, 304/305: College Station TX (Integrated Ocean Drilling Program Management International, Inc.). doi:10.2204/iodp.proc.304305.2006

Blackman, D.K., Ildefonse, B., John, B.E., Ohara, Y., Miller, D.J., and IODP 304-305 Science Party, **2011**. Drilling Constraints on Lithospheric Accretion and Evolution at Atlantis Massif, Mid-Atlantic Ridge 30°N. J Geoph. Res., 116, B07103, doi:10.1029/2010JB007931

Blade Energy Partners, **2011**. Project Mohole Initial Feasibility Study for 2017 drilling, prepared for IODP. Available online (http://www.iodp.org/weblinks/Featured-Publications-HOME-PAGE/IODP-Project-MoHole-Initial-Feasibility-Study-PDF-)

Bosch, D., Jamais, M., Boudier, F., Nicolas, A., Dautria, J.-M. and Agrinier, P., **2004**. Deep and high temperature hydrothermal circulation in the Oman ophiolite-Petrological and isotopic evidence. J. Petrol., 45(6): 1181-1208.

Boudier, F., Nicolas, A. and Ildefonse, B., **1996**. Magma chambers in the Oman ophiolite : fed from the top or from the bottom ? Earth Planet. Sci. Lett., 144: 239-250.

Brandenburg, J.P., Hauri, E.H., van Keken, P.E., and Ballentine, C.J., **2008**. A multiple-system study of the geochemical evolution of the mantle with force-balanced plates and thermochemical effects. Earth Planet. Sci. Lett. 276, 1-13. doi:10.1016/j.epsl.2008.08.027

Broecker, W., and Yu, J.M., **2011**. What do we know about the evolution of Mg to Ca ratios in seawater? Paleoceanography 26, 8. doi:Pa3203 10.1029/2011pa002120

Browning, P., **1984**. Cryptic variation within the cumulate sequence of the Oman ophiolite: magma chamber depth and petrological implications. In Gass, I.G., Lippard, S.J., and Shelton, A.W. (Eds.), Ophiolites and Oceanic Lithosphere. Spec. Publ.—Geol. Soc. London, 13:71–82.

Browning, P., Roberts, S., and Alabaster, T., **1989**. Fine-scale modal layering and cyclic units in ultramafic cumumlates from the CY-4 borehole, Troodos ophiolite: evidence for an open system magma chamber, in drillhole CY-4, the Troodos ophiolite, Cyprus. In Gibson, I.L., Malpas, J., Robinson, P.T., and Xenophontos, C. (Eds.), Cyprus Crustal Study Project: Initial Report, Hole CY-4. Pap.—Geol. Surv. Can., 193–220.

Brunelli, D., Seyler, M., Cipriani, A., Ottolini, L. and Bonatti, E., **2006**. Discontinuous melt extraction and weak refertilization of mantle peridotites at the Vema lithospheric section (Mid-Atlantic ridge). J. Petrol., 47(4): 745-771; doi:10.1093/petrology.egi092.

Buck, W.R. and Su, W., **1989**. Focused mantle upwelling below mid-ocean ridges due to feedback between viscosity and melting. Geophys. Res. Lett., 16(7): 641-644.

Burmin, V.Y., **2008**. Viscosity of the Earth's core based on seismic data. Doklady Earth Sciences 419, 316-319. doi:10.1134/s1028334x08020293

Canales, J.P., Carton, H., Carbotte, S.M., Mutter, J.C., Nedimović, M.R., Xu, M., Aghaei, O., Marjanović, M., and Newman, K., **2012**. Network of off-axis melt bodies at the East Pacific Rise, Nat. Geosci., doi:10.1038/NGEO1377

Canales, J.P., Detrick, R.S., Bazin, S., Harding, A.J., and Orcutt, J.A., **1998**. Off-axis crustal thickness across and along the East Pacific Rise within the MELT area. Science 280, 1218-1221. doi:10.1126/science.280.5367.1218

Canales, J.P., Detrick, R.S., Lin, J., Collins, J.A. and Toomey, D.R., **2000**. Crustal and upper mantle seismic structure beneath the rift mountains and across a nontransform offset at the Mid-Atlantic Ridge (35 degrees N). J. Geophys. Res., 105(B2): 2699-2719.

Canales, J.P., Detrick, R.S., Toomey, D.R. and Wilcock, W.S.D., **2003**. Segment-scale variations in the crustal structure of 150-300 kyr old fast spreading oceanic crust (East Pacific Rise, 8 degrees 15' N-10 degrees 5' N) from wide-angle seismic refraction profiles. Geophys. J. Int., 152(3): 766-794.

Canales, J.P., Nedimovic, M.R., Kent, G.M., Carbotte, S.M., Detrick, R.S., **2009**. Seismic reflection images of a near-axis melt sill within the lower crust at the Juan de Fuca ridge. Nature 460, 89-U100. doi:10.1038/nature08095

Cannat, M., **1996**. How thick is the magmatic crust at slow spreading oceanic ridges? J. Geophys. Res., 101(B2): 2847-2857.

Cannat, M., Mevel, C., Maia, M., Deplus, C., Durand, C., Gente, P., Agrinier, P., Belarouchi, A., Dubuisson, G., Humler, E. and Reynolds, J., **1995**. Thin crust, ultramafic exposures, and rugged faulting patterns at Mid-Atlantic Ridge (22 degrees 24 degrees N). Geology, 23: 49-52.

Carlson, R.L., **2010**. How crack porosity and shape control seismic velocities in the upper oceanic crust: modeling downhole logs from Holes 504B and 1256D. Geochem. Geophys. Geosyst., 11: Q04007. doi:10.1029/2009GC002955

Carlson, R.L. and Johnson, H.P., **1994**. On Modeling the Thermal Evolution of the Oceanic Upper-Mantle - an Assessment of the Cooling Plate Model. J. Geophys. Res., 99(B2): 3201-3214.

Carlson, R.L. and Miller, D.J., **1997**. A new assessment of the abundance of serpentinite in the oceanic crust. Geophys. Res. Lett., 24(4): 457-460.

Caro, G., **2011**. Early Silicate Earth Differentiation. Annual Review of Earth and Planetary Sciences, Vol 39 39, 31-58. doi:10.1146/annurev-earth-040610-133400

Cherkaoui A. S. M., W. S. D. Wilcock, R. A. Dunn, D. R. Toomey, **2003**. A numerical model of hydrothermal cooling and crustal accretion at a fast spreading mid-ocean ridge, Geochem. Geophys. Geosyst., 4 (9), 8616, doi:10.1029/2001GC000215

Chou, C. L., **1978**. Fractionation of siderophile elements in the Earth's upper mantle. Proc. Lunar Planet. Sci. Conf. 9, 219–230.

Christie, D.M., Ildefonse, B., Abe, N., Arai, S., Bach, W., Blackman, D.K., Duncan, R., Hooft, E., Humphris, S.E., and Miller, D.J., **2006**. Meeting report. Mission Moho: Formation and Evolution of Oceanic Lithosphere. Eos, Trans., AGU, 87 (48), 539.

Clague, D.A., Holcomb, R.T., Sinton, J.M., Detrick, R.S., Torresan, M.E., **1990**, Pliocene and Pleistocene alkali flood basalts on the seafloor north of the Hawaiian Islands: Earth. Planet Sci. Lett., 98, 175-191.

Clague, D.A., Uto, K., Satake, K., and Davis, A., **2002**, Eruption style and flow emplacement in the submarine North Arch volcanic field, Hawaii: in: Am. Geophys. Union Monograph 128, p. 65-84.

Coggon, R.M., and Teagle, D.A.H., **2011**. Hydrothermal calcium-carbonate veins reveal past ocean chemistry. Trends Anal. Chem., 30, 1252-1268. doi:10.1016/j.trac.2011.02.011

Coggon, R.M., Teagle, D.A.H., Cooper, M.J. and Vanko, D.A., **2004**. Linking basement carbonate vein compositions to porewater geochemistry across the eastern flank of the Juan de Fuca Ridge, ODP Leg 168. Earth Planet. Sci. Lett., 219(1-2): 111-128.

