The MoHole

A Crustal Journey and Mantle Quest

Workshop Report

Kanazawa, Japan, 3-5 June 2010

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Executive Summary

Drilling an ultra-deep hole in an intact portion of oceanic lithosphere, through the crust to the Mohorovičić discontinuity (the 'Moho'), and into the uppermost mantle is a long-standing ambition of scientific ocean drilling, and remains essential to answer fundamental questions about the dynamics of the Earth and global elemental cycles. The 2010 MoHole workshop had two interconnected objectives, which have been discussed jointly between ocean lithosphere specialists, marine geophysicists, and engineers:

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

New deep drilling technology now make it possible to fulfill our long term aspiration to drill completely through intact oceanic crust and a significant distance into the upper mantle, and address a number of first-order scientific goals: what is the geological nature of the Moho? How is the oceanic crust formed at mid-ocean ridges, and what processes influence its subsequent evolution? What are the geophysical signatures of these magmatic, tectonic, hydrothermal, and biogeochemical chemical processes? What is the global composition of the oceanic crust, and what are the magnitudes of interactions with the oceans and biosphere, and their influence on global chemical cycles? What are the limits of life, the factors controlling these limits, and the changes in biological community composition with depth? What is the physical and chemical nature of the uppermost mantle, and how does it relate to the overlying magmatic crust?

The selected MoHole target would ideally meet a suite of scientific requirements including fast spreading rate, simple tectonic setting, "normal" crustal seismic structure, and strong reflectivity of Moho. Several technological constraints limit the range or possible sites, including in particular the trade-off between seafloor depth, which should be small enough to allow using mud re-circulating technologies, and temperature at Moho/upper mantle depths, which should be low enough (~≤250°C) to allow ultra deep drilling (6000 to 7000 meters below seafloor) in basement. The workshop participants discussed three areas in the Pacific Basin:

- The Cocos plate region encompasses a section of the Cocos Plate off Central America with crustal ages between 15 and 25 Ma. This area includes ODP Hole 1256D, a site of on-going deep drilling into intact ocean crust. This region sits within a corridor that includes a complete tectonic plate life cycle, making it an excellent candidate for understanding ocean crust evolution from a spreading center to subduction. However, temperature at Moho depth at Site 1256 may exceed technology limitations.
- The Off Southern/Baja California region encompasses a section of the eastern Pacific Plate between ~10-33°N, and ~130-115°W, with crustal ages 20-35 Ma. Very little modern geophysical information exists in this region.
- The Hawaii region is located north of Oahu in the flexural arch, where the crust is 80 Ma, and was formed at an intermediate half spreading rate of 35-40 mm/yr. This site offers the lowest temperature at Moho depth, but crustal structure is potentially

affected by hotspot volcanism, and its cretaceous age makes it difficult to relate geochemical changes to modern ocean chemistry or conditions.

Short-term priority is to conduct large-scale geophysical surveys (spatially coincident MCS, wide-angle OBS, multi-beam bathymetry, gravity, heat flow, and magnetic anomaly data) in the three selected regions, which will lead to the identification of a MoHole target that best satisfies the listed requirements. The first large-scale survey will be in the Off Southern/Baja California region; baseline reconnaissance seismic data are urgently required to assess whether this area can possibly meet the requirements. After an appropriate drilling target has been identified, the community should conduct detailed seismic surveys in its vicinity, to accurately image intracrustal reflectors and Moho, and to assess crustal structure and thickness variability and upper mantle velocity structure/anisotropy. Although JAMSTEC is taking the lead for conducting the first large-scale survey in 2011, other partners should make efforts to conduct or contribute to other large- and small-scale surveys. The scope and costs of these are too large to be undertaken by a single nation or funding agency; international collaboration is required.

Engineering efforts must be directed to ensure that our scientific goals are achieved. The technology and engineering development should be launched as soon as possible in conjunction with site-survey activities. To do so, establishing a realistic roadmap of technological development and testing is imperative. To drill an ultra deep borehole, the provision for continuous mud circulation is a top priority technology requirement. Various options were discussed at the workshop, and will need to be fully evaluated. Other major areas requiring engineering consideration include logging and coring in high temperature environment, drill bits (specifically designed for abrasive, hard rocks) and drill string (high tensile strength), drilling mud (developed for high temperature environment), and casing/cementing materials and strategies (specifically designed, ideally to the bottom of the hole).

Major challenges of the MoHole project will be associated with collecting the cored material, making in-situ measurements, installing casing and keeping the borehole open for successive episodes of deepening in a multiyear, multiphase operation. To gear up for operations, all issues related to drilling, casing, coring, and logging must be adequately explored and included in a comprehensive and complete operation plan, as soon as the site characteristics are known. The well design of the primary site may require data from a pilot hole, to properly evaluate parameters such as mud weights and casing set points. The pilot hole may be either a separate hole, or simply a pilot section of the main hole.

The keys for a successful MoHole project include scientific considerations, as well as technology development, industry engagement, and public engagement through outreach activities and education. The MoHole project will be one of the largest scientific endeavors in Earth science history, and this formidable challenge should provide precious opportunities to diverse scientific and technology communities. It will be essential to share these opportunities and achievements across a broad spectrum of Earth and Life scientists. Many of our primary scientific goals will require continuous core samples. To be regarded as successful, the MoHole project must at least return:

- Continuous cores of critical intervals (lithological boundaries; the region identified by seismic imaging as the Moho; the lower ~500m of the mafic and ultramafic

cumulate rocks in the oceanic crust; ~500m of peridotites and associated lithologies in the uppermost mantle below the Moho; sufficient sections of the igneous oceanic crust to test models of crustal accretion, melt movement, resolve the geometry and intensity of hydrothermal circulation, and document the limits and activity of the deep microbial biosphere).
- A continuous, comprehensive suite of geophysical logs and borehole experiments to measure in situ physical properties, to acquire borehole images, and to identify key geophysical and lithologic regions and transitions throughout the ocean crust and into the upper mantle.

Measurements of temperature and chemical compositions of the fluids are required together with biological analyses. Ultimately, it will be essential to integrate core/log/survey data in a comprehensive synthesis study of the Project Area. Post-drilling studies, such as successive fluid measurements/sampling, in situ microbial incubation in the borehole, or VSP experiments should also be performed.

As the oil and gas industry conducts operations in increasingly deep water, continuous collaboration with industry, and introduction of new technologies to the MoHole project will be keys to success. It will be necessary to establish a strategy to engage the industry in the project, exchange personnel, and plan joint development work.

Another key component of the success of a Mohole project will be to improve public support and understanding of the scientific goals and excitement of the project. Engaging the public through outreach and education activities, as well as being pro-active in advertising the project to the wider scientific community, will be essential. One tool to greatly increase the public and scientific profile of the project should be a dedicated, multi-language MoHole website, that should be implemented as soon as formal scoping activities commence.

The size and duration (10 years or more) of the MoHole project will require an appropriately funded, centralized science operations and engineering management group to oversee the project from start to successful completion. This project office will be vital key to success, and in order to succeed, it must be a truly international effort staffed by the best available project managers, engineers, and scientists.

1. Introduction

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

The 2010 MoHole workshop in Kanazawa, Japan, followed on from several recent scientific planning meetings on ocean lithosphere drilling, in particular the Mission Moho Workshop in 2006(http://www.iodp.org/mission-moho-workshop; Christie et al., 2006; Ildefonse et al., 2007), and the "Melting, Magma, Fluids and Life" meeting in 2009 (http://www.interridge.org/WG/DeepEarthSampling/workshop2009, Teagle et al., 2009). Participants to these previous meetings reached consensus that a deep hole through a complete section of fast-spread ocean crust is a renewed priority for the ocean lithosphere community. The scientific rationale for drilling a MoHole in fast-spread crust is developed in the workshop reports (available online), and most thoroughly articulated in the 2007 IODP Mission Moho drilling proposal (IODP Prop 719MP; http://www.missionmoho.org; see also Appendix 1).

The 2010 MoHole workshop had two interconnected objectives:

- To initiate a roadmap for the technology development and the project implementation plan that are necessary to achieve the deep drilling objectives of the MoHole project;
- To identify a limited number of potential MoHole sites in the Pacific (i.e., in fast-spread crust), where the scientific community will focus geophysical site survey efforts over the next few years. Selecting drilling sites is essential to clearly identify the range of water depths, drilling target depths and temperatures that we anticipate, and better define the technology required to be developed and implemented to drill, sample and log the MoHole.

The MoHole workshop discussions were held jointly between ocean lithosphere specialists, marine geophysicists, and drilling engineers, with the aim of identifying the best possible sites in fast-spread crust given our current geological, geophysical and technological knowledge and expertise, and to list the items that will need to be considered in a technology roadmap for the MoHole. This report summarizes these discussions, and provides the starting point to initiate the MoHole project.

2. Scientific Rationale for the MoHole, a Crustal Journey and Mantle Quest

The Moho is the fundamental boundary within the upper part of our planet, yet we have little knowledge of its geological meaning. New deep drilling technology now make it possible to fulfill scientists' long term aspiration to drill completely through intact oceanic crust, through the seismically defined Moho, and then a significant distance (~500 m) into the upper mantle. Our scientific goals can be divided into the following principal tightly interconnected threads:

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

These objectives (figure 1) are comprehensively articulated in the 2007 Mission Moho proposal (http://www.missionmoho.org; see Appendix 1), as well as in the 2006 "Mission Moho" workshop report (http://www.iodp.org/mission-moho-workshop; Christie et al., 2006) and the 2009 "Magma, Melting, Fluids and Life" meeting report (http://www.interridge.org/WG/DeepEarthSampling/workshop2009; Teagle et al., 2009), and are briefly summarized below.

2.1. The Mohorovičić Discontinuity

In the oceans, the Moho is commonly a bright seismic reflector at 5 to 8 km depth and marks an abrupt increase in P-wave seismic velocity (Vp) to values in excess of 8 km/s. It is generally assumed that the Moho also represents the boundary between mafic igneous rocks crystallized from magmas that form the crust and residual peridotites of the upper mantle. However, this interpretation has never been tested. Alternatively, there are geologically valid scenarios where the Moho might delineate the boundary between mafic and ultramafic cumulate rocks within the crust, or it may be located below serpentinized peridotites that were previously part of the mantle. Observations and sampling of the Moho, the petrologic crust-mantle boundary and the rocks of the upper mantle are fundamental to understanding the geodynamics and chemical differentiation of our planet. A foremost goal is to reconcile geophysical imaging of the Moho with direct geological observations of cores and downhole measurements; e.g., is the Moho in our study region a sharp compositional boundary or a transition zone of significant thickness (~100s of m)?

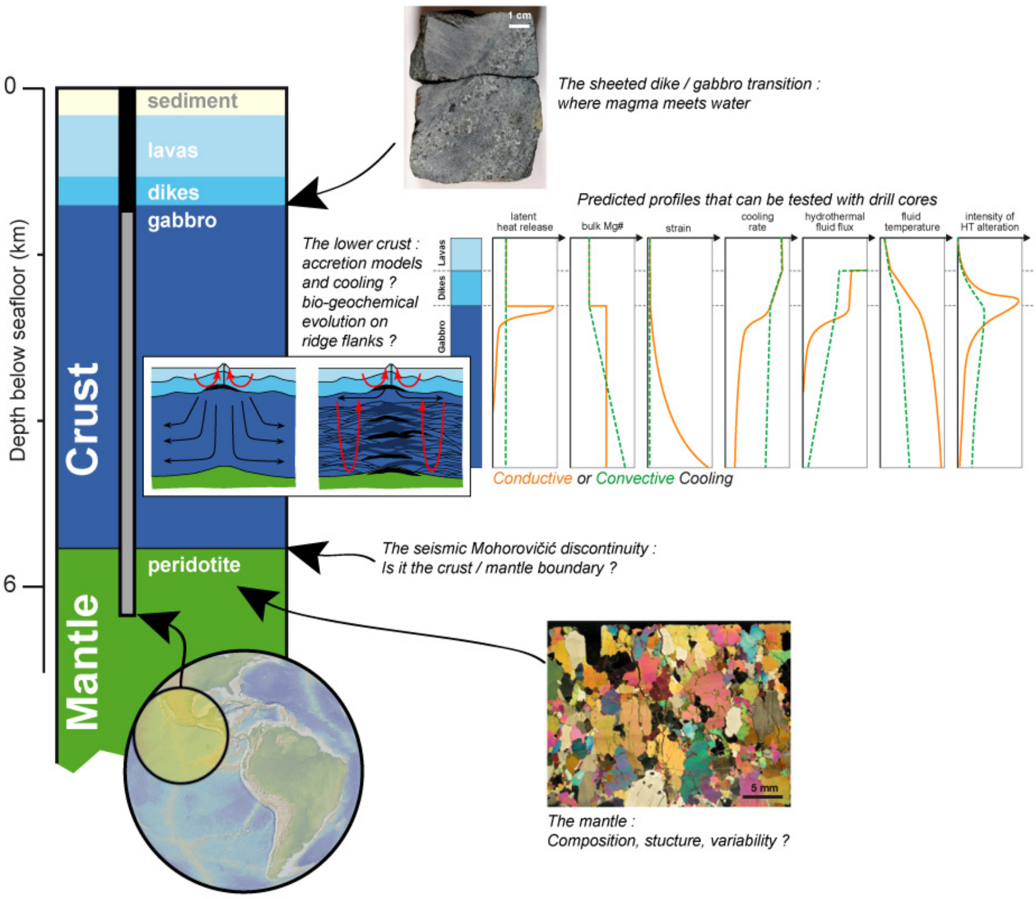


Figure 1: Schematic cross-section of fast-spread crust with anticipated MoHole penetration. The thicknesses of sediment, lavas and sheeted dike complex are taken from ODP/IODP Hole 1256D (Teagle et al., 2006). Top photograph: sheeted dike complex / gabbro contact in Hole 1256D. Predicted physical/chemical profiles in the crust: original figure from Rosalind Coggon (NB : the predicted Mg# profile for a sheeted sill model assumes that on average deeper sills will be more primitive and tend to feed shallower ones, the intrusion of primitive sills at shallow levels cannot be excluded though); lower crust accretion models: after Korenaga and Kelemen (1998). Bottom microphotograph: Mantle peridotite xenolith from French Polynesia (Tommasi et al., 2004). Figure by Benoît Ildefonse.

2.2. Formation of the lower crust

On the road to the Moho, we will make paradigm-testing observations of the lower oceanic crust and the deep magmatic, tectonic and hydrothermal processes that occur at the mid-ocean ridges. Our principal target will be intact ocean crust formed at a fast-spreading ridge, which should be relatively laterally uniform, and where we have well-developed theoretical models of crustal accretion that can be tested by drilling. Is the lower oceanic crust formed from the subsidence of a high-level magma chamber, or are there multiple melt bodies at different levels within the oceanic crust (or upper mantle) at fast spreading ridges?

