

Breakthrough the Discontinuity: 21st Century Mohole

Umino, S. (Kanazawa Univ.), Abe, N. (IFREE, JAMSTEC), Arai, S. (Kanazawa Univ.), Kodaira, S. (IFREE, JAMSTEC), Seama, N. (Kobe Univ.), Nozaka, T. (Okayama Univ.), Takazawa, E. (Niigata Univ.), Miyashita, S. (Niigata Univ.), Tatsumi, Y. (IFREE, JAMSTEC) and Mohole Working Group Japan*

Abstract:

We propose to penetrate the entire oceanic crust formed at fast-spreading ridges and further drill into the uppermost mantle across the Moho, in order to comprehensively understand (1) the nature and origin of Moho discontinuity, (2) architecture and compositions of the oceanic crust and upper mantle, and (3) alteration processes and the frontiers of deep biosphere. The distribution of well-imaged Moho exhibiting seismological characteristics representative of sub-oceanic Moho should be indispensable to a possible drilling site. Furthermore, technological requirements may limit sites to be water depth < 4500m, with low Moho temperature (<250°C), DRF (Drilling depth below rig floor) <12 km, close to operational base (< 300 km) and stable sea current and weather conditions. Three sites in the Pacific Ocean may meet most but not all of the above criteria for the Mohole site; 1) the region around IODP-Site 1256, 2) the eastern edge of the north Hawaiian arch, and 3) the eastern Pacific plate off Mexico. Development of new technology must be required to complete the "21st Century Mohole". While waiting for the technological development and site survey, we propose to accomplish a "Pre-Mohole" with existing technology including off-set drilling, then proceed to the "Full-Mohole" that penetrates through normal, intact oceanic crust and the typical Moho discontinuity in the Pacific Ocean formed at a fast-spreading rate and into the uppermost mantle as deep as possible.

Introduction

The Moho discontinuity is the outermost boundary within the solid Earth (Fig. 1) and plays a major role in differentiation and evolution of the Earth's interior and the surface environment. Upwelling asthenosphere adiabatically melts to fractionate magma to form crust and the residual mantle through the Moho discontinuity. Hydrothermal circulation from the crust into the uppermost mantle through the Moho not only changes the physicochemical properties of the lithosphere and the chemical composition of the ocean but also modifies the Moho discontinuity by serpentinization of the mantle peridotite, where deep frontiers of microbes are expected. Subduction of altered lithosphere promotes geochemical differentiation and evolution of the mantle by dehydration in the shallow mantle and material transport deep into the mantle, which is in turn recycled as the crust by hot plumes and diapirs.

Thus, the processes of material and heat exchange through the Moho discontinuities govern the dynamics and evolution of the surface and the interior of the Earth. However, the nature of the Moho is poorly constrained and our knowledge on the origin of the Moho is solely based on fossil Moho such as those exposed in tectonic windows and ophiolites. To understand the nature of the Moho and the processes that operate through the Moho and to address the issues raised below, a complete penetration of intact normal oceanic crust into the uppermost mantle through the Moho is required. We propose to drill into a fast-spread crust in the Pacific which can be regarded as a representative, because it represents 50% of the entire oceanic plates on earth.

Nature of Moho

What is the Moho and how does it look like?

As a first step to address this fundamental proposition, an intensive seismic project in the northwestern Pacific has begun since 2009 by a Japanese group. The project is planned to cover a wide area of the Pacific plate at seaward side of the Kuril – Japan- Izu – Bonin trenches. Since the crust in this area is considered to be a representative of the old, stable and first-spreading oceanic crust based on clearly aligned strong magnetic anomalies, results from this project will significantly improve our knowledge of the seismological structure of the Moho and the upper mantle through the deep crust. The seismic images from this project will be used to compare synthetic Moho reflections calculated from a realistic model, which is created by referring field observations of crust/mantle transitions of ophiolite. Similar quality of pre-drilling seismological data must be acquired at candidate areas of the Mohole. Detailed implementation plans of intensive geophysical survey toward a site selection should be made under an international cooperation. Further issues and discussions relevant to the Moho are raised in a white paper by Shuichi Kodaira and others.

What operates in the Moho?

Studies on the Oman ophiolite suggest that the crust-mantle boundary is a transitional zone (Moho Transition Zone) consisting of dunites interlayered with gabbroic bands and wehrlites. The MTZ is formed by a significant mantle-melt reaction, which gives us a clue to understand material transfer from the upper mantle to the lower crust beneath mid-ocean ridges. Variations in mineral compositions across a complete section of the MTZ will be a key information to elucidate the progressive change in melt compositions and in mantle-melt reaction as a melt ascends through the MTZ. More directly, melt inclusions in spinel in the MTZ dunites can also provide the compositions of melt reacted with the MTZ peridotite. Eventually, coring the uppermost mantle peridotite beneath the MTZ provides us *in situ* mantle rocks for the first time in human history. This observation will be a direct constraint on the lithology of the uppermost mantle in the oceanic lithosphere. Further issues relevant to the Moho are discussed in white papers by Shoji Arai and Susumu Umino.