Coggon, R.M., Teagle, D.A.H., and Jones, T.D., **2011**. Comment on "What do we know about the evolution of Mg to Ca ratios in seawater?" by Wally Broecker and Jimin Yu. Paleoceanography 26, 6. doi:Pa3224 10.1029/2011pa002186

Coggon, R.M., Teagle, D.A.H., Smith-Duque, C.E., Alt, J.C., and Cooper, M.J., **2010**. Reconstructing Past Seawater Mg/Ca and Sr/Ca from Mid-Ocean Ridge Flank Calcium Carbonate Veins. Science, 327, 1114-1117. doi:10.1126/science.1182252

Coogan, L.A., **2008**. Reconciling temperatures of metamorphism, fluid fluxes, and heat transport in the upper crust at intermediate to fast spreading mid-ocean ridges. Geochemistry Geophysics Geosystems 9. doi:Q02013 10.1029/2007gc001787

Coogan, L.A., Hain, A., Stahl, S. and Chakraborty, S., **2005a**. Experimental determination of the diffusion coefficient for calcium in olivine between 900 degrees C and 1500 degrees C. Geochim. Cosmochim. Acta, 69: 3683-3694.

Coogan, L.A., Howard, K.A., Gillis, K.M., Bickle, M.J., Chapman, H., Boyce, A.J., Jenkin, G.R.T. and Wilson, R.N., **2006**. Chemical and thermal constraints on focused fluid flow in the lower oceanic crust. Am. J. Sci., 306(6): 389-427.

Coogan, L.A., Jenkin, G.R.T. and Wilson, R.N., **2002**. Constraining the cooling rate of the lower oceanic crust: a new approach applied to the Oman ophiolite. Earth Planet. Sci. Lett., 199: 127-146.

Coogan, L.A., Kasemann, S.A. and Chakraborty, S., **2005b**. Rates of hydrothermal cooling of new oceanic upper crust derived from lithium-geospeedometry. Earth Planet. Sci. Lett., 240: 415-424.

Crawford, W.C. and Webb, S.C., **2002**. Variations in the distribution of magma in the lower crust and the Moho beneath the East Pacific Rise at 9°-10° N. Earth Planet. Sci. Lett., 203: 117-130.

Crombie, W.J., **1964**. Why the Mohole? Adventures in the Inner Space. Little, Brown & Co, Boston, 230 pp.

Davis, A.C., Bickle, M.J. and Teagle, D.A.H., **2003**. Imbalance in the oceanic strontium budget. Earth Planet. Sci. Lett., 211(1-2): 173-187.

Davis, E.E. and Lister, C.R.B., **1974**. Fundamentals of ridge crest topography. Earth Planet. Sci. Lett., 21: 405-413.

Delacour, A., Fruh-Green, G.L., Frank, M., Gutjahr, M., and Kelley, D.S., **2008**. Sr- and Nd-isotope geochemistry of the Atlantis Massif (30 degrees N, MAR): Implications for fluid fluxes and lithospheric heterogeneity. Chemical Geology 254, 19-35. doi:10.1016/j.chemgeo.2008.05.018

Demouchy, S., Jacobsen, S.D., Gaillard, F., Stern, C.R., **2006**. Rapid magma ascent recorded by water diffusion profiles in mantle olivine. Geology 34, 429-432. doi:10.1130/g22386.1

Detrick, R.S., Buhl, P., Vera, E., Mutter, J., Orcutt, J., Madsen, J. and Brocher, T., **1987**. Multi-channel seismic imaging of a crustal magma chamber along the East Pacific Rise. Nature, 326: 35-41.

Detrick, R., Collins, J., Stephen, R. and Swift, S., **1994**. In situ evidence for the nature of the seismic layer 2/3 boundary in oceanic crust. Nature, 370(6487): 288-290.

Dick, H.J.B., **1989**. Abyssal peridotites, very slow spreading ridges and ocean ridge magmatism, in Saunders, A.D., and Norry, M.J., eds., Magmatism in the Ocean Basins, Geol. Soc. Spec. Pub. 42, p. 71-105.

Dick, H.J.B., Meyer, P.S., Bloomer, S., Kirby, S., Stakes, D. and Mawer, C., **1991**. Lithostratigraphic evolution of an in-situ section of oceanic layer 3. In: R.P. Von Herzen, P.T. Robinson et al. (Editors), Proc. ODP, Sci. Results, 118: College Station, TX (Ocean Drilling Program), 439–540.

Dick, H.J.B., J.H. Natland, J.C. Alt, W. Bach, D. Bideau, J.S. Gee, S. Haggas, J.G.H. Hertogen, G. Hirh, P.M. Holm, B. Ildefonse, G.J. Iturrino, B.E. John, D.S. Kelley, E. Kikawa, A. Kingdon, P.J. LeRoux, J. Maeda, P.S. Meyer, J.D. Miller, H.R. Naslund, Y. Niu, P.T. Robinson, J. Snow, R.A. Stephen, P.W. Trimby, H.U. Worm, and A. Yoshinobu. **2000**. A long in-situ section of the lower ocean crust: results of ODP Leg 176 drilling at the Southwest Indian Ridge. Earth Planet. Sci. Lett. 179:31-51.

Dick, H.J.B., Natland, J.H., and Ildefonse, **2006**. Past and Future Impact of Deep Drilling in the Ocean Crust and Mantle: An Evolving Order Out of New Complexity. Oceanography, 19 (4): 72-80.

Drouin, M., Godard, M., Ildefonse, B., Bruguier, O., and Garrido, C., **2009**. Geochemical and petrographic evidence for magmatic impregnation in the oceanic lithosphere at Atlantis Massif, Mid-Atlantic Ridge (IODP Hole U1309D, 30°N). Chem. Geol., 264, 71-88. doi:10.1016/j.chemgeo.2009.02.013

Drouin, M., Ildefonse, B., and Godard, M., **2010**. A microstructural imprint of melt impregnation in slow spreading lithosphere: Olivine-rich troctolites from the Atlantis Massif, Mid-Atlantic Ridge, 30°N, IODP Hole U1309D, Geochem. Geophys. Geosyst., 11, Q06003, doi:10.1029/2009GC002995.

Dunn, R.A., Toomey, D.R., and Solomon, S.C., **2000**. Three-dimensional seismic structure and physical properties of shallow mantle beneath the East Pacific Rise at 9°30'N. J. Geophys. Res. 105, 23537-23556. doi:10.1029/2000JB900210

Dunn, R.A., Toomey, D.R., Detrick, R.S. and Wilcock, W.S.D., **2001**. Continuous mantle melt supply beneath an overlapping spreading centre on the East Pacific Rise. Science, 291: 1955-1958.

Dunn, R.A., and Forsyth, D.W., **2003**. Imaging the transition between the region of mantle melt generation and the crustal magma chamber beneath the southern East Pacific Rise with short-period Love waves. J. Geophys. Res.108. doi:2352 10.1029/2002jb002217

Edwards, K.J., Wheat, C.G., and Sylvan, J.B., **2011**. Under the sea: microbial life in volcanic oceanic crust. Nature Reviews Microbiology. doi:10.1038/nrmicro2647

Eittreim, S.L., Gnibidenko, H., Helsley, C.E., Sliter, R., Mann, D. and Ragozin, N., **1994**. Oceanic Crustal Thickness and Seismic Character Along a Central Pacific Transect. J. Geophys. Res., 99(B2): 3139-3145.

Faul, U.H. and Jackson, I., **2005**. The seismological signature of temperature and grain size variations in the upper mantle. Earth Planet. Sci. Lett., 234(1-2): 119-134.

Fisk, M.R., Giovannoni, S.J., Thorseth, I.H., **1998**. Alteration of oceanic volcanic glass: Textural evidence of microbial activity. Science, 281, 978-980.

Fontaine, F.J., Wilcock, W.S.D., **2007**. Two-dimensional numerical models of open-top hydrothermal convection at high Rayleigh and Nusselt numbers: Implications for mid-ocean ridge hydrothermal circulation. Geochem. Geophys. Geosyst., 8. Q07010. doi:10.1029/2007gc001601

Forsyth, D.W., Scheirer, D.S., Webb, S.C., Dorman, L.M., Orcutt, J.A., Harding, A.J., Blackman, D.K., Morgan, J.P., Detrick, R.S., Shen, Y., Wolfe, C.J., Canales, J.P., Toomey, D.R., Sheehan, A.F., Solomon, S.C., and Wilcock, W.S.D., **1998**. Imaging the deep seismic structure beneath a mid-ocean ridge: The MELT experiment. Science 280, 1215-1218.

Furnes, H., Staudigel, H., Thorseth, I.H., Torsvik, T., Muehlenbachs, K., Tumyr, O., **2001**. Bioalteration of basaltic glass in the oceanic crust. Geochem. Geophys. Geosyst., 2, 2000gc000150.

Furnes, H., Banerjee, N.R., Muehlenbachs, K., Staudigel, H., and de Wit, M., **2004**, Early life recorded in Archean pillow lavas. Science, 304, 578-581.