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

2.3. Composition and hydration of the ocean crust

A full penetration will provide the first direct estimate of the bulk composition of ocean crust critical for Earth differentiation models. How deeply do seawater-derived hydrothermal fluids penetrate and how efficient is hydrothermal circulation at heat extraction and chemical alteration? Is fluid flow channeled by major faults or more pervasive? (Fig. 2)

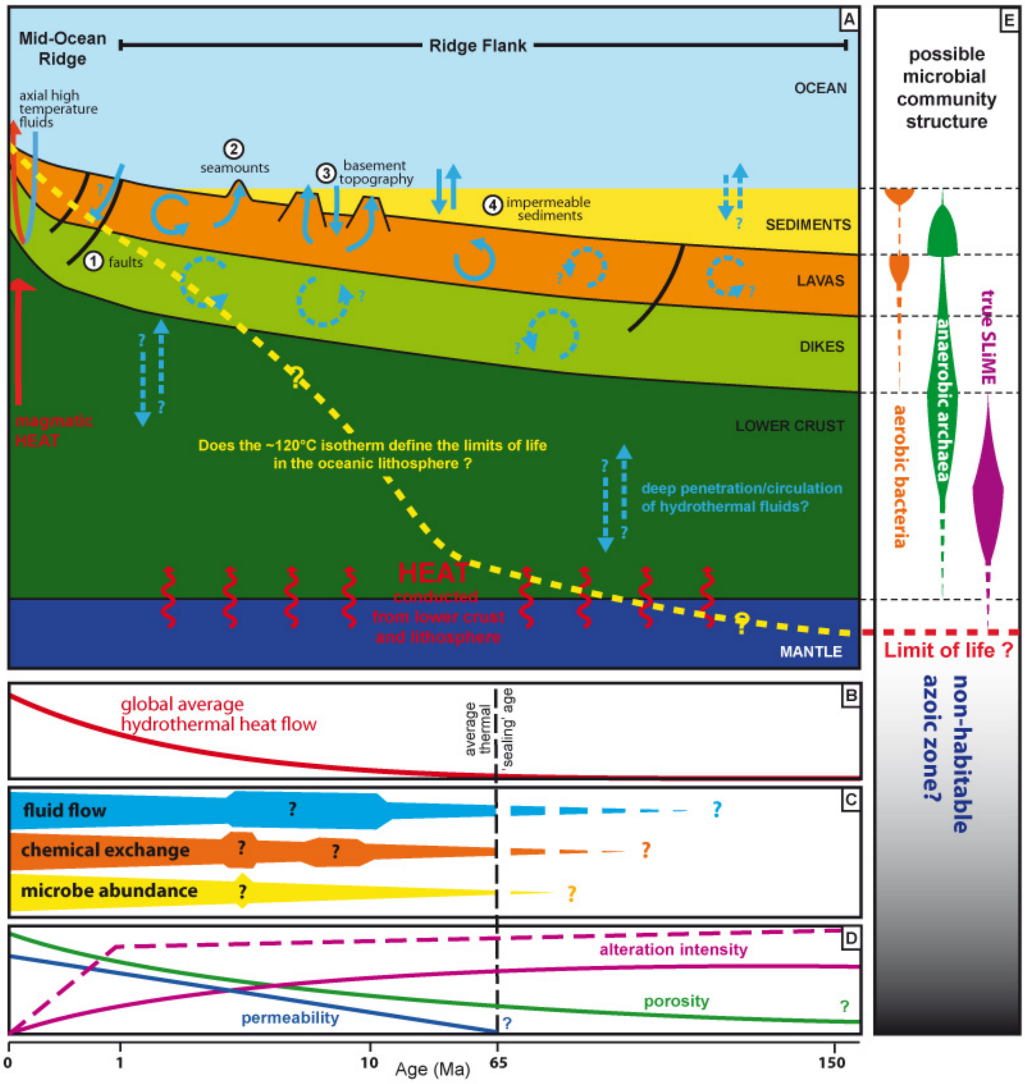


Figure 2. A. Schematic architecture of a mid-ocean ridge flank (not to scale), illustrating parameters that may influence the intensity and style of hydrothermal circulation through the ridge flanks, such as faults, seamounts, basement topography, and impermeable sediments, which isolate the crust from the oceans. Arrows indicate heat (red) and fluid (blue) flow. The yellow dashed line is a hypothetical trajectory of the ~120°C isotope as ocean crust moves away from the ridge crest. B. The calculated global hydrothermal heat flow anomaly decreases to zero, on average, by 65 Ma. C. The effects of parameters such as basement topography and sediment thickness on the intensity and relative cessations 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. F. Schematic cross-section of fast-spread crust with anticipated MoHole penetration. Figure by Rosalind Coggon; Damon Teagle, and Kentaro Nakamura.

We distinguish two end-member modes of fluid circulation through oceanic crust, i.e., high-temperature circulation at on-/near-axis and low-temperature circulation at off-axis. Near the ridge axis, seawater penetrating into oceanic crust is heated by high-temperature heat source (magma), resulting in vigorous hydrothermal reactions with surrounding rocks and/or phase separation into vapor and brine at relatively shallow level in the oceanic crust, close to the gabbro/sheeted dike interface. Parts of the high-temperature hydrothermal fluids upwell through oceanic crust and finally venting at the seafloor. Some fraction of the high temperature fluids, perhaps segregated brines, may penetrate deeper into the crust, and possibly the mantle, with fluids physical and chemical properties altered by phase separation and host-rock reactions. To date, the physicochemical characteristics, volumes, and depth of penetration of high-temperature fluids are unknown. The MoHole project will provide the first opportunity to access the samples necessary to address these questions.

Equally important will be the characterization of late stage, off-axis low-temperature fluid interactions that will leave an imprint on rocks as the crust ages and cools away from the ridge axis. These lower temperature reactions may be related to, enhanced by, or promote biological activity.

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

2.4. Limits and controlling factors of life

Earth is known as a watery planet that is characterized by the presence of liquid water on its surface. Water plays a key role in the cycling of material between lithosphere and hydrosphere (see section 2.3 above). It is well accepted that liquid water is one of the key ingredient contributing to the emergence and development of life on Earth. Elucidating the extent and characteristics of the deep hydrosphere is crucial to understanding not only chemical exchanges between ocean and oceanic crust but also biological activity in the deep subseafloor.

Understanding the limits of life, and the factors controlling these limits, is one of the most fundamental scientific goals for geo- and biosciences, essential for understanding the origin, evolution, distribution, and future of life on Earth as well as celestial bodies. To date, the limits of life even on our own planet remain poorly defined. The MoHole project provides a unique opportunity to address this limit in the oceanic lithosphere that covers ~60% of our planet (Fig. 2E). Numerous factors may control the limits of life, such as temperature, water activity, salinity, pH, energy and carbon sources. Among these, temperature plays a key role, because organism cannot survive beyond as yet poorly known temperature threshold (~110-120 °C?). The ability of seawater to penetrate into the deep crust or mantle and be available for micro-organisms (e.g., minimum pore space), will also have a strong impact on the distribution of living organisms.

2.5. Physical and chemical nature of the upper mantle

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

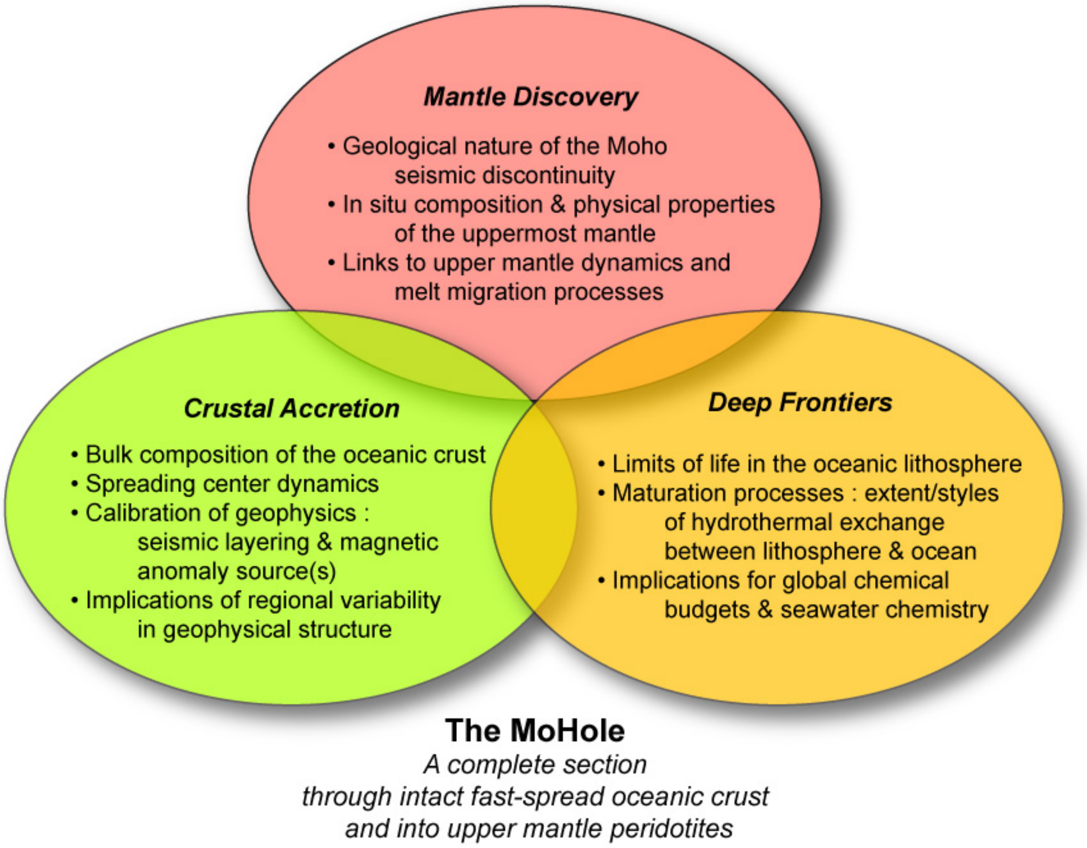


Fig. 3 - Schematic summary of the MoHole scientific objectives

3. Geophysical Site Surveys

3.1. Scientific Requirements

The criteria for an ideal deep crustal penetration sites have been discussed in previous meetings and workshops (e.g., Christie et al., 2006). Here, we reformulate these criteria based on site survey discussions held during the 2010 MoHole workshop. The selected target would ideally meet all of the following requirements. Satisfying requirements for Points a-e is essential for success. More flexibility is allowed in meeting Points f-h, which are highly desirable but not essential:

a. Crust formed at fast spreading rate (>40 mm/yr half rate).
b. Simple tectonic setting with very low-relief seafloor and smooth basement relief; away from fracture zones, propagator pseudo faults, relict overlapping spreading basins, seamounts, or other indicators of late-stage intraplate volcanism. Connection to the host plate active constructive and destructive boundaries would provide important scientific information.
c. Crustal seismic velocity structure should not be anomalous relative to current understanding of "normal" fast-spread Pacific crust, indicative of layered structure (Fig. 4).
d. A sharp, strong, single reflection Moho imaged with Multi-Channel Seismic (MCS) techniques (Fig. 4).
e. A strong wide-angle Moho reflection (PmP), as observed in seismic refraction data, with distinct and clearly identifiable sub-Moho refractions (Pn).
f. A clear upper mantle seismic anisotropy.
g. A crust formed at an original latitude greater than ±15°.
h. A location with relatively high upper crustal seismic velocities indicative of massive volcanic formations to enable the initiation of a deep drill hole.

3.2. Technological Constraints

Several technological constraints limit the range of potential sites. These constraints are:

- Technology for re-circulating drilling mud (riser or alternative) 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.
- Prior scientific ocean drilling experience is mostly limited to temperatures less than 200 °C. Temperatures higher than ~250°C may limit choices of drill bits and logging tools, may decrease core recovery, and may increase risk of hole failure, or require substantial re-design of drilling equipment. Based on plate cooling models, crust older than ~15-20 Ma should meet this requirement at Moho depths (Fig. 5).
- 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. For example, if total drilling depth cannot exceed 6 km in 4000 m of water, the targeted crustal section should have a crustal thickness of ~5.5 km, somewhat less than average Pacific crust.
- Target area should be in a region with good weather conditions at least 8 months/year, 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) to major port facilities for logistical practicalities.

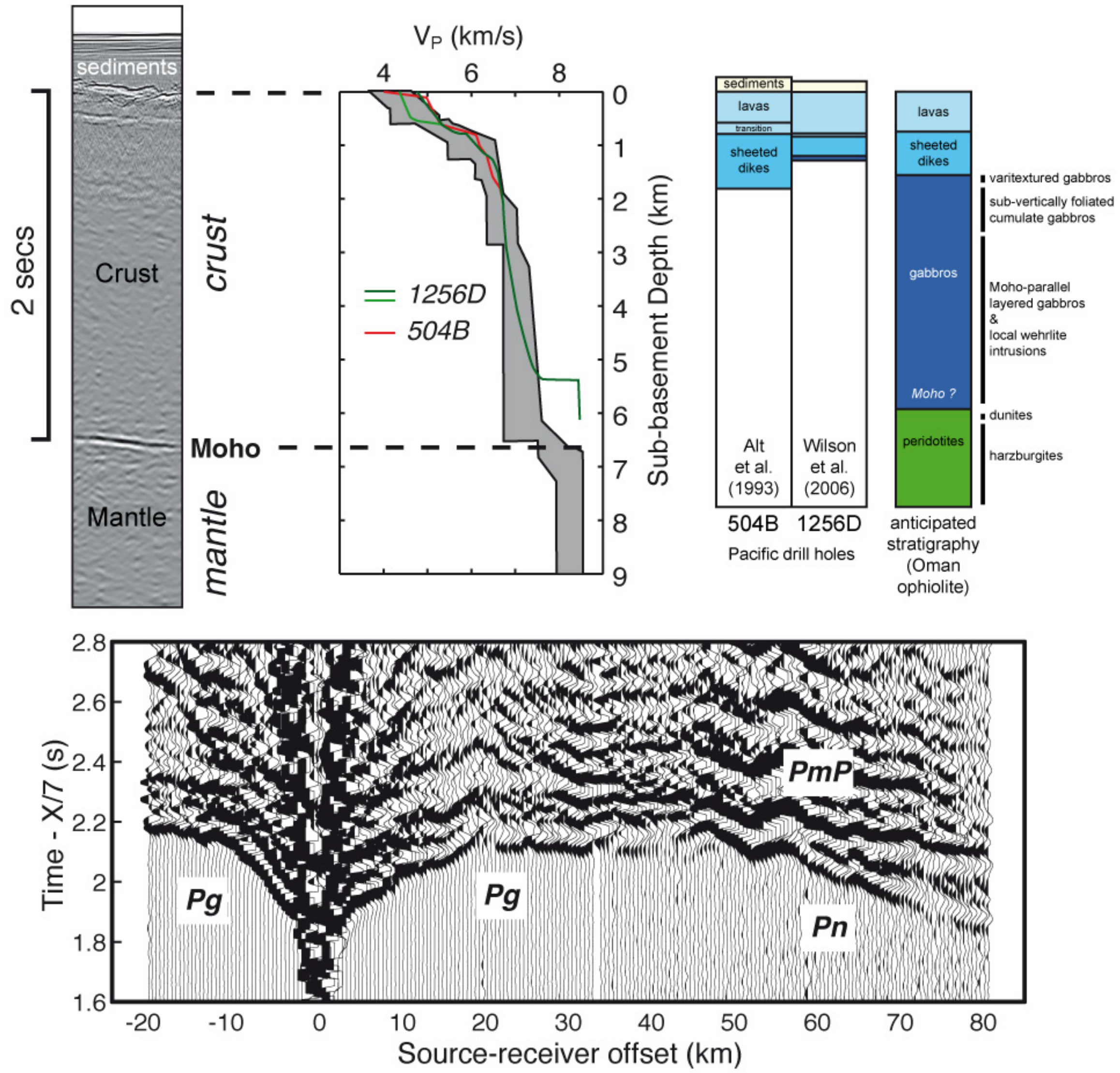


Fig. 4 - Top left: Example of multichannel seismic reflection image showing a crustal column over a sharp, strong single Moho reflection at the crust-mantle transition zone (image from Nedimovic et al., 2005). Top middle: Seismic structure (one-dimensional Vp models) of Pacific crust (Grey: Bounds of average "normal" crust older than 29 Ma (after White et al., 1992); Green: ODP site 1256 (Teagle et al., 2006); Red: ODP site 504 (Swift et al., 2008). Top right: Drilled and cored sections in Holes 504B and 1256D (Alt et al., 1993; Wilson et al., 2006), and anticipated lithostratigraphy of MoHole (from Oman ophiolite, e.g., Nicolas and Boudier, 1991). Bottom: Example of OBS wide-angle seismic record section showing crustal refractions (Pg), high-amplitude wide-angle Moho reflections/refractions (PmP), and uppermost mantle refractions (Pn) (after Canales et al., 2002). These examples illustrate the characteristics of the MCS Moho reflection, wide-angle OBS seismic data, and P-wave velocity structure that will be required to select the MoHole target area.