Architecture and compositions of the oceanic crust

Knowledge of the bulk chemical composition of the oceanic crust is critical to assess the total degree of melting of the source mantle and to put a constraint on the dynamics of magma genesis. Information of the bulk composition of the entire crust and the uppermost mantle as well as alteration mineralogy provides a fundamental data set as an input to the subduction factory.

Data set of the upper crustal structure such as stratigraphic variation of lithology and lithofacies, the occurrences of eruptive products, and lithodensity as well as the whole rock chemistry is crucial as it provides not only qualitative information of the volcanic activity but also quantitative information such as the depth of axial magma chamber (AMC) and the excess pressure of magma in the AMC. This is critical to understand the ridge dynamics that constructed the upper crust.

Geophysical modeling on the AMC beneath fast-spreading ridges show the presence of thin melt lens underlain by thick semi-consolidated crystal mush that extends down to the Moho but is only a few kilometers wide. There is a controversy how to accrete the thick lower crust from a thin melt lens. In addition to this, the mechanism of cooling the thick lower crust is vastly unknown. The lower crust is most likely composed of vari-textured and foliated upper gabbros underlain by layered gabbros. Cooling models of the lower crust suggest that the thicknesses of the upper and layered gabbros vary depending on the rates of magma supply and cooling. Then we may expect a systematic correlation between the lower and upper crustal structures. What are the origins of foliation and layering? A complete crustal penetration followed by detail analyses of mineral chemistry and textures can address these questions.

Alteration processes and the frontiers of deep biosphere

The oceanic lithosphere formed on the ridge subsequently changes its chemical and mineralogical compositions through hydrothermal alteration (Fig.2). Hydrothermal circulation paths are poorly constrained in time and space; when and where alteration take place? Does the hydrothermal circulation form a single cell through the upper crust or double convective cells? How deep and how far off the ridge does the alteration front proceed? Alteration processes of the deeper parts of the oceanic lithosphere are poorly known but of interest because microbes migrate along fluid pathways. Incipient and subsequent stages of alteration can be revealed by careful observations of mineralogy and textures in rocks. New findings on ecosystems dependent on H_2 released by serpentinization of mantle peridotite and Fe^{2+} in the basement basalt expanded the possibility of biosphere deep in the oceanic crust and mantle. More than 99% of the total biomass in oceanic area exists in the deep biosphere. These findings urge us to add search for the frontiers of subsurface ecosystems to the objectives of Mohole.

Criteria for site selection and description of potential sites

Taking into account the scientific objectives, the criteria for selecting the Mohole site are listed below:

- (1) Fast-spread oceanic lithosphere with normal crustal thickness (~6 km)
- (2) The presence of well-imaged Moho by seismic explorations with technological limitations of
- (3) Water depth < 4500m
- (4) Moho temperature (~250°C)
- (5) DRF (Drilling depth below rig floor) <12 km
- (6) Close to operational base (< 300 km)
- (7) Stable sea current and weather condition

Three sites in the Pacific Ocean meet the criteria for the Mohole; 1) the region around Site 1256, 2) the eastern edge of the north Hawaiian arch, and 3) the eastern Pacific plate off Mexico. No site fits all criteria, but all will be feasible to drill to the mantle. There could also be other recognized prospective sites and ideas are invited for additional possible sites that meet a majority of the long-term Mohole scientific objectives, although the water depth and lithospheric age (temperature) criteria strongly limit windows for the Mohole site because a model gives the lower Moho temperature for the older plate age but the deeper water depth. Further technological developments are needed to accomplish the drilling into the mantle.

The candidate sites are listed below:

1) Around Site 1256

- shallowest water depth (~3650m)
- highest Moho temperature (>250°C?)*
- well-known tectonics
- nearby a large port

2) The east of north Hawaiian arch

- great water depth (4100-4300 m)
- lowest-T ($\sim 150^{\circ}\text{C}$)*
- nearby a large port
- Effect of the arch magmatism should be avoided

3) The eastern Pacific plate off Mexico

- water depth (< 4500 m)
- Modest Moho-T ($\sim 250^{\circ}\text{C}$)*
- few data available
- no large port around

* Inferred temperatures

Technology and strategy

As is raised in the Initial Science Plan, technological innovation is longed for to put "21st Century Mohole Project" on track. Great water-depth (4500 m) and deep subbasement (7 km) drilling using riser technology, improvement of core recovery, logging tools operatable at high temperature ($< 250^{\circ}\text{C}$) and water pressure are required for accomplishment of the Mohole. Side-wall and branching drilling technology is needed to obtain as much data as possible from a single, ultradeep borehole. However, technological development takes a significant time and immense expenditure sustained by our persistent endeavors to carry out this historical project "21st Century Mohole". To overcome these difficulties, we propose a stepwise strategy toward the ultimate goal of Mohole:

(1) First step is to drill "Pre-Mohole" with current technology; Off-set drilling technique into aged cold lithosphere will be conducted. Meanwhile, technological development and required site survey of the "ultimate" Mohole are carried on. One candidate for this Pre-Mohole would be the fore-arc, trench-slope of an intra-oceanic arc.