Garmany, J., **1989**. Accumulations of melt at the base of young oceanic crust. Nature, 340: 628-632.

Garrido, C.J., Kelemen, P.B. and Hirth, G., **2001**. Variation of cooling rate with depth in lower crust formed at an oceanic spreading ridge: Plagioclase crystal size distributions in gabbros from the Oman ophiolite. Geochem. Geophys. Geosyst., 2, 10.1029/2000GC000136.

Gee, J.S., Meurer, W.P., Selkin, P.A. and Cheadle, M.J., **2004**. Quantifying three-dimensional silicate fabrics in cumulates using cumulative distribution functions. J. Petrol., 45(10): 1983-2009.

Gilbert, L.A., and Salisbury, M.H., **2011**. Oceanic crustal velocities from laboratory and logging measurements of Integrated Ocean Drilling Program Hole 1256D. Geochem. Geophys. Geosyst., 12, Q09001, doi:10.1029/2011GC003750.

Gillis, K.M., and Coogan, L.A., **2011**. Secular variation in carbon uptake into the ocean crust. Earth Planet. Sci. Lett. 302, 385-392. doi:10.1016/j.epsl.2010.12.030

Gillis, K.M., Coogan, L.A. and Pedersen, R., **2005**. Strontium isotope constraints on fluid flow in the upper oceanic crust at the East Pacific Rise. Earth Planet. Sci. Lett., 232: 83-94.

Godard, M., Awaji, S., Hansen, H., Hellebrand, E., Brunelli, D., Johnson, K., Yamasaki, T., Maeda, J., Abratis, M., Christie, D., Kato, Y., Mariet, C., Rosner, M., **2009**. Geochemistry of a long in-situ section of intrusive slow-spread oceanic lithosphere: Results from IODP Site U1309 (Atlantis Massif, 30 degrees N Mid-Atlantic-Ridge). Earth Planet. Sci. Lett. 279, 110-122.

Godard, M., Jousselin, D. and Bodinier, J.-L., **2000**. Relationships between geochemistry and structure beneath a palaeo-spreading centre: A study of the mantle section in the Oman Ophiolite. Earth Planet. Sci. Lett., 180: 133-148. doi:10.1016/S0012-821X(00)00149-7

Godard, M., Lagabrielle, Y., Alard, O., Harvey, J., **2008**. Geochemistry of the highly depleted peridotites drilled at ODP Sites 1272 and 1274 (Fifteen-Twenty Fracture Zone, Mid-Atlantic Ridge): Implications for mantle dynamics beneath a slow spreading ridge. Earth Planet. Sci. Lett. 267, 410-425. doi:10.1016/j.epsl.2007.11.058

Gregory, R.T. and Taylor, H.P.J., **1981**. An oxygen isotope profile in a section of Cretaceous oceanic crust, Samail ophiolite, Oman: evidence for δ18O buffering of the oceans by deep (>5km) seawater-hydrothermal circulation at mid-ocean ridges. J. Geophys. Res., 86: 2737-2755.

Hallenborg, E., Harding, A.J., Kent, G.M. and Wilson, D.S., **2003**. Seismic structure of 15 Ma oceanic crust formed at an ultrafast spreading East Pacific Rise: Evidence for kilometer-scale fracturing from dipping reflectors. J. Geophys. Res., 108(B11), 2532, doi:10.1029/2003JB002400.

Hardie, L.A., **1996**. Secular variation in seawater chemistry: An explanation for the coupled secular variation in the mineralogies of marine limestones and potash evaporites over the past 600 my. Geology 24, 279-283. doi:10.1130/0091-7613(1996)024<0279:svisca>2.3.co;2

Harding, A.J., Orcutt, J.A., Kappus, M.E., Vera, E.E., Mutter, J.C., Buhl, P., Detrick, R.S., Brocher, T.M., **1989**. Structure of young oceanic crust at 13°N on the East Pacific Rise from expanding spread profiles. J. Geoph. Res., 94, 12163-12196. doi:10.1029/JB094iB09p12163

Hart, S.R., Blusztajn, J., Dick, H.J.B., Meyer, P.S. and Muehlenbachs, K., **1999**. The fingerprint of seawater circulation in a 500-meter section of ocean crust gabbros. Geochim. Cosmoch. Acta, 63(23-24): 4059-4080.

Harvey, J., Gannoun, A., Burton, K.W., Rogers, N.W., Alard, O., Parkinson, I.J., **2006**. Ancient melt extraction from the oceanic upper mantle revealed by Re-Os isotopes in abyssal peridotites from the Mid-Atlantic ridge. Earth Planet. Sci. Lett. 244, 606-621.

Hazen, R.M., Hemley, R.J., and Mangum, A.J., **2012**. Carbon in Earth's interior: storage, cycling and life. Eos Trans. AGU, 93(2), 17-18. doi:10.1029/2012EO020001

Henstock, T.J., Woods, A.W. and White, R.S., **1993**. The accretion of oceanic crust by episodic sill intrusion. J. Geophys. Res., 98(B3): 4143-4161.

Hess, H.H., **1960**. Evolution of ocean basins. Report to Office of Naval Research. Contract No. 1858(10), NR 081-067. pp. 38.

Hess, H.H., **1962**. The history of the ocean basins, in: Engel, A.E.J., James, H.L., Leonard, B.F. (Eds.), Petrologic studies: a volume in honor of A.F. Buddington. Geol. Soc. Am. Bull., pp. 599-620.

Hiraga, T., Anderson, I.M., Kohlstedt, D.L., **2004**. Grain boundaries as reservoirs of incompatible elements in the Earth's mantle. Nature 427, 699-703. 10.1038/nature02259

Hiraga, T., Hirschmann, M.M., Kohlstedt, D.L., **2007**. Equilibrium interface segregation in the diopside-forsterite system II: Applications of interface enrichment to mantle geochemistry. Geoch. Cosmoch. Acta 71, 1281-1289. 10.1016/j.gca.2006.11.020

Hirschmann, M., and Kohlstedt, D., **2012**. Water in Earth's mantle. Phys. Today 65, 40. doi:10.1063/PT.3.1476

Holtzman B. K., N. J. Groebner, M. E. Zimmerman, S. B. Ginsberg, and D. L. Kohlstedt, **2003**. Stress-driven melt segregation in partially molten rocks, Geochem. Geophys. Geosyst., 4 (5), 8607, doi:10.1029/2001GC000258s

Horen, H., Zamora, M. and Dubuisson, G., **1996**. Seismic waves velocities and anisotropy in serpentinized peridotites from Xigaze ophiolite: Abundance of serpentine in slow spreading ridge. Geophys. Res. Lett., 23(1): 9-12.

Horita, J., Zimmermann, H., and Holland, H.D., **2002**. Chemical evolution of seawater during the Phanerozoic: Implications from the record of marine evaporites. Geoch. Cosmoch. Acta 66, 3733-3756. doi:10.1016/s0016-7037(01)00884-5

Ildefonse, B., Billiau, S. and Nicolas, A., **1995**. A detailed study of mantle flow away from diapirs in the Oman ophiolite. In: R.L.M. Vissers and A. Nicolas (Editors), mantle and lower crust exposed in oceanic ridges and in ophiolites. Kluwer, Dordrecht, pp. 163-177.

Ildefonse, B., Christie, D.M., and Mission Moho Workshop Steering Committee, **2007a**. Mission Moho workshop : drilling through the oceanic crust to the Mantle. Scientific Drilling, 4:11-18. doi:10.2204/iodp.sd.4.02.2007.

Ildefonse, B., Rona, P.A., and Blackman, D.K., **2007b**. Deep Sampling of the Crust formed at Mid- Ocean Ridges : Scientific Ocean Drilling provides perspective 'in-depth'. Oceanography, 20(1) : 22-33.

Ildefonse, B., Blackman, D.K., john, B.E., Ohara, Y., Miller, D.J., MacLeod, C.J., and the IODP Expeditions 304-305 Scientists, **2007c**. Oceanic Core Complexes and Crustal Accretion at Slow-Spreading Ridges. Geology, 35, 623-626. doi:10.1130/G23531A.1

Ildefonse B., Abe, N., Blackman, D.K., Canales, J.P., Isozaki, Y., Kodaira, S., Myers, G., Nakamura, K., Nedimovic, M., Seama, N., Skinner, A., Takazawa, E., Teagle, D.A.H., Tominaga, M., Umino, S., Wilson, D.S., and Yamao, M., **2010a**. The MoHole : A Crustal Journey and Mantle Quest, Workshop Report, Kanazawa, Japan, 3-5 June 2010. http://mohole.org

Ildefonse, B., Abe, N., Blackman, D.K., 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., **2010b**. The MoHole: A Crustal Journey and Mantle Quest, Workshop in Kanazawa, Japan, 3–5 June 2010. Scientific Drilling, 10, 56-62. doi:10.2204/iodp.sd.10.07.2010

Javoy, M., **1997**. The major volatile elements of the Earth: Their origin, behavior, and fate. Geophys. Res. Lett. 24, 177-180. doi:10.1029/96gl03931

Kárason H., and van der Hilst R.D., **2000**. Constraints on mantle convection from seismic tomography. In Richards, M.R., Gordon, R., van der Hilst, R.D., (eds) The history and dynamics of global plate motion. AGU Geophys. Mono. 212:277-288.