3.3. Potential Sites

Based on the scientific requirements and technological constraints described above, the workshop participants focused the discussions on three areas in the Pacific Basin: Cocos Plate, Off Southern and Baja California, and Hawaii (Tables 1 and 2; Fig. 6). One of the most important issues to take into consideration is the trade off between seafloor depth and temperature at Moho depths (Fig. 5). Most ocean seafloor subsides below 4000 m by ~25 Ma, whereas at Moho depths of 5-7 km temperatures of 200 °C or less are expected for crustal ages of 17-35 Ma.

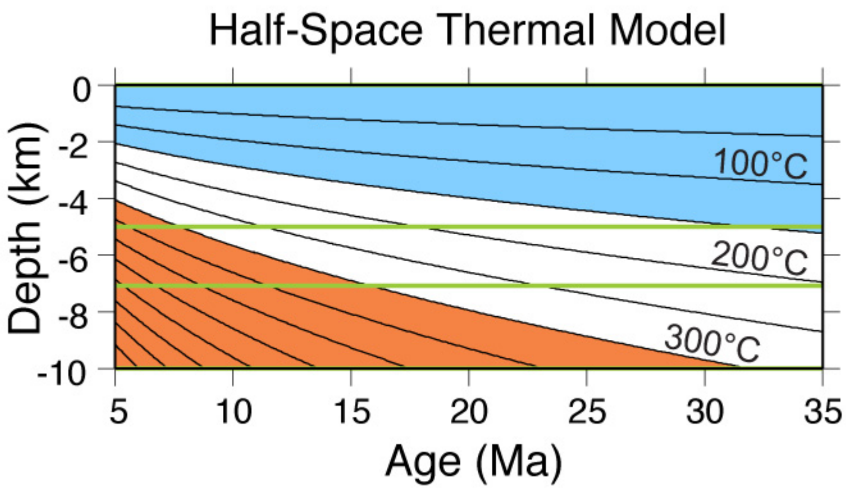


Figure 5 - Predicted Temperature as a Function of Age and Depth (Half-space thermal model by D. Wilson). Thermal diffusivity is 6x10-7 m2s-1, the initial mantle temperature is 1340°C, the surface temperature is 0°C. At 6 km, cooling below 200°C occurs after 25 Ma.

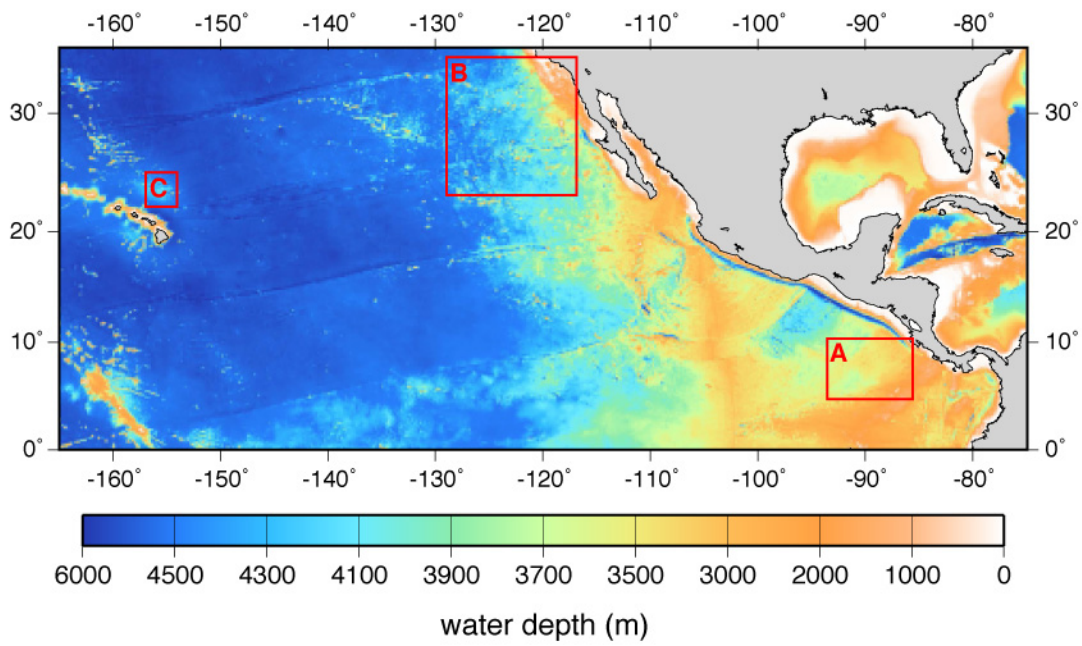


Fig. 6 - Bathymetric map showing the three selected areas for large-scale MoHole site survey. [A] Cocos plate region, [B] off Southern/Baja California region, [C] off Hawaii region.

Region	Advantages	Disadvantages
Off Southern/Baja California	- Large range of water depth - Modest Moho T - higher latitude	- Few data available - Off-ridge volcanism
Cocos Plate	- Shallowest water depth - Well-known tectonics - Sits within a corridor that includes a complete tectonic plate life cycle	- Highest Moho T - Faster than present-day fastest spreading rate - Near equator
Hawaii	- Lowest T - Nearby a large port	- Deepest water - Near large Hotspot - Close to arch volcanism - Near equator - Lowest end of fast-spreading rates

Table 1 – Regions of interest for preliminary site survey, with principal advantages and disadvantages

Candidate Site	Location	Half spreading rate (mm/yr)	Crustal Age (Ma)	Inferred Moho-T (°C)	Water Depth (m)	Sediment Thickness (m)	Crustal thickness (km)	Total length to the Moho (km)	Original latitude
off S/Baja California A (DeepTow Site)	31-33N, 125-127W	60	30-27	<200	4300-4500	~100	~5.5?	~10?	~30-33
off S/Baja California B	28-29N, 123-125W	50	27-22	~200	4200-4400	~100	?	?	~28
off S/Baja California C	25-26N, 120-122W	60	27-22	~200	3900-4300	~80	?	?	~30
off S/Baja California D	30.5-31N, 121W	45	20-22	~250	2700-4100	~130	?	?	~25
Cocos A (Site 1256)	6.7N, 91.9W	110	15	>250	3646	250	5,5	8.7-9.2	Near equator
Cocos B (Site 844)	8N, 90.5W	100	17	>250	3414	290	5,5?	8.7-9.2?	Near equator
Cocos C	8.7N, 89.5W	100	19	~250	~3400	~300	5,5?	8.7-9.2?	Near equator
Hawaii	22.9-23.7N, 154.9-155.8W	35-40	79-81	~150	4050-4300	~200	~6?	10-10.5?	Near equator
Hawaii	23.5-23.9N, 154.5-154.8W	35-40	78	~150	4300-4500	~200	~6?	10-10.5?	Near equator

Table 2 - Possible candidate sites, with principal characteristics

3.3.1. Cocos Plate (aka 1256 area)

This region encompasses a section of the Cocos Plate off Central America (from Guatemala to northern Costa Rica, Fig. 3A) with lithospheric ages between 15 and 25 Ma (Fig. 7). At its western limit on 15 Ma crust, this area includes the ODP Hole 1256D (Wilson et al., 2006; Teagle et al., 2006), a site of on-going IODP deep drilling into intact ocean crust. MCS (Hallenborg et al., 2003; Wilson et al., 2003) and wide-angle OBS data exists for the 15-17 Ma area in the vicinity of Site 1256.

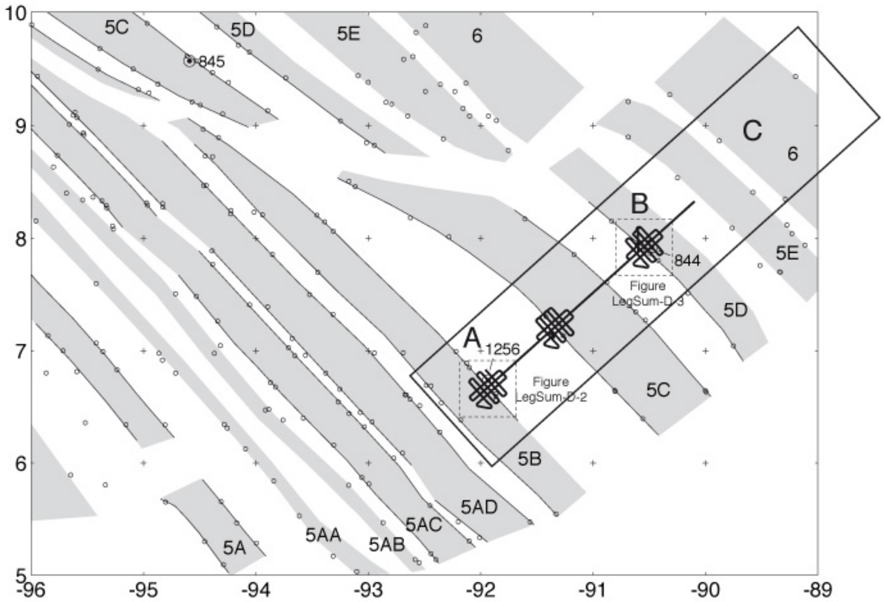


Figure 7 - Map of magnetic anomalies in IODP Site 1256 area (Cocos plate; after Wilson et al., 2003). A-C boxes correspond to the areas detailed in table 2.

The advantages of this region include:

- Super-fast spreading rate (half-spreading rate 110 mm/yr).
- Water depths < 3650 m.
- Crustal thickness: ~5.0 km.
- Nearly planar, sub-horizontal Moho (based on 3D wide-angle OBS data).
- Drilling experience at Site 1256 demonstrates that here the dike section can be drilled successfully.
- This region sits within a corridor that includes a complete tectonic plate life cycle, making it an excellent candidate for understanding ocean crust evolution from a spreading center to subduction. Structure of the crust within this area can be directly related to processes occurring at the modern East Pacific Rise and the Central American subduction zone.
- Areas of older crust (17-24 Ma) probably have drillable Moho temperatures (~200 °C).
- 12-month weather window, 3-m swell rare.

Disadvantages are:

- Elevated Moho temperature (~250-300 °C) at Site 1256.
- Crust formed near the paleo-equator.
- Faster than present-day fastest spreading rate.

- Available MCS data (cruise EW9903) shows poor Moho reflection. Two reasons for this were discussed: (a) weak reflectivity of the Moho is a natural consequence of crust formed at such super-fast rates; or (b) the data may not be of optimal quality (poorly tuned airgun array? source configuration not optimal for low frequencies?)
- 1.0-1.5 knots whole-water-column tidal currents.

3.3.2. Off Southern/Baja California

This region encompasses a section of the eastern Pacific Plate off Southern and Baja California, between ~20-33°N, and ~130-118°W (Fig. 3B, Fig. 8). Crustal ages are ~20-35 Ma. Very little modern geophysical information exists from this region. The best-studied area is in the northernmost part off San Diego, the "Deep Tow" site at 32°25'N, 125°45'W (31-32 Ma; Luyendyk, 1970). Historical data there include deep-tow sidescan and bathymetry, 3.5 kHz profiler, magnetics, and single channel seismics. Spreading rate is 55 mm/yr (half rate), sediment thickness is 40-60 m. No modern geophysical data is available to evaluate crustal structure and the presence/characteristics of Moho.

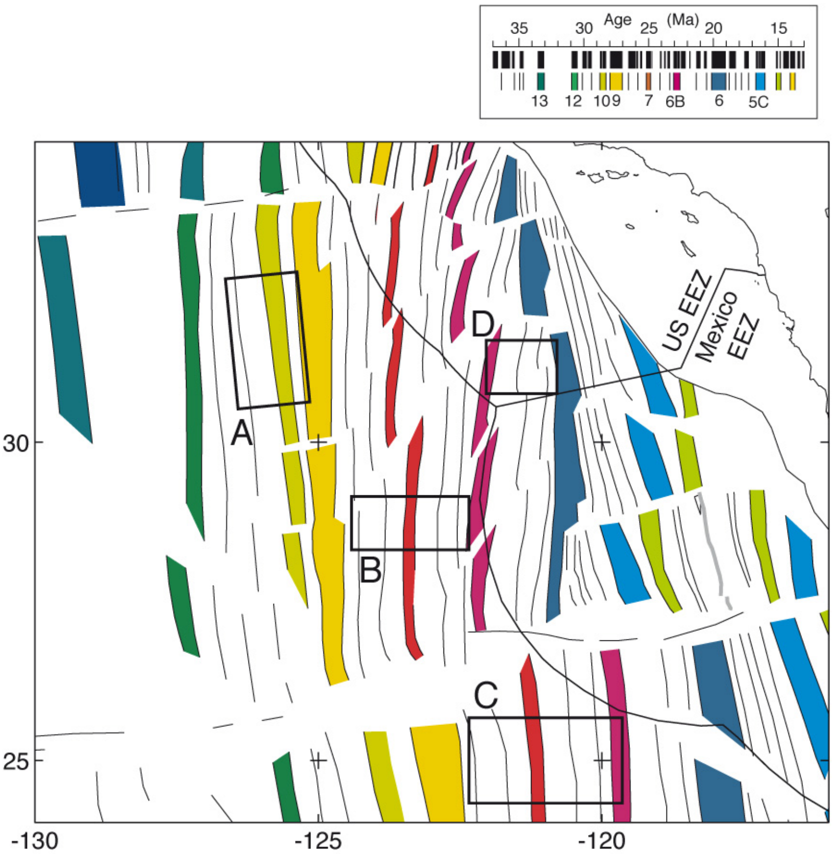


Figure 8 – Map of magnetic anomalies in the region off southern/Baja california. A-D boxes correspond to the areas detailed in table 2. Figure by Doug Wilson.

Advantages of this area are:

- Water depth varies mostly between 4,000-4,500 m, but some areas are shallower than 4,000 m.
- Modest inferred Moho temperature (<250 °C).
- Crustal thickness: 5.5 km estimated 70 km NW of Deep-Tow site using constant layer modeling (Shor, 1968 communication to Luyendyk, 1970).

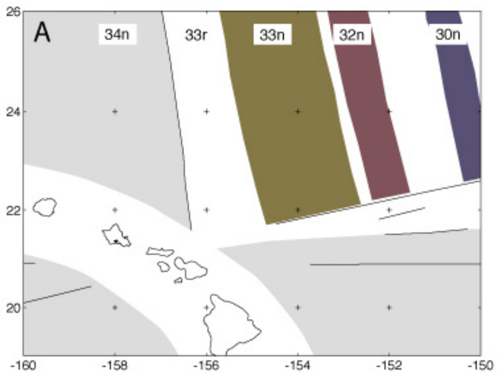
- Portions of region are close enough for shore logistics base.

Disadvantages are:

- Most of the region has no opportunity to place results within context of ridge processes/evolution since spreading axis is subducted or (micro) plate reorganization have occurred.
- There is so little sub-sediment seismic information available that it is difficult, at this point, to assess either advantages or disadvantages in this region.