(2) " Full-Mohole" penetrates through normal, intact oceanic crust and the typical Moho discontinuity in the Pacific Ocean formed at a fast-spreading rate and into the uppermost mantle as deep as possible.

Both geophysical and geological studies of the present ocean floor that extends beyond the mid-ocean ridges are prerequisite for understanding the variations of the Moho discontinuity and for selecting the drill sites of Mohole as described above. Compilation of available seismic profiles of oceanic crust and uppermost mantle as well as experiments on rock physical properties provide necessary datasets in modeling and interpreting the Moho reflection amplitudes and help determining the drill sites. Comparative studies of the present ocean floor and ophiolites will be essential experiences to understand the information obtained from the Mohole.

Figures

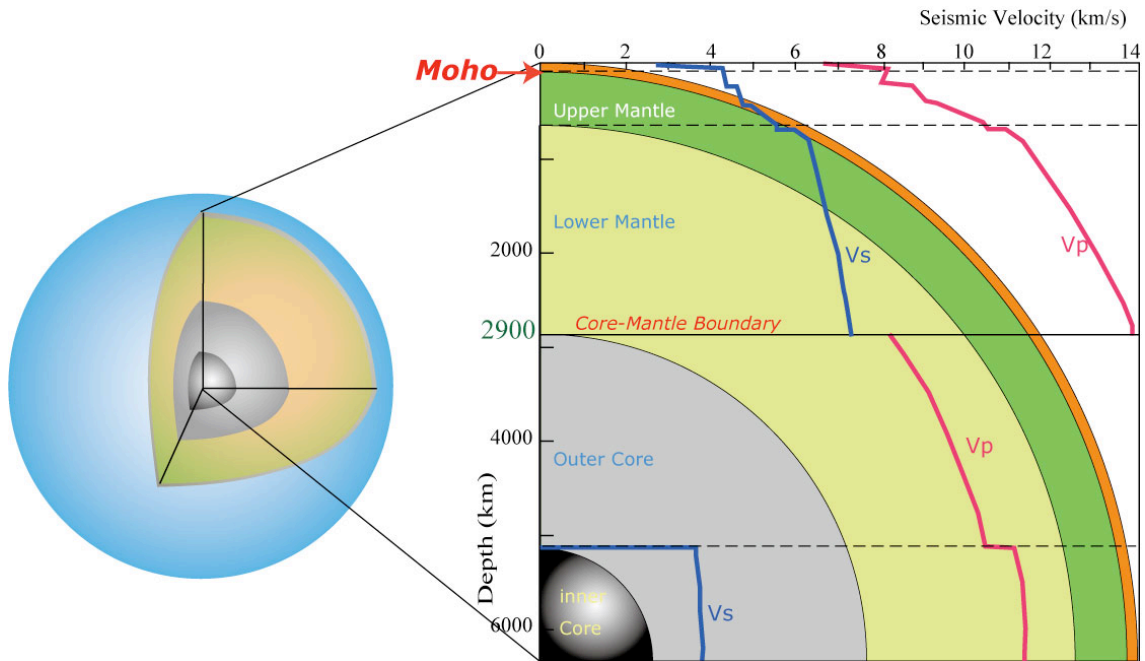


Fig. 1 Velocity-depth curves for P- and S-waves, and the interior structure of Earth.

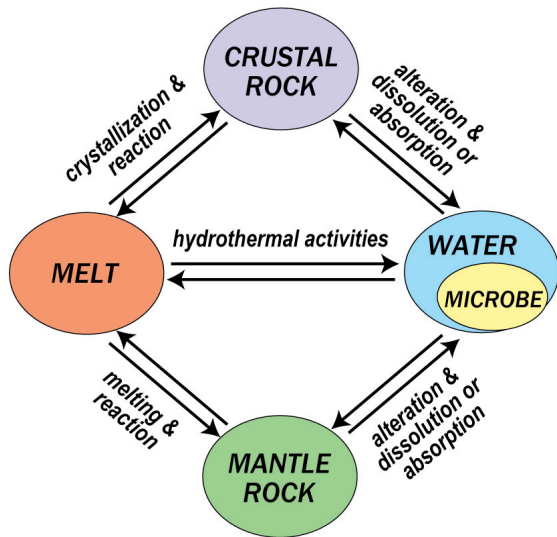


Fig. 2 "Moho system" -- Exchange of materials and energy