Karson, J.A., and Elthon, D., **1987**. Evidence for variations in magma production along oceanic spreading centers: a critical appraisal. Geology, 15: 127-131.

Kashefi K., and Lovley D.R., **2003**. Extending the Upper Temperature Limit for Life. Science, 301 (5635), 934. doi:10.1126/science.1086823

Kelemen, P.B., and Dick, H.J.B., **1995**. Focused Melt Flow and Localized Deformation in the Upper-Mantle - Juxtaposition of Replacive Dunite and Ductile Shear Zones in the Josephine Peridotite, Sw Oregon. J. Geophys. Res., 100(B1): 423-438.

Kelemen, P.B., Hirth, G., Shimizu, N., Spiegelman, M., and Dick, H.J.B., **1997a**. A review of melt migration processes in the adiabatically upwelling mantle beneath oceanic spreading ridges. Philosophical Transactions of the Royal Society of London Series a-Mathematical Physical and Engineering Sciences, 355(1723): 283-318.

Kelemen, P.B., Kikawa, E., Miller, D.J., et al., **2004**. Proc. ODP, Init. Repts., 209: College Station, TX (Ocean Drilling Program). doi:10.2973/odp.proc.ir.209.2004.

Kelemen, P.B., Kikawa, E., Miller, D.J., and Shipboard Scientific Party, **2007**. Leg 209 summary: processes in a 20-km-thick conductive boundary layer beneath the Mid-Atlantic Ridge, 14°–16°N. In Kelemen, P.B., Kikawa, E., and Miller, D.J. (Eds.), Proc. ODP, Sci. Results, 209: College Station, TX (Ocean Drilling Program), 1–33. doi:10.2973/odp.proc.sr.209.001.2007

Kelemen, P., Koga, K. and Shimizu, N., **1997b**. Geochemistry of gabbro sills in the crust-mantle transition zone of the Oman ophiolite: implications for the origin of the oceanic lower crust. Earth Planet. Sci. Lett., 146: 475-488.

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_2 Capture and Storage. Annual Review of Earth and Planetary Sciences, Vol 39 39, 545-576. doi:10.1146/annurev-earth-092010-152509

Kelemen, P., Shimizu, N. and Salters, V.J.M., **1995**. Extraction of mid-ocean-ridge basalt from the upwelling mantle by focused flow of melt in dunite channels. Nature, 375: 747-753.

Kelley, D.S., Karson, J.A., Fruh-Green, G.L., Yoerger, D.R., Shank, T.M., Butterfield, D.A., Hayes, J.M., Schrenk, M.O., Olson, E.J., Proskurowski, G., Jakuba, M., Bradley, A., Larson, B., Ludwig, K., Glickson, D., Buckman, K., Bradley, A.S., Brazelton, W.J., Roe, K., Elend, M.J., Delacour, A., Bernasconi, S.M., Lilley, M.D., Baross, J.A., Summons, R.T. and Sylva, S.P., **2005**. A serpentinite-hosted ecosystem: The lost city hydrothermal field. Science, 307(5714): 1428-1434.

Kennett B.L.N., **1991**. IASPEI 1991 Seismological Tables, pp vii+167, Research School of Earth Sciences, ANU (compiler & editor), distributed by Bibliotech, Canberra.

Kent, G.M., Singh, S.C., Harding, A.J., Sinha, M.C., Orcutt, J.A., Barton, P.J., White, R.S., Bazin, S., Hobbs, R.W., Tong, C.H. and Pye, J.W., **2000**. Evidence from three-dimensional seismic reflectivity images for enhanced melt supply beneath mid-ocean-ridge discontinuities. Nature, 406(6796): 614-618.

Kidd, R.G.W., **1977**. Nature and shape of sources of marine magnetic anomalies. Earth Planet. Sci. Lett. 33, 310-320. doi:10.1016/0012-821x(77)90083-8

Kimura, H., Asada, R., Masta, A., Naganuma, T., **2003**. Distribution of microorganisms in the subsurface of the Manus Basin hydrothermal vent field, Papua New Guinea. Appl. Environ. Microbiol. 69, 644-648. doi:10.1128/AEM.69.1.644-648.2003

Kimura, H., Mori, K., Tashiro T., Kato, K., Yamanaka, T., Ishibashi, J., Hanada, S., **2010**. Culture-independent estimation of optimal and maximum growth temperatures of archaea in subsurface habitats based on the G+C content in 16S rRNA gene sequences. Geomicrobiol. J. 27, 114-122. doi:10.1080/01490450903456699

Kimura, K., Lewis, R.S., Anders, E., **1974**. Distribution of gold and rhenium between nickel-iron and silicate melts: implications for the abundances of siderophile elements on the earth and moon. Geoch. Cosmoch. Acta 38, 683-701. doi:10.1016/0016-7037(74)90144-6

Klein, E.M. and Langmuir, C.H., **1987**. Global Correlations of Ocean Ridge Basalt Chemistry with Axial Depth and Crustal Thickness. J. Geophys. Res., 92(B8): 8089-8115.

Kodaira, S., Fujie, G., Yamashita, M., Noguchi, N., Sato, T., Takahashi, T., Kaiho, Y., Tamamoto, Y., Takahashi, N., **2010**. New seismic images in the NW Pacific and its implications for tectono-magmatic processes at paleo-fast-spreading ridge. Abstract T21H-07 presented at 2010 Fall Meeting, AGU, San Francisco, Calif., 13-17 Dec.

Koepke, J., Berndt, J., Feig, S.T., Holtz, F., **2007**. The formation of SiO2-rich melts within the deep oceanic crust by hydrous partial melting of gabbros. Contrib. Mineral. Petrol., 153:67–84. DOI 10.1007/s00410-006-0135-y

Korenaga, J., **2008**. Urey ratio and the structure and evolution of Earth's mantle. Rev. Geophys., 46, RG2007, doi:10.1029/2007RG000241

Korenaga, J., Holbrook, W.S., Detrick, R.S. and Kelemen, P.B., **2001**. Gravity anomalies and crustal structure at the southeast Greenland margin. J. Geophys. Res., 106(B5): 8853-8870.

Korenaga, J. and Kelemen, P.B., **1997**. Origin of gabbro sills in the Moho transition zone of the Oman ophiolite: Implications for magma transport in the oceanic lower crust. J. Geophys. Res., 102(B12): 27729-27749.

Korenaga, J. and Kelemen, P.B., **1998**. Melt migration through the oceanic lower crust: a constraint from melt percolation modeling with finite solid diffusion. Earth Planet. Sci. Lett., 156: 1-11.

Labrosse, S., Hernlund, J.W., and Coltice, N., **2007**. A crystallizing dense magma ocean at the base of the Earth's mantle. Nature 450, 866-869. doi:10.1038/nature06355

Langmuir, C.H., Klein, E.M., and Plank, T., **1982**, Petrological systematics of mid-ocean ridge basalts: Constraints on melt generation beneath ocean ridges, in Phipps Morgan, J., Blackman, D.K., and Sinton, J.M., eds., Mantle flow and melt generation: Washington, DC, AGU, p. 183-280.

Leahy, G.M., Collins, J.A., Wolfe, C.J., Laske, G., and Solomon, S.C., **2010**, Underplating of the Hawaiian Swell: evidence from teleseismic receiver functions. Geophys. J. Int., 183, 313-329.

Lissenberg, C.J., Dick, H.J.B., **2008**. Melt-rock reaction in the lower oceanic crust and its implications for the genesis of mid-ocean ridge basalt. Earth Planet. Sci. Lett. 271, 311-325.