3.3.3. Hawaii

This area is located north of Oahu in the flexural arch, where water depths are 4000-4300 m (Fig. 9). The crust is ~80 Ma, and was formed at a half spreading rate of 35-40 mm/yr.



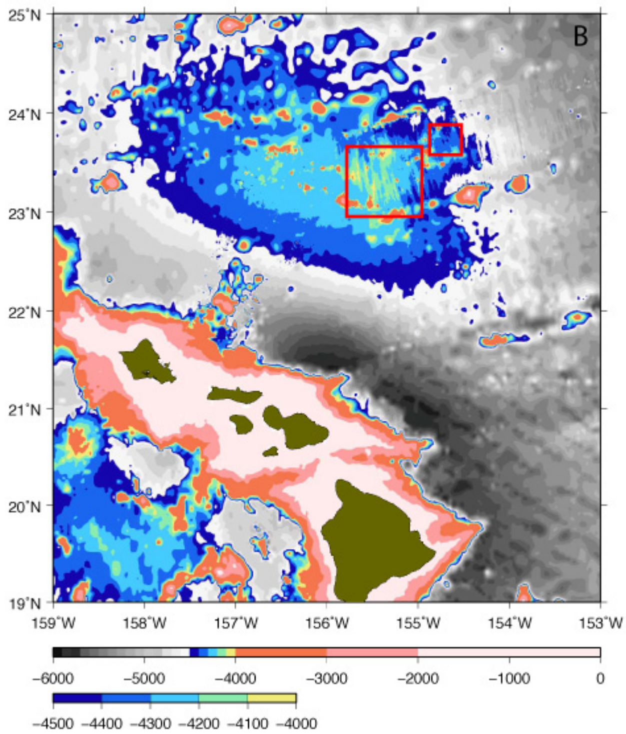


Fig. 9 – Magnetic anomaly (A) and bathymetric (B) maps of the region of interest north of Hawaii. Red boxes correspond to the two areas detailed in table 2.

Advantages of this area are:

- Moho temperatures are inferred to be in the 100-150 °C range.
- Close to major port for logistics support.
- 12-month weather window (consistent trade winds but only episodic storms).

Disadvantages are:

- Original latitude near the equator.
- Many seafloor volcanic fields.
- Crustal structure is potentially affected by hotspot volcanism (underplating? crustal intrusions?)
- Spreading rate at the lowest end of what is considered “fast”.

- Cretaceous age make complicate interpretations of hydrothermal alteration due to major differences from modern oceanic chemistry.

3.4. Large Scale Surveys: Finding the Right Project Area

The existing geophysical data at the three potential sites are not sufficient to identify a clear MoHole Project target area. Consensus at the workshop was that the priority of the community should be directed toward conducting large-scale seismic surveys in the three regions that will lead to the identification of a Moho target that meets the requirements indicated above (Fig. 4). These surveys should collect spatially coincident MCS data, wide-angle OBS data, multi-beam bathymetry and gravity. As feasible, heat flow and magnetic anomaly data would be useful. The seismic surveys should include the following characteristics:

MCS surveys:

- 2D profiles both parallel and orthogonal to paleo-spreading direction.
- 6 km or longer streamer
- Powerful airgun array well tuned and configured for broadband source rich in low frequencies.

OBS surveys:

- 2D profiles both parallel and orthogonal to paleo-spreading direction with enough aperture to record Pn first arrivals.
- Instrument spacing in the range of 5-10 km.
- Powerful airgun array well tuned and configured for broadband source rich in low frequencies.

JAMSTEC indicated that in 2011 they will dedicate 3 months of science ship time for large-scale surveys. Time required for obtaining environmental permitting for Hawaii precludes conducting surveys in this area in the short term. Discussions were then focused on prioritizing the 1256 region and the Off Southern/Baja California region. Consensus was to prioritize the Off Southern/Baja California region, because so little is known in this area (where depth/age/logistical criteria are viable) that it is urgent to obtain baseline reconnaissance seismic data to assess if the area can possibly meet the scientific requirements. Two factors contributed to the choice of this region as top priority for initial reconnaissance: crustal ages are greater than near Site 1256 so temperatures are expected to be cooler; the existing data suggest that Moho in the 1256 area may not be associated with a simple, continuous, strong reflector.

Survey(s) for the 1256 area remain unplanned and new reconnaissance profiling was considered second priority since EW9903 data provides some information in that region (Wilson et al., 2003; Hallenborg et al., 2003). However it was emphasized that conducting a small survey in this area with state of the art seismic capabilities for comparing with the EW9903 data will be crucial to assess the reason(s) for their low apparent Moho reflectivity (natural structure or data quality?).

The scope and costs of these surveys are too large to be conducted by a single nation or funding agency; *international collaboration is required*.

3.5. Small-Scale Surveys: Detailed Imaging of Project Area and Target

After an appropriate drilling target has been found and selected, the community should conduct detailed seismic surveys in the vicinity of the target. The recommended detailed surveys are:

- 2D very-long offset (+8 km) MCS for high-resolution modeling of velocity (i.e., porosity) structure of the upper-mid crust.
- 2D high-resolution, large aperture (+100 km) (crustal and upper mantle) OBS profiles (instrument spacing of ~500 m) for fine-scale structure and physical properties of the drilling target.
- 3D multi-streamer MCS survey for accurate and geometrically correct imaging of intracrustal reflectors (faults, sills, etc.) and Moho.
- 3D crustal and upper mantle scale OBS survey (instrument spacing of ~5 km) to assess crustal structure and thickness variability and upper mantle velocity structure/anisotropy.

While JAMSTEC is taking the lead for conducting large-scale surveys at the Off Southern/Baja California region, other partners (US, Europe) should make an effort to conduct or contribute to other large- and small-scale surveys.

4. Technology & Engineering Development

The technology selection and required engineering development will be key components for the success of the MoHole project. It is important to identify potential issues in drilling and coring engineering from the past and on-going ocean drilling expeditions, and to find solutions to overcome the problems encountered. Engineering efforts must remain closely focused on delivering the samples and observations required to achieve the scientific goals of the MoHole endeavor.

Technology selection process and planning for the key engineering developments should be launched as soon as possible in conjunction with site-survey efforts. To do so, establishing a realistic roadmap, which includes project scoping, development and testing elements all controlled by proper project management, is imperative (see "Key for success" section). In the sections to follow, we summarize discussion on each of these items in the Mohole workshop at Kanazawa.

MoHole target sites are all located in Ultra-deep water of approximately 4000m water depth or beyond, and the drilling depth to achieve the MoHole objectives is estimated to extend more than 6000m below seafloor. To drill an ultra deep borehole in such deep water, the provision for continuous mud circulation is a top priority technology requirement. Conventional IODP drilling has utilized riserless drilling which has, given our current experience, drilling depth limit of approximately 2000 to 3000 m.

A promising candidate for drilling to the Moho is riser drilling which provides a conduit for the mud to be returned to the vessel for cleaning, evaluation and recirculation. The drilling vessel *Chikyu* is currently equipped with a deep riser system for maximum rated water depth of 2500m. Significant engineering development is required to prepare *Chikyu* for riser service in water depth near 4000m. In addition to riser drilling several other technologies are being considered to safely and efficiently drill to the targeted depth.

Major areas requiring engineering consideration include :

- mud circulation,
- logging and coring,
- drill bits and drill string,
- drilling mud, and
- casing/cementing.

4.1. Mud Circulation Technology

Drilling mud circulation is essential for ultra deep drilling to reach the mantle. We have examined several candidate systems to be equipped on *Chikyu* :

- Riser and BOP (blow out preventer): include CFRP (carbon fiber reinforced plastic) or other light material riser.
- BOP-less: only riser pipes without BOP.
- Surface BOP and SID: slim riser pipe (casing pipe) and Subsea Isolation Device (SID).
- RMR: Riserless mud recovery with mud circulation pump and mud return line (e.g., Myers, 2008).
- Free Standing riser: conventional Riser and BOP on top of huge buoyant& riser.

During the workshop, high-level evaluations were made on each candidate system (table 3). Further investigation should be made including system feasibility, lead-time, safety and cost.

	Riser and BOP (CFRP riser or other material)	Surface BOP plus SID(ESG)	RMR	RMR with EGS (SID)	Free Standing Riser	BOP-less
Cost	1	3	3	2	2	3
Risk	3	3	2	3	3	0
Lead time	1	3	2	2	1	2
Flexibility	1	3	3	3	2	2
Feasibility	2	3	3	3	2	2
Environmental / Safety	3	3	2	2	3	0
Heat tolerance	2	2	2	2	2	2
Deployment time	1	3	3	2	1	3
Adaptable to *Chikyu*	3	2	2	2	1	2
Reentry	2	3	3	2	2	2
System reliabilty	3	3	2	2	2	2
VIV susceptibility	2	2	3	3	2	1
Existing vs development	1	3	3	2	2	3
Seaworthyness	3	2	2	2	3	2
Max. mud weight	3	2	3	3	3	1
Max. flow rate	3	2	2	2	3	2
Casing size options	3	2	2	2	3	3
Max. pressure	3	3	1	1	3	1
Corrosion resistance	2	3	2	2	2	2
M.ax water depth	1	3	3	3	2	2
Total	43	53	48	45	44	37

Table 3 – Evaluation of mud circulation systems under consideration for MoHole drilling. Evaluation ranking : 3 Premium/ 2 Medium/ 1 Poor.

4.2. Logging/ Coring

High formation temperatures (>150°C) are expected at depth in all the candidate sites. Currently available electronic components in logging tools, seal material/bearing, etc., have temperature limits of approximately 150-180°C, and only a small subset of these tools can tolerate short-term exposure to temperatures up to 250°C.

Thus, with current technology, only a few basic measurements such as borehole fluid temperature can be made beyond 250°C, and full suite of measurements needed for the in-situ petrophysical studies will simply not be possible. Therefore, multiple in-situ temperature profiles of ODP Hole 1256D, a riserless hole in which deepening operations are scheduled for 2011 (IODP Expedition 335), are necessary for more accurate predictions of geothermal gradients to assist planning of further engineering development.

Operational practices such as pumping relatively cooler drilling fluid continuously will be implemented throughout drilling in Hole 1256D. Cooling of the borehole by fluid circulation during wireline logging is also possible.

New, higher temperature, petrophysical logging tools are currently being developed by a number of research groups (e.g., European project HiTi _High Temperature Instruments, conducted in the frame of the ICDP project IDDP _Iceland Deep Drilling Project: http://www.hiti-fp6.eu), and it is essential that these developments are success in time for Mohole drilling.

4.3. Drill Bit, Drill String, and Core Barrels

Igneous crustal and upper mantle rocks are much harder than sedimentary formations, and are likely to require long drilling times.

Based on past non-riser drilling experience, core recovery rates and the recovery of different rock types can be highly biased, particularly in the upper extrusive sections and dikes, due to variations in fracturing, brecciation, and hydrothermal alteration. On the other hand, core recovery rates are expected to be as high as 80 -100 % in lower crust (gabbros and peridotites), though drilling/coring may suffer from other factors, such as high temperatures, or large in situ deviatoric stresses at depth.

In hard rock formations, drilling/coring bits will be relatively quickly worn out and susceptible to failure, which will significantly reduce the rates of penetration (ROP), and require frequent bit changes. Thus, specifically designed bits for hard and abrasive rocks must be developed with hard bit teeth (e.g., PDC _polycrystaline diamond compact), and diamond impregnated cutting. Drillbit seals and bearings must also be able to survive long durations in hostile conditions.

The total anticipated depth of operations in the MoHole from sea level is about 10000 to 11000m, which includes water depth of 4000m + drilling depth of 6000 to 7000m. At this great depth, the drill string weight will be close to its maximum tensile strength under its own weight, leaving only a small margin for over-pull. To provide prudent safety margins, ultra-high tensile strength drill pipe must be fabricated (e.g., S160 grade steel that has larger tensile strength than current S140 and S150).

Conventional core barrels may be used if the temperature is not too high, but core barrels developed for geothermal drilling for IDDP may also work at the temperatures anticipated in a MoHole. Developing a wireline coring version of the Iceland Deep Drilling core barrel may be possible.

CDEX (Center for Deep Earth Exploration, JAMSTEC) is currently developing coring bits and drill pipe for ultra-deep drilling.

4.4. Drilling Mud

High formation temperature will negatively impact drilling muds, leading to mud decomposition. The steep temperature gradient between the bottom of the hole and the seafloor may further exacerbate mud stability problems.

For ultra-deep hard-rock drilling, the development of a high density weighed mud for service in high formation temperature is imperative. Currently, the oil and gas industry routinely uses several types of high temperature muds (e.g., oil-based mud, and synthetic based mud _SBM). However, using such mud types requires leakage-prevention safeguards to avoid adverse environmental impacts.

Geothermal drilling on land has been conducted in very high formation temperatures (>300°C; e.g. Saito et al., 1998; Skinner et al., 2010). Yet, in most cases using water or simple light weight mud with minimum mud contents is sufficient for the completion of the well.

Ultra-deep drilling at sea will require high-density weighed mud to balance high rock pressure and to prevent hole collapse. However, presently available high density weighted muds can be damaged by high temperatures. An alternative might be to develop lighter weight but higher viscosity muds to lift the cuttings as the formation stability in hard igneous rocks should be much higher than the sedimentary rocks encountered in oilfield drilling.

CDEX has initiated discussions with mud engineering companies concerning the development of a muds to withstand high temperatures up to 250°C.

4.5. Casing/Cementing

Casing strings, greater than 6000m, will be extremely heavy and will need to be suspended by drill pipe and lifting rigs on *Chikyu*. Light-weight casing strings may need to be investigated. Detailed well casing designs are essential to safely reach target depths in deep boreholes. The development of a successful well design requires accurate knowledge of pore pressures and fracture gradients. These can be estimated from seismic data, or from offset well data, and must be conducted prior to the commencement of drilling operations in the main hole.

It is common industry practice to drill a pilot well to develop an optimal casing design, and pore pressure gradients can be determined by vertical seismic profiling (VSP) in the pilot hole. High pore pressure may be less of an issue in the igneous rocks to be drilled in the MoHole. It is recognized that trade offs may have to be made regarding the drilling of a pilot hole since it is likely that drilling two deep holes (i.e., a pilot hole and the MoHole) would be prohibitively expensive. However, if drilling is undertaken in discrete stages, drilling can still directly inform the casing program. Possibly a shallow (2000 to 300 m?) pilot hole could be cored to inform the casing plan for the upper section of the deep hole (See also section 5.3.1).

It is essential, for the casing program to successfully enable ultra-deep drilling, that the casing strings are securely bonded to the borehole walls. Secure cementing is also required for the accurate acquisition of data from long-term data monitoring systems that may be placed in the borehole.

This issue of cement and casing must be investigated further with specialist cement engineering companies to develop high temperature, light-weight cements that will ensure excellent bonding between the casing strings and the borehole walls.

4.6. Assessing the Past Experience in Crustal Drilling

It is important to assess the past experience in crustal drilling for optimizing the engineering development and drilling operations. There are several deep holes in the history of the scientific ocean drilling: ODP Holes 504B, 735B, ODP/IODP Hole 1256D, and IODP Hole U1309D. Each hole had different lithology, drilling/coring conditions and strategies, and sea weather conditions. It is noteworthy that 504B and 735B failed due to hole collapse and/or equipment loss (drill bit, pipe).

Assessment of the causes of these events has been partially undertaken by ODP and IODP, but these investigations are not directly available as a self-consistent resource. Past deep drilling information should be compiled and documented for future reference. We suggest that the future scoping group for the Mohole project should include a team to gather the TAMU reviews and IODP-MI Operation Task Force reports of these holes, as well as the driller's log from Transocean and earlier rig-floor operators (SEDCO; Hughes Petroleum for Glomar Challenger).

4.7. Accumulating Experience in Hard-Rock Drilling

In conjunction with the site-survey efforts and the engineering and technology development, it is imperative for ship crews, drilling crews, and scientific technicians on IODP vessels to test capability of the vessels, equipment, and procedures, as well as to accumulate experiences in hard-rock drilling. This will allow the development of drilling/coring strategies, timelines, and protocols for handling the core samples. Prior to the MoHole drilling, thus, it would be prudent to bring *Chikyu* outside of Japan territorial waters to gain valuable drilling experience in ocean crust. The location for this drilling should be based on excellent scientific proposals, some of which have already been developed by the ocean lithosphere drilling community and undergone peer-review (e.g., ocean detachments in slow spreading environment where the lower crust is exposed in relatively shallow water depth). There will be significant return to the MoHole project from the collection of physical property data during ocean crust drilling, allowing to further estimation of borehole stability conditions related to formation types and other factors (e.g., pore pressures, thermal cracking). Such information will provide useful input for the engineering/technology roadmap.

5. Operations

Drilling the MoHole will be a challenging enterprise requiring years of detailed preparation, planning, and engineering. The depth of the required borehole is not as deep as other boreholes previously drilled. In fact many boreholes have been drilled to deeper depth including a recently drilled industry hole to over 10 km in the Gulf of Mexico[1]. However, the MoHole is a very different proposition, as it will be cored into hard igneous rocks. To date, the deepest scientific marine borehole is less than 1850 m into igneous basement (ODP Hole 504B; Alt et al., 1993). Operationally, major challenges will be associated with collecting the cored material, making the in-situ measurements, installing casing and keeping the borehole open for successive episodes of deepening in a multiyear, multiphase operation. To gear up for the operations, the following issues must be adequately explored and included in the comprehensive and complete operation plan. At the Kanazawa workshop, it was largely accepted that the drilling to upper mantle in water depths greater than 3650 meters (12000 feet) is feasible. The MoHole initiative is arguably now at the point where the framework for the operations can be constructed since the technology to drill such a hole exists or least has been shown to be feasible.

5.1. Professional Planning

This plan must be developed by a dedicated international project office, adequately staffed with scientists, drilling engineers, well designers, engineers, operation specialists, geoscientists, and outreach experts. The current model for managing large projects within the Integrated Ocean Drilling Program is not satisfactory for an undertaking of the scale of the MoHole project. For this project to succeed scientifically, technically, and politically, a central office must be appropriately funded and staffed to take full advantage of all the IODP scientific and technical resources. It is anticipated that all available drilling options, *JOIDES Resolution*, *Chikyu*, as well as Mission Specific Platforms, will be utilized at key stages in the MoHole project to drill boreholes and test newly developed equipment.

5.2. Site Characterization Data

Before any detailed plan can be created, the operation group must be supplied with accurate data on the expected borehole temperatures, pressures and lithology to be encountered at all depths of the borehole to be drilled. Fully realizing that there will be some level of uncertainty with this data, such data must be supplied with confidence ranges. Unexpected conditions encountered within the borehole could well terminate deepening operations due to safety concerns, or greatly extended drilling times and costs.

When site characterization is completed together with estimates of expected target depths and sampling plan, detailed design of the well can begin. The key elements of the drilling/coring/downhole measurement are listed below. Each issue must be evaluated to ensure the targets can be reached and to allow an accurate costing for the entire

[1] http://www.bp.com/genericarticle.do?categoryId=2012968&contentId=7055818
http://www.deepwater.com/fw/main/IDeepwater-Horizon-i-Drills-Worlds-Deepest-Oil-and-Gas-Well-419C1.html?LayoutID=6

project to be determined. This will allow planners to decide which optional elements can be achieved within the available budget.

5.3. Well Design Considerations

5.3.1. Pilot Hole Options

The well design of the primary site may require data from a pilot hole or pilot section. The pilot may be a separate hole or it may simply be a pilot section of the main hole. Drilling engineering data from pilot section will be critical in managing the pressure, temperatures and stress within the borehole. Parameters such as mud weights, casing set points will much more accurately be evaluated with the data from the pilot hole. The expected budget constraints may determine whether a separate pilot hole is viable or not.

5.3.2. Well Control and Borehole Pressure Management

The rock types intersected by the borehole drilled to Moho depths are unequivocally expected to be devoid of free gas, overpressured fluid, significant hydrocarbons or other geohazards. Recent events in the Gulf of Mexico may result in future regulatory changes, imposing the use of blow-out prevention (BOP) in mud circulation systems, even in non-hydrocarbon regions. Hence, although a BOP will likely not be needed for well control, the use of a BOP will be considered by the MoHole well planning group.

Mud circulation must be provided to achieve the Mohole objectives and this may be accomplished through the use of a drilling riser or via a riserless mud circulation system. All the requisite support equipment must be considered (see table 3 in section 4.1).

5.3.3. Mud program

The composition of the mud to drill a 6-7 km borehole in crystalline rocks will be vitally important. The engineering decision for which mud circulation option to utilize (see engineering section) will affect the maximum mud weight and viscosity that can be continuously circulated. The mud costs will be a significant portion of the project costs, yet these costs will be minimized since there will be none or only minimal "pump and dump" drilling. Current drilling mud technology is limited to a working temperature of up to 200 to 250°C. Mud will be purchased directly from commercial mud supply companies with representatives onboard during the drilling operation. Personnel will also be required from the mud circulation companies.

5.3.4. Casing design

The casing plan must be created to ensure hole stability to the target depth is achieved with a significant margin of error. The casing plan should be based on widely available casing sizes, and installation hardware. The casing program will hinge on the type of mud circulation system selected and also the type of seafloor safety device (if needed) whether it is conventional blow out preventer (BOP) or a Subsea Isolation Device (SID). If a narrow throat, SID is utilized, then expandable casings must be considered. Regardless of the type of casing, the casing design will need to be extremely comprehensive. The installation of casing the Mohole will be an extremely time consuming and expensive component of the operation. Drill bit selection will be a critical factor for ensuring the successful installation of all the casing strings.

5.3.5. Cementing plan

Ensuring the casing is effectively coupled to the formation is another critical element in drilling and coring to the target depth, as well as being essential for the long-term success of borehole sampling/experiments, geophysical logging, and post-drilling observations. Many measurements require complete acoustic coupling for the acquisition of useful data. The cement program must be designed and implemented by cementing professionals with appropriate budget supplied to this element. Personnel from the cementing company will be onboard to oversee the cementing operations.

5.3.6. Directional drilling options

Drilling a parallel borehole may be an extremely valuable science tool that, if planned for from the beginning, could be initiated following the completion of the main hole. The design of the direction selection from the main borehole must not impart any risk to the success of the main mission of sampling the lower crust-and mantle rocks. The Integrated Ocean Drilling Program has no experience drilling directional wells, and thus outside consultation and installation expertise must be retained.

5.4. Downhole drilling tool selection

The bits and core barrels to be utilized for drilling to the mantle require careful consideration. Bits for drilling versus coring, and the tradeoff between making hole and taking core will require continual discussion and the coring strategy selected may be governed by financial constraints. As drilling in the lower crust approaches the Moho (+500 m), continuous wireline coring will be necessary for the remainder of the well installation. Advances in diamond impregnated coring bits may provide a pathway for improved core recovery. Bottom hole assembly (BHA) hardware choices will also affect hole verticality, thus stabilizers, logging while drilling and deviation avoidance techniques will be critical.

Core barrels and their liners require investigation. With the success of metal liners on MSP expeditions in coral reefs, where the metal liners helped reduce jamming, materials other than plastic should be considered. Most of the drilling in Hole 1256D has been done without plastic liners. Drilling without liners has been common practice in other hard rock sites (Holes 504B, 735B; ODP Leg 209)

5.5. Downhole Measurements

5.5.1. Drill collar measurements - Logging While Drilling/Measurement While Drilling

Measurements will be made continuously in the drilled borehole, whether it is through logging while drilling (LWD), or coupled with Measurement While Drilling (MWD), where data can be transmitted to the vessel in real-time. In areas of the borehole where continuous wireline coring is required, LWD will not be feasible due to the lack of a provision for a core barrel in current drill collar designs. Logging While Coring (LWC), which allows for simultaneous logging and coring, is possible. Cores can be taken while making resistivity, gamma and resistivity at bit measurements, although such techniques need refinement for hard rock coring (Goldberg et al., 2004). These devices will be very useful in a pilot hole, or just the pilot section of the primary borehole. It must be noted that drill collar measurements afford excellent depth control, but with a trade off of poorer vertical resolution of the tools, which is lower than that of wireline tools.

5.5.2. Wireline tools

Following drilling or coring, a full suite of wireline tools will be deployed into the open borehole. Specialty tools including fluid and gas sampling, (bio)geochemical measurements, and even hard rock sidewall coring may be deployed. The temperature of the borehole will be a key limiting factor in the tools that can be deployed. Most commercially available tools have a maximum temperature rating of 175°C, unless new instruments can be developed. Some standard suites of tools can be configured with short-term high temperature exposure ratings up to 250°C. The required temperature tolerances for all required wireline tools need to be explicitly stated, and necessary developments or adaptations compiled to provide necessary lead times. During logging operations, wireline tools and engineers can be called out to the rig as needed, in the same fashion as the oil and gas industry.

5.5.3. VSP experiment

Offset vertical seismic profiling will be a critical element of a successful Mohole project. Given the extreme depth of the borehole to be drilled, at least two offset VSP's will be ideally required; one at the estimated half-way point of the well, and one at final depth.

5.5.4. Long-term monitoring

Instrumenting the borehole resulting from the Mohole project will eventually become a key, second-stage goal. Thus, the sub-sea equipment and borehole must be constructed to accommodate observatory science. This implies ROV access to the well head and the ability to access the borehole through a BOP or SID.

5.6. Logistics

Moving personnel, equipment and supplies routinely, to and from the vessel, will be a critical component of the MoHole operations. Helicopter access and/or workboat access must be provided. Crew changes, provisions, drilling consumables, medical emergencies must all be incorporated in the logistics plans. It was suggested that ideally the drill site should be within 1000 km of major port facilities.

6. Keys for success

In this section, we list what are presently considered as the key achievements of a successful MoHole project. These include scientific (essentially sampling strategy) considerations, as well as technology development, industry engagement, and return to the public through outreach and education.

6.1. Geophysical surveys and Hole location

The first step to the MoHole Project is the series of geophysical surveys that will be required to identify and characterize an appropriate Project Area within which the drilling will be undertaken. Based on past discussions and consensus (see Christie et al., 2006, Teagle et al., 2009), the MoHole drill site should be in oceanic crust formed at a fast spreading rate, in a region that has aged from the ridge crust with zero perturbation by off-axis volcanism (e.g., seamounts), plume interactions or tectonic disturbance. The Project Area must show a clearly discernible Moho seismic boundary visible in both seismic reflection and refraction records. This drill site will have sufficient sedimentary cover to allow the installation of the (sub-)seafloor infrastructure to enable ultra-deep riser drilling. Relatively high upper crustal seismic velocities, indicating more massive formations in the uppermost volcanic sequences of the crust, will probably be mandatory for successful initiation of a deep drill hole.

6.2. Scientific coring, sampling and measurements

Many of our primary scientific goals (see section 2 "scientific rationale") will require continuous core samples.

To be regarded as successful, this experiment must return at least (see also fig. 10):

- Continuous core, including samples of all boundaries, across the region identified by seismic imaging as the Mohorovičić Discontinuity, and the geologic crust-mantle 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.
- Continuous coring of 500 m of peridotites and associated lithologies in the uppermost mantle below the Moho.
- Sufficient cores from intervals of the igneous lower oceanic crust to test models of crustal accretion, melt movement, resolve the geometry and intensity of hydrothermal circulation, and document the limits and activity of the deep microbial biosphere (probably a number of intervals of x100s m of continuous cores).
- Core samples for microbiological studies, using well-established protocols that avoid and/or control chemical and microbiological contaminations from drilling equipments and circulating mud.
- Gas and formation fluid samples from regular intervals within the borehole
- A continuous, comprehensive suite of geophysical logs (wireline, LWD, LWC) and borehole experiments to measure in situ conditions (e.g., temperature and temperature change/gradients) and physical properties, to acquire borehole images, and to identify key geophysical and lithologic regions and transitions (e.g., Layer 2-3 boundary, the Moho) throughout the ocean crust and into the upper mantle.

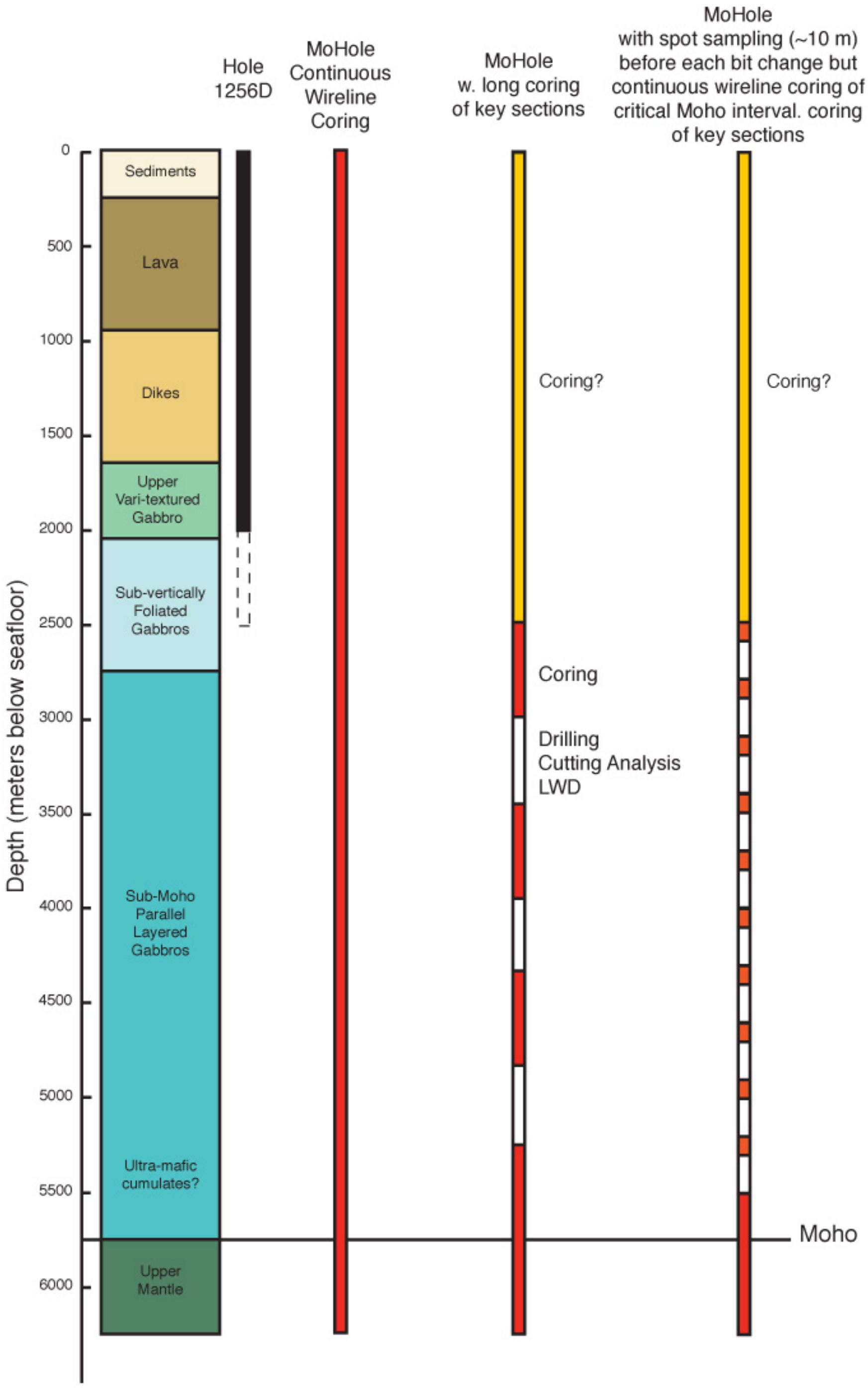


Figure 10. Technology and financial constraints willing, continuous coring all the way to the Moho and then a significant distance (~500 m) into the uppermost mantle would be the best approach to achieve the scientific goals of this project. However, approaches that mix spot coring (e.g., 10 m coring before bit change every 50 m) with continuous wireline coring may need to be considered. Significant lengths of continuous cores across major lithologic and geophysical transitions will be required and are imperative to answer the fundamental scientific questions posed.