Lorand, J.P., Alard, O., Luguet, A., Keays, R.R., **2003**. Sulfur and selenium systematics of the subcontinental lithospheric mantle: Inferences from the Massif Central xenolith suite (France). Geoch. Cosmoch. Acta 67, 4137-4151. doi:10.1016/s0016-7037(00)00305-3

Lorand, J.-P., Alard, O., **2010**. Determination of selenium and tellurium concentrations in Pyrenean peridotites (Ariege, France): New insight into S/Se/Te systematics of the upper in mantle samples. Chemical Geology 278, 120-130. doi:10.1016/j.chemgeo.2010.09.007

Luyendyk, B.P., **1970**. Origin and History of Abyssal Hills in Northeast Pacific-Ocean. Geological Society of America bulletin, 81(8): 2237-2260. doi:10.1130/0016-7606(1970)81[2237:OAHOAH]2.0.CO;2

Maclennan, J., Hulme, T. and Singh, S.C., **2004**. Thermal models of oceanic crustal accretion: Linking geophysical, geological and petrological observations. Geochem. Geophys. Geosyst., 5, Q02F25, doi:10.1029/2003GC000605.

Maclennan, J., Hulme, T. and Singh, S.C., **2005**. Cooling of the lower oceanic crust. Geology, 33(5): 357-360.

MacLeod, C.J. and Yaouancq, G., **2000**. A fossil melt lens in the Oman ophiolite: implications for magma chamber processes at fast spreading ridges. Earth Planet. Sci. Lett., 176: 357-373.

Malpas, J., Brace, T., and Dunsworth, S.M., **1989**. Structural and petrologic relationships of the CY-4 drill hole of the Cyprus Crustal Study Project, in: I.L. Gibson, J. Malpas, P.T. Robinson, C. Xenophontos (Eds.), Cyprus Crustal Study Project: Initial Report, Hole CY-4, Geological Survey of Canada Paper 88-9, pp. 39-67.

Manning, C.E., Weston, P.E. and Mahon, K.I., **1996**. Rapid high-temperature metamorphism of east Pacific rise gabbros from Hess deep. Earth Planet. Sci. Lett., 144(1-2): 123-132.

Marty, B., **2012**. The origins and concentrations of water, carbon, nitrogen and noble gases on Earth. Earth Planet. Sci. Lett. 313, 56-66.

Mason, O.U., Nakagawa, T., Rosner, M., Van Nostrand, J.D., Zhou, J.Z., Maruyama, A., Fisk, M.R., Giovannoni, S.J., **2010**. First Investigation of the Microbiology of the Deepest Layer of Ocean Crust. Plos One, 5. doi:e15399 10.1371/journal.pone.0015399

McCollom, T.M. and Seewald, J.S., **2001**. A reassessment of the potential for reduction of dissolved CO2 to hydrocarbons during serpentinization of olivine. Geochimica Cosmochimica Acta, 65(21): 3769-3778.

McCollom, T.M., Lollar, B.S., Lacrampe-Couloume, G., Seewald, J.S., **2010**. The influence of carbon source on abiotic organic synthesis and carbon isotope fractionation under hydrothermal conditions. Geoch. Cosmoch. Acta, 74, 2717-2740. doi:10.1016/j.gca.2010.02.008

McKenzie, D.P., **1967**. The viscosity of the mantle. Geophys. J. Royal Astr. Soc., 14, 297-305.

McKenzie, D. and Bickle, M.J., **1988**. The Volume and Composition of Melt Generated by Extension of the Lithosphere. J. Petrol., 29(3): 625-679.

McLoughlin, N., Furnes, H., Banerjee, N.R., Muehlenbachs, K., and Staudigel, H., **2009**. Ichnotaxonomy of microbial trace fossils in volcanic glass. J. Geol. Soc., 166: 159-169.

Michibayashi, K., Gerbert-Gaillard, L., Nicolas, A., **2000**. Shear sense inversion in the Hilti mantle section (Oman ophiolite) and active mantle uprise. Mar. Geophys. Res. 21, 259-268.

Morton, J.L. and Sleep, N.H., **1985a**. Seismic reflections from a Lau basin magma chamber. In: D.W. Scholl and T.L. Vallier (Editors), Geology and offshore resources of pacific island arcs-Tonga region. Circum-Pacific Council for Energy and Mineral Resources, Earth Science Series, Houston, Texas, pp. 441-453.

Morton, J.L. and Sleep, N.H., **1985b**. A mid-ocean ridge thermal model : constraints on the volume of axial hydrothermal heat flux. J. Geophys. Res., 90(B13): 11345-11353.

Murray, R.W., Schrag, D.P., and Wheat, C.G., **2002**. Opportunities in Geochemistry for Post-2003 Ocean Drilling: Tyngsboro, MA (JOI/USSSP).

Myers, G., **2008**. Ultra-deepwater riserless mud circulation with dual gradient drilling. Scientific Drilling, 6, 48-51. doi:10.22 04/iodp.sd.6.07.2008

Nakagawa, T., and Tackley, P.J., **2004**. Thermo-chemical structure in the mantle arising from a three-component convective system and implications for geochemistry. Phys. Earth Planet. Int. 146, 125-138. doi:10.1016/j.pepi.2003.05.006

Natland, J.H., and Dick, H.J.B., **1996**. Melt migration through high-level gabbroic cumulates of the East Pacific Rise at Hess Deep: the origin of magma lenses and the deep crustal structure of fast-spreading ridges. In Mével, C., Gillis, K.M., Allan, J.F., and Meyer, P.S. (Eds.), Proc. ODP, Sci. Results, 147: College Station, TX (Ocean Drilling Program), 21–58.

Nedimovic, M. R., Carbotte, S. M., Harding, A. J., Detrick, R. S., Canales, J. P., Diebold, J. B., Kent, G. M., Tischer, M., and Babcock, J. M., **2005**. Frozen magma lenses below the oceanic crust. Nature, 436: 1149-1152. doi:10.1038/nature03944

Nicolas, A., **1986**. A melt extraction model based on structural studies in mantle peridotites. J. Petrol., 27: 999-1022.

Nicolas, A., Boudier, F., and France, L., **2009**. Subsidence in magma chamber and the development of magmatic foliation in Oman ophiolite gabbros. Earth Planet. Sci. Lett., 284: 76–87. doi:10.1016/j.epsl.2009.04.012

Nicolas, A., Boudier, F. and Ildefonse, B., **1994**. Evidence from the Oman ophiolite for active mantle upwelling beneath a fast-spreading ridge. Nature, 370: 51-53.

Nielsen, S.G., Rehkamper, M., Teagle, D.A.H., Butterfield, D.A., Alt, J.C. and Halliday, A.N., **2006**. Hydrothermal fluid fluxes calculated from the isotopic mass balance of thallium in the ocean crust. Earth Planet. Sci. Lett., 251(1-2): 120-133.

Niu, Y.L., **2004**. Bulk-rock major and trace element compositions of abyssal peridotites: Implications for mantle melting, melt extraction and post-melting processes beneath mid-ocean ridges. J. Petrol. 45, 2423-2458. doi:10.1093/petrology/egh068

O'Hara, M.J., **1968**. Are ocean floor basalts primary magma? Nature, 220(5168), 683-686.

Orcutt, B.E., Sylvan, J.B., Knab, N.J., and Edwards, K.J., **2011**. Microbial Ecology of the Dark Ocean above, at, and below the Seafloor. Microbiology and Molecular Biology Reviews, 75, 361–422. doi:10.1128/MMBR.00039-10

Ozawa, K., **1986**. Partitioning of elements between constituent minerals in peridotites from the Miyamori ultramafic complex, Kitakami Mountains, Northeast Japan; estimation of P-T condition and igneous composition of minerals. Journal of the Faculty of Science, University of Tokyo, Section 2: Geology, Mineralogy, Geography, Geophysics, 21(3), 115-137.

Pallister, J.S. and Hopson, C.A., **1981**. Semail ophiolite plutonic suite ; field relations, phase variation, cryptic variation and layering, and a model of a spreading ridge magma chamber. J. Geoph. Res., 86: 2593-2644.

Pedersen, R.B., Malpas, J., and Falloon, T., **1996**. In Mével, C., Gillis, K.M., Allan, J.F., and Meyer, P.S. (Eds.), Proc. ODP, Sci. Results, 147: College Station, TX (Ocean Drilling Program), 3–19.

Penrose Conference Participants. **1972**. Penrose field conference on ophiolites. Geotimes 17:24-25.

Phipps Morgan, J., **1987**. Melt Migration beneath Mid-Ocean Spreading Centers. Geophys. Res. Lett., 14(12): 1238-1241.

Phipps Morgan, J. and Chen, Y.J., **1993**. The genesis of oceanic crust: Magma injection, hydrothermal circulation, and crustal flow. J. Geophys. Res., 98: 6283-6297.