Due to the relatively coarse grain-size of the rocks encountered and the fine scales of expected lithologic/geochemical variation, it is anticipated that lithological records provided by mud/chip logging will be insufficient to address the scientific questions posed. However, a continuous series of mud, cuttings, and gas logs will provide useful supplementary information in areas of poor or no core recovery, and should be routine throughout the experiment.

In addition to sampling and analyzing rocks, measurements of temperature and chemical compositions of the fluids are required together with biological analyses such as cell counting and DNA/RNA analyses. For example, sidewall core sampling in fracture and breccia zones where crustal fluids pass through may be an effective way to obtain good samples for microbial investigations.

Ultimately, it will be essential to integrate core/log/survey data in a comprehensive synthesis study of the Project Area. Post-drilling studies, such as successive fluid measurements/sampling, *in situ* microbial incubation in the borehole, or VSP experiments should be performed. Therefore, support for post-drilling studies, such as planning CORK installation for long-term borehole fluid measurements and microbial experiments, examination of casing material to avoid metal corrosion that could affect microbial activities, and developing method and tools for measurements and sampling borehole fluids, are important keys to scientific success for the MoHole project.

6.3. Broadening the scientific spectrum

The MoHole project is one of the largest and most ambitious scientific endeavors in Earth sciences, comparable to the space exploration missions such as the Apollo Project. This unique challenge will provide precious opportunities to a wide diversity of scientists, engineers and technologists. From a scientific point of view, one of the keys to success of the MoHole project will be the engagement of a broad range of scientific communities. Some, including petrologists, geochemists and geophysicists, have been strongly engaged in science planning for this project so far, but efforts will need to be made to more closely involve other colleagues, such as those from the biological, hydrological or experimental backgrounds. It is important that the MoHole project leaves the door open to new participants, new ideas, and new science.

6.4. Drilling technology

At the Kanazawa workshop, it was recognized that several conditions associated with drilling to the MoHole require technological solutions that are yet to be developed. Conditions such as the ultra-deepwater, ultra-deep drilling, the hard dense rock to be drilled, and the extremely high temperature anticipated, are just some of key issues that must be addressed with technology.

Among the many listed items (see section 4, Technology and Engineering Development), the most important one is to develop the technology to drill in the ultra-deepwater close to, or even beyond 4000m. Technologies that are applicable to the MoHole project are now being developed within the oil and gas industry and were presented at the workshop (see also next section). Conversely, some of the technologies required are very specific to scientific drilling, such as logging/coring in high temperature, or drilling the harder crustal and mantle rocks. Therefore, we need to develop such technologies within the IODP community, although these developments may be informed by geothermal projects such as the IDDP in Iceland. CDEX has started to develop some of these technologies using funds outside of the IODP. Key to successfully developing many of the required technologies necessary to complete the MoHole project will be to supplement IODP financial support with other sources of external funding.

The implementation of some of the suggested technologies required to drill the MoHole may require improvements and modifications to the equipment, systems and vessel used for the drilling, most probably the *Chikyu*.

The MoHole undertaking will require more than 10 years to complete, cost hundreds of millions of dollars, and engage a broad international science community. The size and duration of the MoHole effort will require an appropriately funded centralized operations and engineering management group to oversee the project from start to successful completion. This project office will be vital key to success, and in order to succeed, it must be a truly international effort staffed by the best available project managers, engineers, and scientists.

6.5. Industrial engagement

Many technologies required to successfully complete the objectives of the MoHole project are "conventional" deep-drilling technologies that are presently being used in the oil and gas industry. At the workshop, technologies for ultra-deep water drilling, such as surface-mounted BOP systems, or the riserless mud recovery system (RMR) were introduced. Such technologies are already being used for deep water drilling in the hydrocarbon industry and are potential candidates for the MoHole project. Other technologies are currently being developed in industry, such as the free-standing riser concept, which would require levels of funding far beyond what is available within the IODP to develop.

Because of the ongoing activities and developments being conducted in ultra-deep water by the oil and gas industry, close and continuous collaboration with industry, and the introduction of new and existing technologies to the MoHole project will be keys to success. For this purpose, it will be necessary to establish a strategy to engage the industry, exchange human resources, and plan joint development work.

Industrial engagement should occur at several levels:

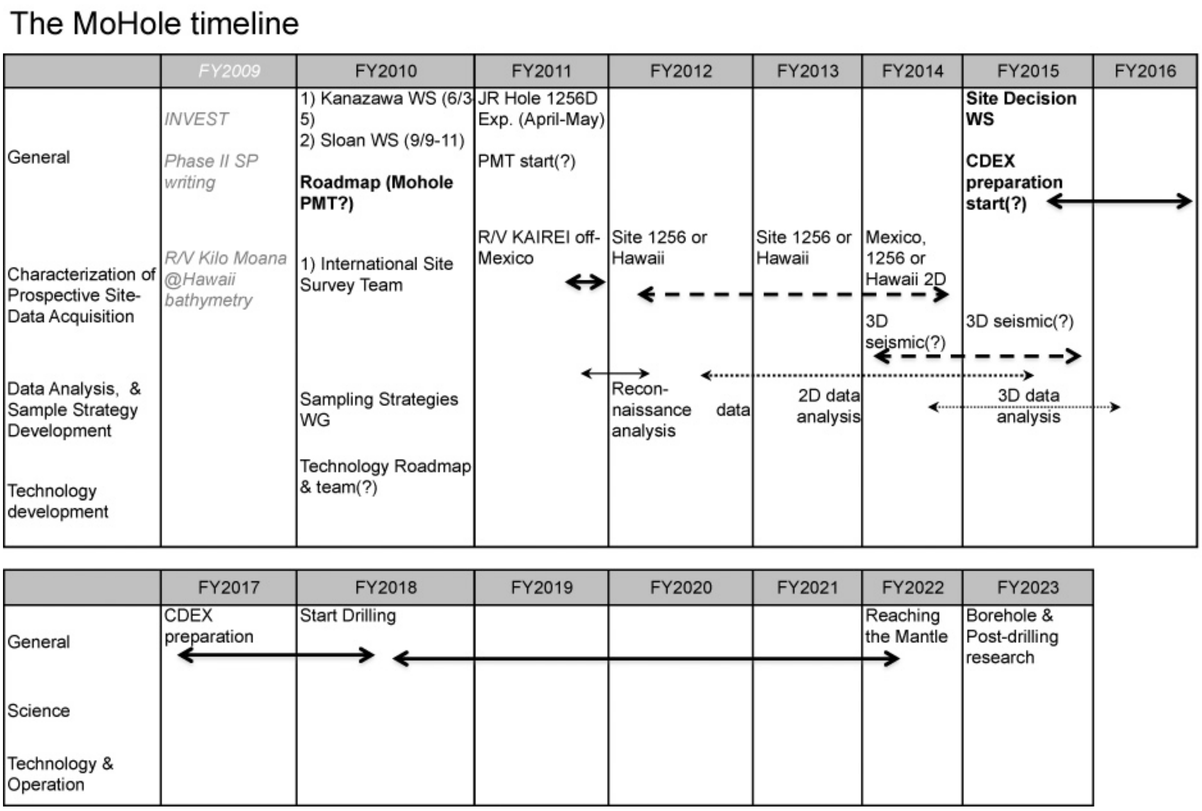
- Ad-hoc collaboration should be continued by inviting oil and gas industry representatives to participate in future planning activities, and to gain their “pro-bono” perspective through the existing IODP science advisory structure and community workshops. This is not a sustainable approach for the safe and complete execution of the MoHole project, but it is useful for scoping technical issues at the beginning of the project.
- Contracting services from planning to execution. This will be the most effective way of benefitting from industry experience in the development and execution of the MoHole drilling initiative.
- Participation of engineers and scientists engaged in the MoHole project to industry workshops, symposiums and technology development forums such as DeepStar (http://www.deepstar.org) and RPSEA (http://www.rpsea.org). These are important steps in learning about what industry is doing to achieve their technological goals.

6.6. Public engagement, outreach, education

In IODP, there have been limited support structures for outreach/education activities mostly from national funding sources, including the Deep Earth Academy and the USIO School of Rocks (Consortium for Ocean Leadership), the ECORD summer schools, and the Core School at the Kochi Core Center (CDEX, Japan). In addition to those initiatives, there have also been significant outreach activities organized on a case-by-case basis such as the very successful public visits of *Chikyu* in Japan, or the outreach and education team participation on IODP Expedition 327 (Juan de Fuca Hydrogeology 2) in July-August 2010.

One of the key components for the success of the Mohole project will be to improve public support for, and understanding of the scientific goals and excitement of the project. Also we will need to broaden the scientific community engagement by encouraging the involvement of the widest possible range of disciplines (see section 6.5 above). We recommend that engaging the public through outreach and education activities, as well as being pro-active in advertising the project to the wider scientific community and engaging new groups of scientists, be integral parts of the activities carried out by the MoHole project, under the umbrella of IODP and future scientific ocean drilling collaborations. One tool to greatly increase the public and scientific profile of the MoHole project should be a dedicated, multi-language MoHole website, aimed at a range of audiences, that should be implemented as soon as formal scoping activities commence.

6.7. Anticipated time table for the MoHole project



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8. Workshop Agenda

Thursday, June 3 - Day 1

09:00 - Registration at Kanazawa-Shi Bunka Hall

09:20 / 10:00 - Workshop Introduction

• Meeting overview and information (B. Ildefonse, S. Umino)
• Inaugural speech (Shingo Shibata, Director for Deep Sea Research, MEXT)
• Beyond the Moho: scientific justification for a complete penetration of intact in situ ocean crust and into the upper mantle (D. Teagle)

10:00 / 12:30 - Available site survey data in the Pacific

• The Trade-off of depth and temperature in choosing a MoHole site (D. Wilson)
• Hawaii site in comparison with IODP site 1256 (N. Seama)
• Site survey data at ODP Site 1256 (D. Wilson)
• "Deep Tow" Site : ~30 Myr Old Crust off Southern California (D. Blackman)
• IFREE seismic studies toward the Mohole project: results and future plans (S. Kodaira)

13:30 / 14:30 - Current understanding of technological feasibility

• MoHole Engineering… Seeking solutions inside and outside of IODP (G. Myers)
• *Chikyu* Drilling challenge for the MoHole (S. Kobayashi)
• The *Chikyu* engineering development (M. Yamao)
• Technical Development of Coring System in the Quest to reach the Earth's Mantle (Y. Shinmoto)

14:30 / 15:00 - Plenary discussion on lectures

15:00 / 15:40 - Breakout sessions 1

• 1 - Ultra deep drilling technology and project planning (including High Temperature/High Pressure drilling and coring) - Chairs : Y. Isozaki, G. Myers and M. Yamao

• 2 - Site selection and site survey plans - Chairs : P. Canales, M. Nedimovic, and D. Blackman

16:00 / 17:10 - Breakout sessions 2

• Continuation of discussion on topics 1 and 2

17:10 / 18:00 - Plenary session

• Summaries from breakout group chairs & scribes
• Planning, scoping and funding the MoHole within the context of the10-year renewal cycle (Y. Tatsumi)

Friday, June 4 - Day 2

Kanazawa-Shi Bunka Hall

09:00 / 10:00 - Drilling and coring at high temperatures

• Iceland Deep Drilling Project (A. Skinner)
• Drilling deep into hot oceanic crust : constraints and challenges (D. Mainprice)

10:00 / 10:50 - Breakout sessions 3

• Continuation of discussion on topics 1 and 2
Breakout group #1 session included presentations from Cameron and Shell representatives :
- Deepwater drilling with Cameron's ESG system & HPHT BOPs (J.E. Kotrla)
- Major Advantages and Disadvantages of the HP Casing Riser with Surface BOP and SID (F.R. Foreman)
- Conventional Drilling Riser Vs. High pressure Drilling Riser (S.F. Shimonek)

11:10 / 12:30 - Breakout sessions 4

Both breakout groups start separately discussions on topic 3
• 3 - Science Measurements: determination of requisite data for project success (e.g., continuous coring Vs. spot coring); in-situ measurements, Core/borehole logging/mud logging/survey integration.

13:30 / 15:40 - Breakout sessions 5

• Continuation of discussions on topic 3

16:00 / 18:00 - Plenary session

• Summaries from breakout groups
• Final discussion; identification of action items

19:00 - Banquet at Kanazawa Excel Hotel Tokyu

Saturday, June 5 - Day 3

Kakuma Campus, Kanazawa University

10:00 / 13:00 - Writing Committee meeting (Steering Committee + volunteers)

• Drafting of the meeting report
• Listing action items

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The MoHole

A Crustal Journey and Mantle Quest

Workshop Report

Kanazawa, Japan, 3-5 June 2010

Appendices

Appendix 1 - Scientific Objectives of Mission Moho proposal (2007)

These pages are excerpted from the Mission Moho proposal that was submitted to IODP in April 2007(IODP proposal 719MP). Mission Moho was a multi-stage project comprising five successive targets to be drilled using both non-riser and riser technologies. The "MoHole" was planned as the final stage of Mission Moho. Although, no long-term mission has been adopted by IODP, the scientific objectives related to deep drilling in the ocean crust remain essential to our understanding of the Earth. The full proposal is available online (http://www.missionmoho.org); here we present the scientific objectives, *as articulated in the mission Moho proposal*, which are fully relevant to the MoHole project.

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1. Primary Motivation for Mission Moho

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 and transformation of material and energy from Earth's mantle to the crust and from the crust, to the 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 seafloor spreading centers, the oceanic lithosphere records geomagnetic field variability, providing the basis for geomagnetic polarity timescales, plate reconstructions, and estimates of plate motions. From its formation until it is subducted back into the mantle, the oceanic lithosphere interacts with seawater, sequesters surface materials (including water and CO_2) and recycles them back into the mantle.

Sampling a complete section of crust and shallow mantle was the original motivation for scientific ocean drilling. Mission Moho will be the culmination of a decades-old quest by IODP, ODP and DSDP, since Walter Munk and the AMSOC first proposed Project Mohole in 1957 (e.g., Greenberg, 1974; Shor, 1985). The goal was and remains to understand the composition, structure, and evolution of the oceanic lithosphere through deep scientific drilling, as outlined in the 21st Century Mohole Initiative of the IODP Initial Science Plan. This goal has been a core component of planning documents since the inception of scientific ocean drilling (e.g., the "Road to the Moho" chapter in Murray et al., 2000).