Picard, A., Daniel, I., Testemale, D., Kieffer, I., Bleuet, P., Cardon, H., and Oger, P.M., **2011**. Monitoring microbial redox transformations of metal and metalloid elements under high pressure using in situ X-ray absorption spectroscopy. Geobiology 9, 196-204. doi:10.1111/j.1472-4669.2010.00270.x

Quick, J.E. and Denlinger, R.P., **1993**. Ductile deformation and the origin of layered gabbro in ophiolites. J. Geophys. Res., 98: 14015-14027.

Rabinowicz, M. and Ceuleneer, G., **2005**. The effect of sloped isotherms on melt migration in the shallow mantle: a physical and numerical model based on observations in the Oman ophiolite. Earth Planet. Sci. Lett., 229(3-4): 231-246.

Rabinowicz, M., Nicolas, A. and Vigneresse, J.L., **1984**. A rolling mill effect in asthenosphere beneath oceanic spreading centers. Earth Planet. Sci. Lett., 67: 97-108.

Ravelo, C., Bach, W., Behrmann, J., Camoin, G., Duncan, R., Edwards, K., Gulick, S., Inagaki, S., Pälike, H., and Tada, R., **2010**. INVEST Report: IODP New Ventures in Exploring Scientific Targets (INVEST) - Defining the New Goals of an International Drilling Program. Scientific Planning Conference at Bremen, 2009, 22-25 September, 160pp., http://www.marum.de/Binaries/Binary48779/INVEST_Report_full.pdf.

Ritsema, J., Deuss, A., van Heijst, H.J., and Woodhouse, J.H., **2011**. S40RTS: a degree-40 shear-velocity model for the mantle from new Rayleigh wave dispersion, teleseismic traveltime and normal-mode splitting function measurements. Geophys. J. Int. 184, 1223-1236. doi:10.1111/j.1365-246X.2010.04884.x

Reston, T.J., Ranero, C.R., Belykh, I., **1999**. The structure of Cretaceous oceanic crust of the NW Pacific: Constraints on processes at fast spreading centers. J. Geophys. Res., 104, 629-644. doi:10.1029/98jb02640

Rubin, K.H., Sinton, J.M., **2007**. Inferences on mid-ocean ridge thermal and magmatic structure from MORB compositions. Earth Planet. Sci. Lett. 260, 257-276.

Rudge, J.F., Kleine, T., Bourdon, B., **2010**. Broad bounds on Earth's accretion and core formation constrained by geochemical models. Nature Geoscience 3, 439-443. doi:10.1038/ngeo872

Saal, A.E., Hauri, E.H., Langmuir, C.H., Perfit, M.R., **2002**. Vapour undersaturation in primitive mid-ocean-ridge basalt and the volatile content of Earth's upper mantle. Nature 419, 451-455. doi:10.1038/nature01073

Salters, V. J. M., S. Mallick, S. R. Hart, C. E. Langmuir, and A. Stracke, **2011**. Domains of depleted mantle: New evidence from hafnium and neodymium isotopes, Geochem. Geophys. Geosyst., 12, Q08001, doi:10.1029/2011GC003617.

Schouten, H. and Kelemen, P.B., **2002**. Melt viscosity, temperature and transport processes, Troodos ophiolite, Cyprus. Earth Planet. Sci. Lett., 201(2): 337-352.

Schrenk, M.O., S.A. Bolton, D.S. Kelley, and J.A. Baross. **2004**. Low archaeal diversity linked to subseafloor geochemical processes at the Lost City Field, Mid Atlantic Ridge. Environ. Microbiol., 6: 1086-1095.

Schrenk, M.O., Huber, J.A., Edwards, K.J., **2010**. Microbial provinces in the subseafloor. Annual Review of Marine Science, 2, 279-304. doi:10.1146/annurev-marine-120308-081000

Shipboard Scientific Party, **2004**. Leg 209 summary. In : Kelemen, P.B., Kikawa, E., Miller, D.J., et al., 2004. Proc. ODP, Init. Repts., 209: College Station, TX (Ocean Drilling Program), doi:10.2973/odp.proc.ir.209.101.2004

Simmons, N.A., Forte, A.M., and Grand, S.P., **2009**. Joint seismic, geodynamic and mineral physical constraints on three-dimensional mantle heterogeneity: Implications for the relative importance of thermal versus compositional heterogeneity. Geophys. J. Int. 177, 1284-1304. doi:10.1111/j.1365-246X.2009.04133.x

Singh, S. C., A. J. Harding, G. M. Kent, M. C. Sinha, V. Combier, S. Bazin, C. H. Tong, P. J. Barton, R. W. Hobbs, R. S. White and J. A. Orcutt, **2006**. Seismic reflection images of the Moho underlying melt sills at the East Pacific Rise, Nature, 442, 287-290.

Singh, S.C., Kent, G.M., Collier, J.S., Harding, A.J. and Orcutt, J.A., **1998**. Melt to mush variations in crustal magma properties along the ridge crest at the southern East Pacific Rise. Nature, 394(6696): 874-878.

Sinton, J.M., and Detrick, R.S., **1992**. Mid-ocean ridge magma chambers. J. Geophys. Res., 97, 197–216. doi:10.1029/91JB02508

Sleep, N.H., **1975**. Formation of oceanic crust; some thermal constraints. J. Geophys. Res., 80(29), 4037-4042.

Sleep, N.H., Zahnle, K., **2001**. Carbon dioxide cycling and implications for climate on ancient Earth. Journal of Geophysical Research-Planets 106, 1373-1399. doi:10.1029/2000je001247

Snow, J.E., Hart, S.R., and Dick, H.J.B., **1994**. Nd and Sr isotope evidence linking mid-ocean-ridge bassalts and abyssal peridotites. Nature 371, 57-60. doi:10.1038/371057a0

Sparks, D.W. and Parmentier, E.M., **1991**. Melt Extraction from the Mantle beneath Spreading Centers. Earth Planet. Sci. Lett., 105(4): 368-377.

Spiegelman, M. and Kenyon, P., **1992**. The Requirements for Chemical Disequilibrium During Magma Migration. Earth Planet. Sci. Lett., 109(3-4): 611-620.

Spiegelman, M. and McKenzie, D., **1987**. Simple 2-D Models for Melt Extraction at Midocean Ridges and Island Arcs. Earth Planet. Sci. Lett., 83(1-4): 137-152.

Spinelli, G.A., Harris, R.N., **2011**. Effects of the legacy of axial cooling on partitioning of hydrothermal heat extraction from oceanic lithosphere. Journal of Geophysical Research-Solid Earth 116. doi:B09102 10.1029/2011jb008248

Staudigel, H., Furnes, H., Banerjee, N.R., Dilek, Y. & Muehlenbachs, K., **2006**, Microbes and volcanoes: A tale from the oceans, ophiolites and greenstone belts. GSA Today, v. 16, No. 10, p. 4–10, doi: 10.1130/GSAT01610A.1.

Stein, C. A., Stein, S., **1994**. Constraints on hydrothermal heat flux through the oceanic lithosphere from global heat flow. J. Geophys. Res., 99, 3081-3096, 10.1029/93JB02222.

Steinberger, B., and Holme, R., **2002**. An explanation for the shape of Earth's gravity spectrum based on viscous mantle flow models. Geophys. Res. Lett. 29. doi:2019 10.1029/2002gl015476

Stracke, A., Snow, J.E., Hellebrand, E., von der Handt, A., Bourdon, B., Birbaum, K., Gunther, D., **2011**. Abyssal peridotite Hf isotopes identify extreme mantle depletion. Earth Planet. Sci. Lett. 308, 359-368. doi:10.1016/j.epsl.2011.06.012

Suhr, G., Hellebrand, E., Johnson, K., Brunelli, D., **2008**. Stacked gabbro units and intervening mantle: A detailed look at a section of IODP Leg 305, Hole U1309D, Geochem. Geophys. Geosyst., 9, Q10007, doi:10.1029/2008GC002012

Swift, S., Reichow, M., Tikku, A., Tominaga, M., and Gilbert, L., **2008**. Velocity structure of upper ocean crust at Ocean Drilling Program Site 1256. Geochemistry Geophysics Geosystems, 9, Q10O13. doi:10.1029/2008GC002188

Takai, K., Nakamura, K., Toki, T., Tsunogai, U., Miyazaki, M., Miyazaki, J., Hirayama, H., Nakagawa, S., Nunoura, T., Horikoshi, K., **2008**. Cell proliferation at 122 degrees C and isotopically heavy CH(4) production by a hyperthermophilic methanogen under high-pressure cultivation. Proc. Nat. Acad. Sci. USA, 105, 10949-10954. doi:10.1073/pnas.0712334105

Teagle, D.A.H., Alt, J.C. and Halliday, A.N., **1998a**. Tracing the evolution of hydrothermal fluids in the upper oceanic crust: Sr-isotopic constraints from DSDP/ODP Holes 504B and 896A. In: Mills, R.A. & Harrison, K. (eds) Modern Ocean Floor Processes and the Geological Record, Geological Society, London, Special Publications, 148, 81-97.