The Moho (Mohorovičić Discontinuity) is a seismically imaged, primary acoustic interface that represents the transition between the Earth's crust and the underlying mantle. Whereas oceanic crust is formed by a variety of igneous and metamorphic processes, and has a low seismic velocity, the oceanic mantle has a much higher seismic velocity and is largely composed of residual peridotite. Residual peridotites have lost magma to form the crust during partial melting, and although deformed and recrystallized, have remained relatively solid for more than 4 billion years. Thus the mantle is intrinsically different from the igneous crust.

Uncertainty about the Moho stems from questions about the relationship between the seismic boundary, on the one hand, and the geological crust-mantle transition on the other. Are there "ultramafic" igneous rocks, with high seismic velocities, emplaced below the Moho? Are there hydrothermally altered residual peridotites, with low seismic velocities, above the Moho? Is the Moho an intrusive or tectonic boundary? The floor of a magma body? How sharp is the transition, given the limitations of seismic data analysis (±50m)?

In addition to the mysteries surrounding the Moho, we also have major gaps in knowledge about the oceanic lower crust and mantle themselves. How does the igneous crust form, and how does it exchange heat and chemical components with seawater? How is melt transport focused from a broad melting region to a narrow zone of crustal accretion beneath mid-ocean ridges? What is the composition and physical state of the convecting mantle? We have no fresh, *in situ* mantle sample. A few kilograms of fresh residual peridotite from beneath intact oceanic crust would provide a wealth of new information comparable to the treasure trove obtained from the Apollo lunar samples.

To date, the elusive frontier at the Moho, and the enormous mantle domain beneath, have been symbolic, unattainable goals. However, with the recent commissioning of IODP's new riser-drilling vessel, D/V *Chikyu*, the aspirations of generations of Earth scientists of drilling completely through the oceanic crust to the Moho into the upper mantle ~5-6 km below seafloor, have moved into the realm of technical feasibility.

The wider mid-ocean ridge and oceanic lithosphere community has been involved with the establishment of the plan presented herein via the IODP-MI sponsored Mission Moho workshop held in Portland Oregon in September 2006 (Christie et al., 2006; Ildefonse et al., 2007b; full report: http://www.iodp.org/mission-moho-workshop). The basic strategy of Mission Moho is derived from the consensus of about one hundred representatives from the international community. Mandate was given to the writing team and co-proponents to take forward the outline plan on behalf of the wider community. The six lead proponents are willing to serve in the stage 1 core Mission Team. This Team should also comprise seismologists (of which several are included in the co-proponent list), deep drilling engineers (especially riser drilling) from USIO, CDEX and industry, logging tool specialists, and borehole management experts (to improve our control of borehole stability issues).

2. Road to the Moho

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. 1), 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., 2007c).

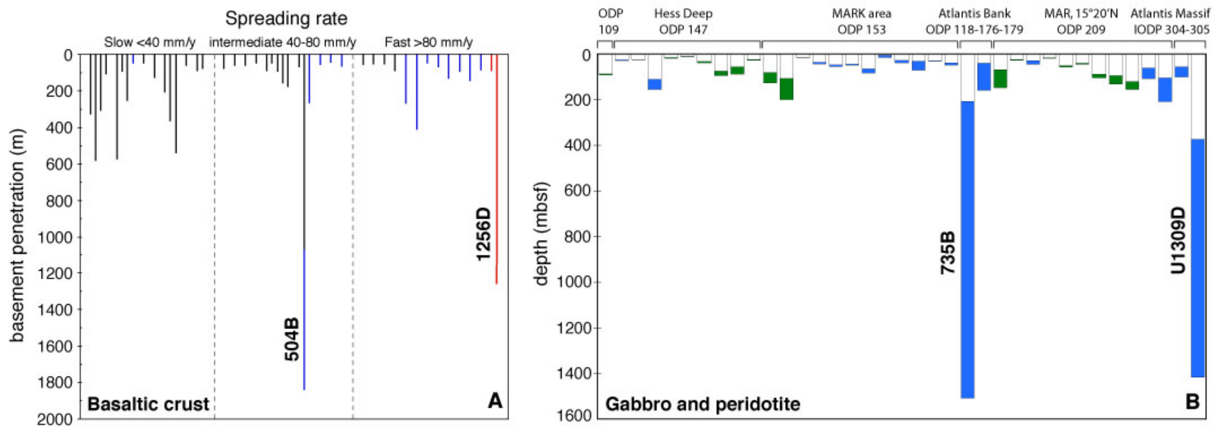

Fig. 1 - Summaries of existing scientific drill holes into oceanic crustal and mantle rocks. [A] Penetration for all holes penetrating more than 50 meters into basaltic basement, as a function of spreading rate. Hole 1256D has reached the base of the sheeted dike complex at a shallower depth than the bottom of Hole 504B, which is still in sheeted dikes. Black = DSDP holes, blue = ODP holes, red = IODP holes. After Teagle et al. (2006). [B] Depth of penetration for all ODP and IODP holes deeper than 10 meters below seafloor into gabbroic rocks or residual mantle peridotite. Blue = dominantly gabbro, green = dominantly peridotite, white = no recovery. After Blackman et al. (2006).

Away from transform faults, ocean crust formed at fast spreading rates exhibits a relatively uniform seismic stratigraphy (e.g., Canales et al., 2003). At the ridge crests continuous axial low-velocity zones interpreted to be high level, axial melt lenses are imaged, and well defined Moho reflectors are present within a few kilometers of the axis. This suggests that ocean crust formed at fast spreading rates (>80 mm/yr full rate) is layered and relatively homogeneous. Although only 20% of modern ridges are fast-spreading (>80 mm/yr), 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 Ma, was produced at fast spreading ridges. Because of the relatively uniform seismic structure and bathymetry of fast-spreading lithosphere, understanding of crust and mantle genesis and evolution at one site can be extrapolated to a significant portion of Earth's surface with some confidence. Importantly, scientists have well developed theoretical models of contrasting styles of magmatic accretion at fast-spreading ridges. Methods have been proposed to test these model using samples recovered from drilled sections of ocean basement together with complementary studies of ophiolites, in particular the Oman ophiolite. Therefore, the highest priority of Mission Moho is to obtain a continuous sample of the entire crust, the Moho and shallow mantle peridotites, in oceanic lithosphere formed at a fast-spreading rate. Scientific and technological progress towards this ultimate goal will require drilling at several additional sites, in crust formed at both fast- and slow-spreading rates.

Ocean crust formed at slow to ultra-slow rates (<40 mm/yr) is highly heterogeneous both along and across axis particularly towards the end of ridge segments where tectonic extension competes with magmatic accretion (e.g., Karson and Elthon, 1987; Dick, 1989; Cannat et al., 1995, 2006; Canales et al., 2000; Kelemen et al., 2004; Ildefonse et al., 2007a). Such is the variety of accretion on slow spreading ridges that fully characterizing the heterogeneity is beyond the scope of this Mission. However, tectonic windows at fast- and slow-spreading ridges provide exposures of deep crustal rocks, serpentinized upper mantle, and possibly fresh upper mantle peridotites that can be sampled in relatively shallow drill holes using existing technologies.

3. Scientific Objectives

By drilling an intact section of ocean crust and upper mantle generated at a fast-spreading ridge, we will address first-order questions about the formation of oceanic crust, the nature of the Moho, and the composition of the Earth's convecting mantle. Specific objectives include:

- Determine the geological meaning of the Moho in a variety of tectonic settings,
- Determine the *in situ* composition of the uppermost mantle, its structure and physical properties, and the physics and chemistry of mantle melt migration processes,
- Determine the bulk composition of the oceanic crust to establish the relationship between the lavas that erupt at the seafloor and the melts that separated from their mantle sources,
- 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 mode of magmatic, crustal accretion at fast spreading mid-ocean ridges. What are the size and architecture of mid-ocean ridge magma chambers responsible for the construction of the lower ocean crust?,
- Determine the linkages and feedbacks between magma intrusion, hydrothermal circulation and tectonic activity,
- Calibrate regional seismic measurements against core samples and borehole experiments,

- Understand the origin of marine magnetic anomalies and quantify the contribution of lower crustal rocks to the magnetic signature of the ocean crust,
- Establish the limits of life in the ocean lithosphere.

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. Details of the individual components of Mission Moho will be fully developed in the proposals hosted beneath the Mission Moho umbrella.

3.1. What is the geological meaning of the Moho and seismic layers?

Understanding the seismic structure of the 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. 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 is a band with 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 the "classical" Pacific seismic profiles a sharp transition from ~7 to ~ 8 km/s occurs within <500 m. By analogy with ophiolites and geological 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).

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/ODP Hole 504B where the inflection in seismic velocity gradient occurs within the sheeted dikes (Detrick et al., 1994; Alt et al., 1996; Carlson, 2001) 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. Elsewhere, Hole 1256D data suggest that the layer 2/3 seismic transition has not been yet reached, even though the hole extends below the first appearance of gabbros at the base of the sheeted dikes (Teagle et al., 2006). Drilling deeper at Site 1256, and through the Layer 2/3 boundary in the MoHole (if not at Site 1256), will continue to reveal the geological meaning of the seismic layering of the upper ocean crust.

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 primary goal of Mission Moho is to sample through the base of Layer 3 and the Mohorovičić discontinuity, and into residual peridotites of the upper mantle. In contrast to the classical interpretation of the Moho as the crust-mantle boundary, Hess (1960) 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 identical to (or even lower than) those of fresh gabbros (e.g. Horen et al., 1996; Carlson and Miller, 1997). At fast-spreading ridges, the Moho is generally sharp, which is thought to indicate that the Moho is a lithological contact between gabbro and ultramafic rock. However, Vp beneath the oceanic Moho is generally 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, this question of the petrological significance of the Moho will remain unresolved.

Laboratory-derived velocities of discrete samples cannot reflect large-scale structures within the oceanic lithosphere. Integration of seismic reflection and drilling data will require detailed wireline sonic logging coupled with vertical and multi-ship offset seismic experiments allowing the measurement of regional mantle anisotropy and crustal structure.

At slow-spreading ridges, serpentinized mantle rocks are commonly incorporated into the crust. Drilling through this type of crust, down to fresh peridotites could provide the first fresh, *in situ* mantle samples and test hypotheses regarding the nature of the Moho. Is it: 1) the boundary between the residual upper mantle and the igneous crust, 2) a broader zone of layered ultramafic and mafic rocks, 3) a serpentinization front, or any combination of these three (Fig. 2)? Assessing the role of serpentinization in modifying the seismic signature of the crust and the transition to typical mantle velocities is most conclusively addressed by deep drilling lower ocean crust and upper mantle unroofed at slow rates of oceanic spreading.

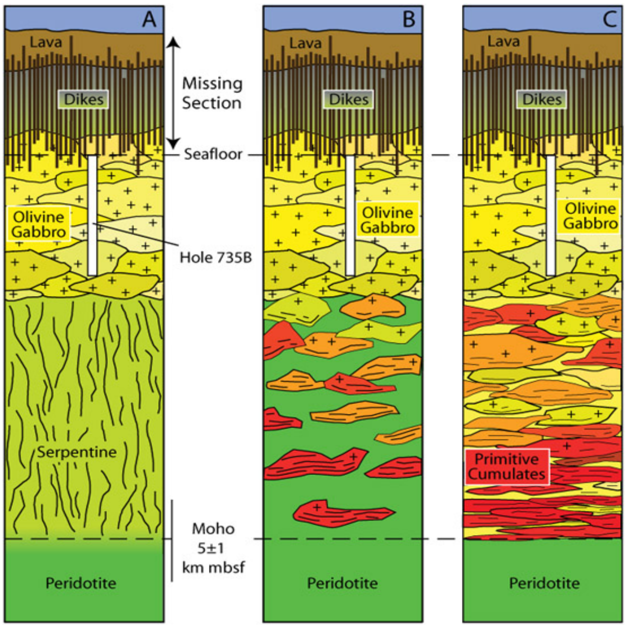

Fig. 2 - Various alternative models of crustal architecture and the Moho for the Atlantis Bank (Southwest Indian Ridge), where Hole 735B was drilled (after Dick et al., 2006). [A] After Muller et al. (1997). [B] After Cannat (1996). [C] After Dick et al. (1991).

3.2. Obtaining the first fresh samples of the Earth's convecting mantle

Presently there are NO fresh samples of the convecting mantle. Xenoliths, inclusions brought to the surface in lavas, are (a) mainly derived from continental lithosphere, rather than the convecting mantle, and (b) contaminated by interaction with host lavas. This problem is particularly acute for understanding volatile chemical components that are modified by hydrothermal alteration in tectonically exposed samples, or by host lavas in xenoliths. 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 in the "MORB source" –the convecting upper mantle that partially melts to form Mid-Ocean Ridge Basalts– are sustained largely by inference and assertion. Concentrations and isotope characteristics of volatile elements in Earth reservoirs are vital tracers for global chemical cycling. Other components, such as heat-producing elements U and Th, may be concentrated on grain boundaries (Niu, 2004), but we have no fresh grain boundaries to examine.

The nature and length scale of heterogeneity in the mantle source of mid-ocean ridge basalts (MORB) remains controversial and has fundamental implications for the most basic structure of mantle convection: are ocean island basalts fed by hot plumes that cut through the upper mantle MORB source, or is the MORB source replenished from the same mantle material as ocean island basalts? Such problems remain unsolved because mantle source characteristics are largely inferred from lava compositions. Tectonically exposed peridotites sampled by dredging and shallow ocean drilling are plagued by contamination problems due to their highly reactive nature on the seafloor. Drill core from fresh, oceanic upper mantle will place constraints on the extent and scale of Sr, Nd, Pb, Hf and Os isotope vertical variability, independent of the effects of near-surface alteration and deformation.

Similarly, the grain size and deformation history of unaltered oceanic peridotite remains unknown. These parameters, essential for understanding mantle seismic data (e.g., Faul and Jackson, 2005), melt transport in the mantle (e.g., Spiegelman and Kenyon, 1992), or deformation at decreasing temperature caused by corner flow beneath the ridge, can only be addressed through the recovery of fresh samples of *in situ* mantle peridotite.

3.3. Melt focusing and extraction beneath mid-ocean ridges

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 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 the locus of spreading. How is this melt extracted and crystallized to form oceanic crust within a narrow region, a few km wide, as seismically imaged along the East Pacific Rise? Several, well-defined hypotheses have been outlined, but no consensus will emerge without the direct evidence that would be provided by drilling *in situ* upper mantle.

A key element of this problem is to understand and characterize the upwelling path of partially molten mantle peridotite. Is it passive, plate-driven flow (e.g., Langseth et al., 1966; McKenzie, 1967; Bottinga and Allegre 1973, 1976; Sleep, 1975) or active, buoyancy-driven flow (e.g., Rabinowicz et al., 1984; Whitehead et al., 1984; Buck and Su, 1989; Fig. 3)?

For samples obtained more than a few kilometers from the ridge axis, both models predict flow trajectories and lineation approximately perpendicular to the ridge axis, in a nearly horizontal foliation. However, passive vs. buoyancy driven upwelling can be distinguished from the flow kinematics recorded by olivine crystallographic preferred orientations. Active upwelling models predict that outward horizontal flow in the upper mantle is faster than plate velocity, resulting in an inversion of shear senses on a vertical section close to the Moho (Ceuleneer et al., 1988; Nicolas et al., 1988, 1994). This has been mapped in the Oman ophiolite (Nicolas et al., 1994; Ildefonse et al., 1995) and would be apparent in drill cores.