Teagle, D.A.H., Alt, J.C., and Halliday, A.N., **1998b**. Tracing the chemical evolution of fluids during hydrothermal recharge: constraints from anhydrite recovered in ODP Hole 504B. Earth Planet. Sci. Lett., 155: 167–182. doi:10.1016/S0012-821X(97)00209-4

Teagle, D.A.H., Alt, J.C., Umino, S., Miyashita, S., Banerjee, N.R., Wilson, D.S., and the Expedition 309/312 Scientists, **2006**. Proc. IODP, 309/312: Washington, DC (Integrated Ocean Drilling Program Management International, Inc.). doi:10.2204/iodp.proc.309312.2006

Teagle, D.A.H., Bickle, M.J. and Alt, J.C., **2003**. Recharge flux to ocean-ridge black smoker systems: a geochemical estimate from ODP Hole 504B. Earth Planet. Sci Lett, 210: 81-89.

Teagle, D.A.H., Ildefonse, B., Blackman, D.K., 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. Southampton, July 2009, http://www.interridge.org/WG/DeepEarthSampling/workshop2009

Teagle, D.,A.H. and Ildefonse, B., **2011**. Journey to the Mantle of the Earth, Nature, 471, 437-439. doi:10.1038/471437a

Teagle, D.A.H., Ildefonse, B., Blum, P., and the Expedition 335 Scientists, **2012**. Proc. IODP, 335: Tokyo (Integrated Ocean Drilling Program Management International, Inc.). doi:10.2204/iodp.proc.335.2012

Teagle, D.A.H., Wilson, D.S., Acton, G.D. and ODP Leg 206 Shipboard Science Party, **2004**. The "Road to the MoHole" four decades on: Deep drilling at Site 1256. EOS, Trans. Am. Geophys. Union, 85: 521,530-531.

Thorseth, I.H., Torsvik, T., Torsvik, V., Daae, F.L., Pedersen, R.B., and Keldysh-98 Scientific Party, **2001**. Earth Planet. Sci. Lett., 194, 31-37. doi: 10.1016/S0012-821X(01)00537-4

Touboul, M., Puchtel, I.S., Walker, R.J., **2012**. W-182 Evidence for Long-Term Preservation of Early Mantle Differentiation Products. Science 335, 1065-1069. doi:10.1126/science.1216351

Turcotte, D.L. and Schubert, G., **1982**. Geodynamics. John WIley, New York, 550 pp.

van Keken, P.E., Hauri, E.H., Ballentine, C.J., **2002**. Mantle mixing: The generation, preservation, and destruction of chemical heterogeneity. Annu. Rev. Earth Planet. Sci. 30, 493-525. doi:10.1146/annurev.earth.30.091201.141236

VanTongeren, J.A., Kelemen, P.B., Hanghoj, K., **2008**. Cooling rates in the lower crust of the Oman ophiolite: Ca in olivine, revisited. Earth Planet. Sci. Lett. 267, 69-82.

Vibetti, N. J., Kerrich, R., and Fyfe, W. S. **1989**. Oxygen and carbon isotope studies of hydrothermal alteration in the Troodos ophiolite complex, Cyprus. In Cyprus Crustal Study Project: Initial Report, Hole CY-4, Geological Survey Canada Paper 88–9, eds. I. L. Gibson, J. Malpas, P. T. Robinson, and C. Xenophontos. Ottawa: Geological Survey Canada, pp. 221–228.

Wanke, H., and Gold, T., **1981**. Constitution of terrestrial planets. Phil. Trans. R. Soc. Lond. A, 3030, 287-302.

Warren, J.M., Shimizu, N., Sakaguchi, C., Dick, H.J.B., Nakamura, E., **2009**. An assessment of upper mantle heterogeneity based on abyssal peridotite isotopic compositions. Journal of Geophysical Research-Solid Earth 114. doi:B12203 10.1029/2008jb006186

White, R.S., McKenzie, D., and O'Nions, R.K., **1992**. Oceanic crustal thickness from seismic measurements and rare earth element inversions. J. Geoph. Res., 97(B13): 19683-19715. doi:10.1029/92JB01749

Wilkinson, B.H., and Algeo, T.J., **1989**. Sedimentary carbonate record of calcium magnesium cycling. American Journal of Science 289, 1158-1194.

Wilson, D.S., Hallenborg, E., Harding, A.J., and Kent, G.M., **2003**. Data report: Site survey results from cruise EW9903. In Wilson, D.S., Teagle, D.A.H., Acton, G.D., et al., Proc. ODP, Init. Repts., 206: College Station, TX (Ocean Drilling Program), 1–49. doi:10.2973/odp.proc.ir.206.104.2003

Wilson, D.S., Teagle, D.A.H., Alt, J.C., Banerjee, N.R., Umino, S., Miyashita, S., Acton, G.D., Anma, R., Barr, S.R., Belghoul, A., Carlut, J., Christie, D.M., Coggon, R.M., Cooper, K.M., Cordier, C., Crispini, L., Durand, S.R., Einaudi, F., Galli, L., Gao, Y.J., Geldmacher, J., Gilbert, L.A., Hayman, N.W., Herrero-Bervera, E., Hirano, N., Holter, S., Ingle, S., Jiang, S.J., Kalberkamp, U., Kerneklian, M., Koepke, J., Laverne, C., Vasquez, H.L.L., Maclennan, J., Morgan, S., Neo, N., Nichols, H.J., Park, S.H., Reichow, M.K., Sakuyama, T., Sano, T., Sandwell, R., Scheibner, B., Smith-Duque, C.E., Swift, S.A., Tartarotti, P., Tikku, A.A., Tominaga, M., Veloso, E.A., Yamasaki, T., Yamazaki, S. and Ziegler, C., **2006**. Drilling to gabbro in intact ocean crust. Science, 312(5776): 1016-1020.

Wood, B.J., **2011**. The formation and differentiation or Earth. Physics Today, Deceember 2011, 40-45. doi:10.1063/PT.3.1362

Wood, B.J., Halliday, A.N., **2010**. The lead isotopic age of the Earth can be explained by core formation alone. Nature 465, 767-U764. doi:10.1038/nature09072

Wood, B.J., Halliday, A.N., and Rehkämper, M., **2010**. Volatile accretion history of the Earth. Nature, 467, doi:10.1038/nature09484

Workshop Report Writing Group, **2011**. Executive Summary: "Mantle Frontier" Workshop. Sci. Drill., 11, 53-57. doi:10.2204/iodp.sd.11.07.2011

Yang, J.S., Dobrzhinetskaya, L., Bai, W.J., Fang, Q.S., Rolbinson, P.T., Zhang, J., Green, H.W., **2007**. Diamond- and coesite-bearing chromitites from the Luobusa ophiolite, Tibet. Geology 35, 875-878. doi:10.1130/g23766a.1

Yaouancq, G. and MacLeod, C.J., **2000**. Petrofabric Investigation of Gabbros from the Oman Ophiolite: Comparison between AMS and rock fabric. Mar. Geoph. Res., 21(3-4): 289-305.

Zhu, W.L., Gaetani, G.A., Fusseis, F., Montesi, L.G.J., and De Carlo, F., **2011**. Microtomography of Partially Molten Rocks: Three-Dimensional Melt Distribution in Mantle Peridotite. Science 332, 88-91. doi:10.1126/science.1202221

FULL LIST OF PROPONENTS

Lead proponents :

Susumu Umino, Kanazawa University, Japan, sesumin@staff.kanazawa-u.ac.jp
Volcanology and igneous petrology
Benoît Ildefonse, CNRS, Montpellier University, France, ildefonse@um2.fr
Petrophysics and tectonics
Peter B. Kelemen, LDEO, Columbia University, USA, peterk@ldeo.columbia.edu
Mantle and igneous petrology and geochemistry
Shuichi Kodaira, JAMSTEC/IFREE, Yokosuka, Japan, kodaira@jamstec.go.jp
Seismology
Katsuyoshi Michibayashi, Shizuoka University, Japan, sekmich@ipc.shizuoka.ac.jp
Mantle and igneous petrology and structures
Tomoaki Morishita, Kanazawa University, Japan, moripta@staff.kanazawa-u.ac.jp
Mantle and igneous petrology and geochemistry
Damon A.H. Teagle, NOCS, Southampton, UK, damon.teagle@southampton.ac.uk
Alteration petrology and geochemistry

Co-proponents :

Natsue Abe, JAMSTEC/IFREE, Yokosuka, Japan, abenatsu@jamstec.go.jp
Mantle petrology and geochemistry
Olivier Alard, CNRS, Montpellier University, France, oalard@univ-montp2.fr
Mantle petrology and geochemistry, planetary evolution
Shoji Arai, Kanazawa University, Japan, ultrasa@staff.kanazawa-u.ac.jp
Mantle and igneous petrology and geochemistry
Gary Acton, University of California, Davis, USA, acton@geology.ucdavis.edu
Paleomagnetism, rock magnetism
Jeffrey C. Alt, University of Michigan, Ann Arbor, USA, jalt@umich.edu
Alteration petrology and geochemistry
Ryo Anma, University of Tsukuba, Japan, ranma@sakura.cc.tsukuba.ac.jp
Structural geology
Wolfgang Bach, Universität Bremen, Germany, wbach@uni-bremen.de
Alteration petrology and geochemistry, subseafloor biosphere
Chris Ballentine, University of Manchester, UK, chris.ballentine@manchester.ac.uk
Isotope geochemistry, planetary evolution
Neil R. Banerjee, University of Western Ontario, Canada, neil.banerjee@uwo.ca
Alteration petrology and geochemistry, Subseafloor biosphere
Juan Pablo Canales, WHOI, Woods Hole, USA, jpcanales@whoi.edu
Seismology
Mathilde Cannat, CNRS, IPG, Paris, France, cannat@ipgp.fr
Geophysics and tectonics
Richard L. Carlson, Texas A&M University, USA, carlson@geo.tamu.edu
Seismology and petrophysics
Rosalind M. Coggon, Imperial College London, UK, r.coggon@imperial.ac.uk
Alteration petrology and geochemistry
Laurence Coogan, University of Victoria, Canada, lacoogan@uvic.ca
Igneous petrology and geochemistry
Henry J.B. Dick, WHOI, Woods Hole, USA, hdick@whoi.edu
Petrology, geochemistry and tectonics
Toshiya Fujiwara, JAMSTEC/IFREE, Yokohama, Japan, toshi@jamstec.go.jp
Marine geophysics

Yoshio Fukao, JAMSTEC/IFREE, Yokosuka, Japan, fukao@jamstec.go.jp
Geophysics, seismology
Jeffrey S. Gee, Scripps, UCSD, San Diego, USA, jsgee@ucsd.edu
Paleomagnetism, rock magnetism
Kathryn Gillis, University of Victoria, Canada, kgillis@uvic.ca
Alteration petrology and geochemistry
Marguerite Godard, CNRS, Montpellier University, France, marguerite.godard@um2.fr
Mantle and igneous petrology and geochemistry
Saskia Goes, Imperial College London, UK, sgoes@imperial.ac.uk
Geophysics, dynamics of lithosphere and mantle
Takeshi Hanyu, JAMSTEC/IFREE, Yokosuka, Japan, hanyut@jamstec.go.jp
Isotope geochemistry
Alistair Harding, Scripps, UCSD, San Diego, USA, aharding@ucsd.edu
Seismology
Yumiko Harigane, AIST, Tsukuba, Japan, y-harigane@aist.go.jp
Structural Geology
Erik Hauri, CIW, Washington DC, USA, hauri@dtm.ciw.edu
Geochemistry, planetary evolution
Eric Hellebrand, University of Hawaii, Honolulu, USA, ericwgh@hawaii.edu
Mantle Petrology and geochemistry
Ikuo Katayama, Hiroshima University, Japan, katayama@hiroshima-u.ac.jp
Rheology, petrophysics
Jeffrey A. Karson, Syracuse University, USA, jakarson@syr.edu
Petrology and tectonics
Hiroyuki Kimura, Shizuoka University, Japan, shkimur@ipc.shizuoka.ac.jp
Microbiology
Jun-Ichi Kimura, JAMSTEC/IFREE, Yokosuka, Japan, jkimura@jamstec.go.jp
Igneous petrology and geochemistry
Juergen Koepke, Universität Hannover, Germany, koepke@mineralogie.uni-hannover.de
Experimental petrology and geochemistry
Hidenori Kumagai, JAMSTEC/IFREE, Yokosuka, Japan, kumagai@jamstec.go.jp
Noble gas and igneous geochemistry
C. Johan Lissenberg, Cardiff University, UK, lissenbergcj@cardiff.ac.uk
Igneous petrology and geochemistry
John Maclennan, University of Cambridge, UK, jmac05@esc.cam.ac.uk
Geophysics
Jinichiro Maeda, Hokkaido University, Japan, jinmaeda@ep.sci.hokudai.ac.jp
Igneous petrology and geochemistry
Christopher J. MacLeod, Cardiff University, UK, macleod@cf.ac.uk
Petrology and tectonics
D. Jay Miller, IODP, TAMU, College Station, USA, miller@iodp.tamu.edu
Petrology and petrophysics, hard rock drilling
Sumio Miyashita, Niigata University, Japan, miyashit@geo.sc.niigata-u.ac.jp
Igneous petrology
Gregory F. Moore, University of Hawaii, Honolulu, USA, gmoore@Hawaii.edu
Seismology
Antony Morris, University of Plymouth, UK, amorris@plymouth.ac.uk
Paleomagnetism, rock magnetism
Kentaro Nakamura, JAMSTEC/PEL, Yokosuka, Japan, kentaron@jamstec.go.jp
Alteration petrology and geomicrobiology
James H. Natland, University of Miami, USA, jnatland@rsmas.miami.edu
Igneous petrology and geochemistry

Toshio Nozaka, Okayama University, Japan, nozaka@cc.okayama-u.ac.jp
Metamorphic petrology
Mladen Nedimovic, Dalhousie University, Canada, mladen@dal.ca
Seismology
Yasuhiko Ohara, Hydrographic and Oceanographic Department of Japan, ohara@jodc.go.jp
Mantle petrology
Eiji Ohtani, Tohoku University, Sendai, Japan, ohtani@m.tohoku.ac.jp
High-pressure mineral physics
Ian J. Parkinson, The Open University, UK, i.j.parkinson@open.ac.uk
Isotope geochemistry and petrology
Philippe Pezard, CNRS, Montpellier University, France, philippe.pezard@gm.univ-montp2.fr
Petrophysics and borehole geophysics
Mark Rehkamper, Imperial College London, UK, markrehk@imperial.ac.uk
Isotope geochemistry
Tetsuya Sakuyama, JAMSTEC/IFREE, Yokosuka, Japan, sakuyama@jamstec.go.jp
Igneous petrology and geochemistry
Takeshi Sato, JAMSTEC/IFREE, Yokohama, Japan, tsato@jamstec.go.jp
Seisomology
Matthew O. Schrenk, East Carolina University, Greenville, USA, schrenkm@ecu.edu
Microbiology
Nobukazu Seama, Kobe University, Japan, seama@kobe-u.ac.jp
Marine geophysics
Jonathan E. Snow, University of Houston, US, jesnow@uh.edu
Mantle petrology and geochemistry
Eiichi Takazawa, Niigata University, Japan, takazawa@geo.sc.niigata-u.ac.jp
Mantle petrology and geochemistry
Masako Tominaga, Michigan State University, East Lansing, USA, mtominaga@whoi.edu
Marine geophysics
Takeshi Tsuji, Kyoto University, Japan, tsuji@earth.kumst.kyoto-u.ac.jp
Seismology, borehole geophysics
Peter E. van Keken, University of Michigan, Ann Arbor, USA, keken@umich.edu
Mantle dynamics, planetary evolution
Jessica M. Warren, Stanford University, USA, warrenj@stanford.edu
Mantle petrology, geochemistry and rheology
Douglas S. Wilson, University of California, Santa Barbara, USA, dwilson@geol.ucsb.edu
Geophysics

NB: given the anticipated duration of the M2M project, the list of lead and co-proponents is expected to evolve with time, as the M2M community will continue building up.

> *"Perhaps it is true that we won't find out as much about the earth's interior from one hole as we hope. To those who raise that objection I say, if there is not a first hole, there cannot be a second or a tenth or a hundredth hole. We must make a beginning."*
> ***Harry Hess, April 1958***