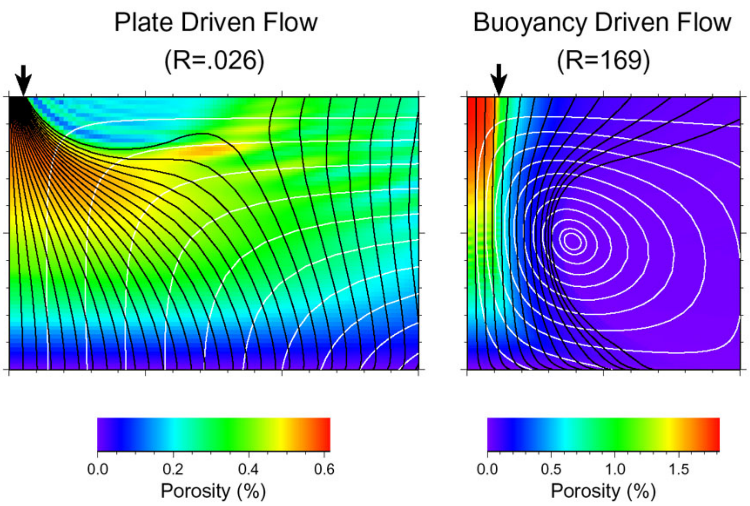

Fig. 3 - Examples of 2D (perpendicular to ridge axis) numerical models of mantle passive upwelling (left) and active, buoyant upwelling (right). Black curves: melt flow; white curves: solid flow (Spiegelman, 1996).

Another key element is to understand the transport of melt through the mantle peridotite host rocks. 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., 1995a, 1995b, 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; Spiegelman, 1993; Ghods and Arkani-Hamed, 2000; Rabinowicz and Ceuleneer, 2005), by focused flow in high porosity shear zones (e.g., Stevenson, 1989; Kelemen & Dick, 1995; Connolly and Podladchikov, 2000; Holtzman et al., 2003), via passive transport within low permeability, partially molten, buoyant diapirs (e.g., Rabinowicz et al., 1984; Whitehead 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, 1990). 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.

Much of what we know about the composition and temperature of the upper mantle, and their global variability, comes from the chemistries of mid-ocean ridge basalts, which are used to infer the composition of the melt that crossed the Moho (e.g., Klein and Langmuir, 1987, McKenzie and Bickle, 1988). However, 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 more primitive cumulates, with Mg# ≤ ~90 (equivalent to that of the mantle residues of MORB formation) before the remaining melt is extracted to erupt as MORB. On average, erupted MORBs record about 50% crystallization (see Shipboard Scientific Party, 2004). 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. We believe that they must comprise much of seismic Layer 3 in fast-spread crust, and must be abundant somewhere (near ridge segment centers? as intrusions into mantle peridotite?) at slow-spreading ridges, but these hypotheses remain completely untested. In addition, because the nature of the primitive cumulates is unknown, determining the composition of unfractionated melts requires making numerous assumptions. These assumptions can only be tested by having a complete crustal section from which the integrated composition of the entire crust can be determined (e.g., O'Hara, 1982).

3.4. Mode(s) of accretion of the lower crust at fast-spreading ridges

Seismic Layer 2A, inferred to be composed mainly of lavas, constitutes less than a sixth of the total crustal thickness in fast-spread crust, so that the majority of the crust is inferred to be formed from melt that is intruded into the crust from the mantle. The nature of this process is hotly debated. Our understanding has been limited by the difficulties of geophysically imaging and directly sampling the crust, in particular *in situ* gabbroic lower crust. Consequently, the nature of the magma chambers beneath mid-ocean ridges and the magmatic processes that build the lower crust remain virtually unconstrained. Many fundamental questions remain unresolved. For example: how is melt transported from the mantle through the crust? Where do melts fractionate and crystallize? How, and how fast is heat extracted?

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, 2006a; Kent et al., 2000). Melt lenses have also been imaged at or close to Moho depth (Garmany, 1989; Dunn et al., 2001; Crawford and Webb, 2002, Nedimovic et al., 2005; Singh et al., 2006b). These observations, combined with geological and petrological evidence from in-situ ocean crust and 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. 4a).

2. Crystallization of lower crustal gabbros occurs partly (Boudier et al., 1996) or essentially *in situ* (Kelemen et al., 1997b; MacLeod and Yaouancq, 2000) via injection of "sheeted sills" (Boudier et al., 1996; Kelemen et al., 1997b; Fig. 4b-c).

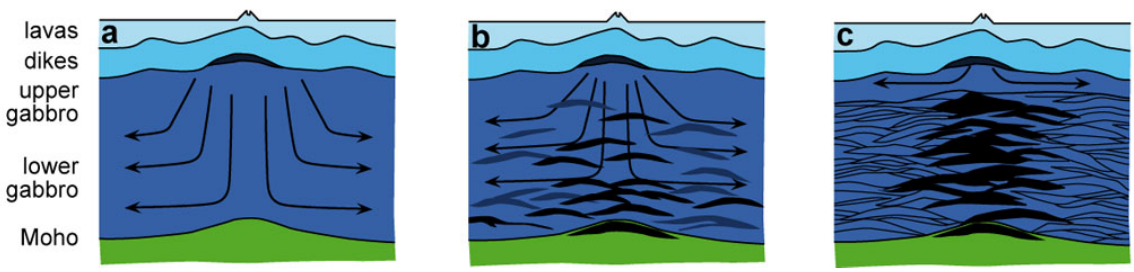

Fig. 4 - Schematic drawings of crustal accretion models (after Korenaga and Kelemen, 1998). [a] Gabbro glacier ductile flow model (e.g., Henstock et al., 1993; Quick and Denlinger, 1993). [b] A hybrid model of ductile flow with sill intrusions (e.g., Boudier et al., 1996). [c] "Sheeted sill" model of in situ formation of the lower crust by on-axis sill intrusions (e.g., Kelemen et al., 1997b).

These 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. Drill core samples from a Pacific Ocean crustal section are essential to distinguish between these competing models directly, through systematic measurements of compositions, textures, structures, and igneous contacts as a function of depth through the lower crustal gabbro section (Fig. 5).

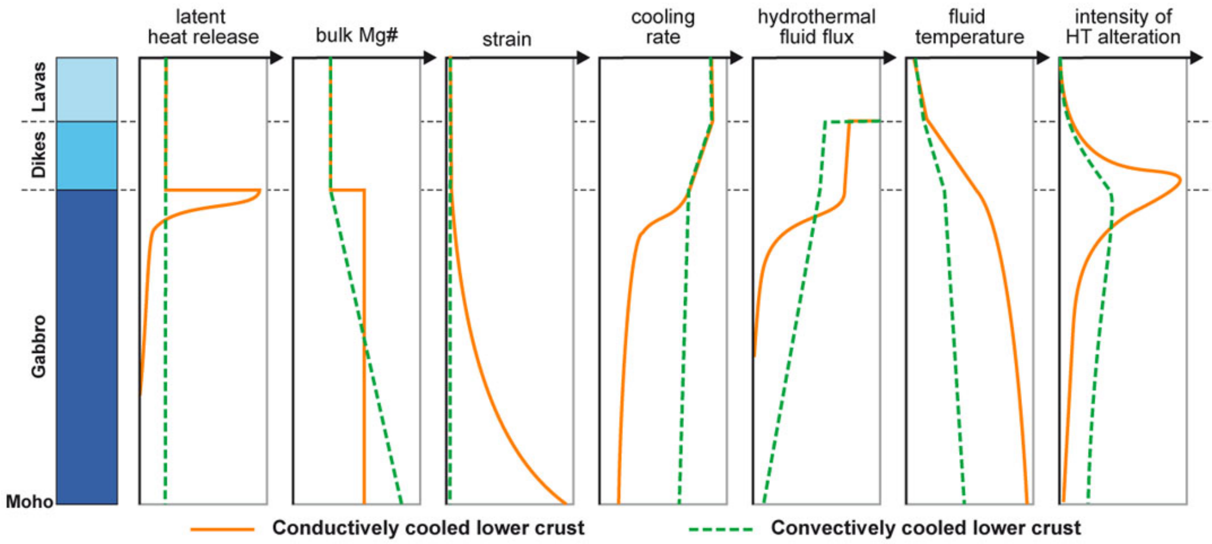

Figure 5 - Schematic relative variations in the general trends of latent heat release, bulk Mg#, strain rate, cooling rate, hydrothermal fluid flux, fluid temperature, and intensity of high temperature alteration with depth predicted by end-member "gabbro glacier" (with mainly conductive cooling of the lower crust) and "sheeted sill" (with convective cooling of the lower crust) models of crustal accretion.

Magmatic processes and architecture of the crust: 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 become more evolved upwards (Fig (5) and sub-Moho sills (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 (Fig 5). 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 the 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; Blackman et al., 2006). 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 (Korenaga and Kelemen, 1997).

The nature of chemical layering can also be used to place constraints on 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 address such chemical variations.

Deformation of the ocean crust: 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. 5). In contrast, crustal construction by successive sill injections will not produce systematic gradients in strain with depth. Published data sets from the Oman ophiolite are too limited to be conclusive, and show no significant downward trend (Yaouancq and MacLeod, 2000). 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.

Cooling the lower ocean crust: As magmas cool and crystallize, both the latent heat of crystallization and 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 in Figure 4a and 4c yield different distributions of latent heat removal with depth (Fig. 5). 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 the 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), and predicts a decrease in cooling rate with depth, assuming that deep cooling is predominantly by conduction. However, the sheeted sill model (Fig. 4b-c) 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; Maclennan et al., 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 (Cherkaoui et al., 2003), rendering thermal models uncertain until tested by data. The contrasting distribution, flux and temperatures of hydrothermal fluids predicted by each of the accretion models imply distinct alteration patterns that will be directly observed in drill cores (Fig. 5).

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 using (i) "geospeedometers" that exploit elemental (Fe, Ca, Li) diffusion rates in olivine, clinopyroxene, and plagioclase (Ozawa, 1986; Coogan et al., 2002, 2005a, 2005b), (ii) 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 in of magnetic 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. Uniform polarity over a great depth range would indicate rapid cooling within a time between field reversals.

Well-established petrologic and geochemical techniques can be used to characterize the nature and relative timing of hydrothermal exchange between seawater and the lower crust, 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, strontium 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 lower crust (e.g., Gregory and Taylor, 1981; Manning et al., 1996; Teagle et al., 1998; 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; Nicolas et al., 2003; 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).

3.5. Crustal aging and chemical fluxes: from mantle to hydrosphere and back again

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 and some seawater-rock exchange probably occurs in ocean crust of all ages. Geochemical and petrological constraints on water/rock ratios, time integrated fluid, chemical and isotopic fluxes and the nature of hydrothermal alteration of the crust (see section 3.4) 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, so that drilling may actually sample an active, low temperature hydrothermal system. In any case, drilling in crust as old as possible (see section 5.2) will allow better constraints on the role of hydrothermal alteration in controlling 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.

3.6. Probing the limits of life

The upper oceanic crust is a 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., Bach and Edwards, 2003; Banerjee and Muehlenbachs, 2003; Staudigel et al., 2006). Hydrogen and simple organic compounds can be produced abiotically where water interacts with ultramafic rocks in a variety of geotectonic settings, including portions of slow-spreading mid-ocean ridges (e.g., McCollom and Seewald, 2001; Kelley et al., 2005). Microbial activity occurring in the sub seafloor biosphere may have a profound impact on processes and chemical fluxes during water-rock reactions but the depth limits of microbiological activity in the oceanic basement have yet to be fully explored.

Exploring and characterizing the sub seafloor biosphere in the ocean crust will be pursued in all oceanic basement holes. 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. An extraordinary diversity of microorganisms exists in high temperature environments (>120ºC; Kashefi & Lovley, 2003), and this diversity is reflected in enzymes and other molecules. Deep drilling will provide access to rocky habitats at the edge of the life envelope (Bach et al., 2006) and an opportunity to search for novel microorganisms from high-temperature sub seafloor environments, leading to discovery of new compounds with biotechnology, medical and engineering applications. These environments may also be key in the search for primordial microbial communities that may have been the earliest life forms on Earth (e.g., Furnes et al., 2004; Banerjee et al., 2006).

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Appendix 2 - Langseth Workshop White Paper (2010)

This white paper was submitted to the NSF "Langseth" workshop (*Challenges and Opportunities in Academic Marine Seismology*, March 22-24, 2010, Incline Village, NV, USA; http://www.unols.org/meetings/2010/201003mls/201003LW_details.html)

Setting up the Stage for Project MoHole:

Seismic Studies of Fast-Spread Ocean Lithosphere

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The mid-ocean ridges and the new oceanic lithosphere that they create are the principal pathway for energy and mass exchange and physical/chemical interactions between the earth's interior, the hydrosphere, and the biosphere. Bio-geochemical reactions between the oceans and oceanic crust occur throughout its lifetime, and hence the ocean lithosphere records the inventory of global thermal, chemical and biological exchanges. The MoHole, an initiative to drill an ultra-deep hole in an intact portion of oceanic lithosphere, through the crust to the Mohorovičić discontinuity (Moho), and into the uppermost mantle is a long-standing goal of scientific ocean drilling. It remains critical to answer many fundamental questions about the dynamics of the Earth and global elemental cycles; its fundamental goals include:

- Determine the bulk composition of the oceanic crust to establish the chemical links between erupted lavas and primary mantle melts, understand the extent and intensity of seawater hydrothermal exchange with the lithosphere, and estimate the chemical fluxes returned to the mantle by subduction,
- Test competing hypotheses of the ocean crust accretion at fast spreading mid-ocean ridges, and quantify the linkages and feedbacks between magma intrusion, hydrothermal circulation and tectonic activity,
- Determine the geological meaning of the Moho in different oceanic settings,
- Determine the in situ composition, structure and physical properties of the uppermost mantle (and its variability), and understand mantle melt migration,
- Calibrate regional seismic measurements against recovered cores and borehole measurements, and understand the origin of marine magnetic anomalies,
- Establish the depth extent of deep biosphere and hydrological/geobiological processes in the lithosphere.

More detailed scientific rationale for the MoHole can be found in recent workshop reports:

- http://www.iodp.org/mission-moho-workshop/
- http://www.interridge.org/WG/DeepEarthSampling/workshop2009

A forthcoming workshop to be held in Kanazawa, Japan, in June 2010 (http://earth.s.kanazawa-u.ac.jp/~Mohole/) will indentify 2-3 potential MoHole sites in the Pacific where the scientific community will focus geophysical site survey and post-drilling research efforts over the next few years. The type, resolving power, and coverage of geophysical data needed for site selection and to accomplish the post-drilling scientific goals will be amply discussed during the workshop.

In particular, seismic surveys are expected be a fundamental component of MoHole critical to accomplish the goals of this ambitious project. These surveys will be more efficiently conducted through international collaborations involving several platforms of different characteristics. Among these platforms, the *R/V Langseth* will undoubtedly be a key resource because of her state-of-the-art seismic capabilities. We envision *Langseth* contributing to acquisition of one or more of several types of seismic data needed to support Project MoHole, which include:

(1) 3D multichannel seismic (MCS) data. MCS reflection imaging of the oceanic Moho is often degraded by in- and out-of-plane energy scattered by the rough igneous basement [e.g., *Kent et al.*, 1996]. Among the many benefits of 3D MCS data and 3D processing techniques is the possibility of accurately collapsing the scattered wavefield to its source location; therefore significantly improving image quality. In addition, obtaining geometrically accurate images of steeply dipping faults that may cut an entire crustal section (and therefore perhaps affecting the physical properties of the Moho) [e.g., *Nedimović et al.*, 2009] will also require 3D MCS data/processing. The potential benefits of combining 3D MCS with 3D borehole VSP for a project of these characteristics need to be explored.

(2) 2D long-offset (^{3}8-km streamer) MCS data. In recent years 2D MCS data collected with 6-km-long hydrophone streamers have resulted in seismic images of the lower oceanic crust, Moho, and sub-Moho structure of unprecedented quality and detail, contributing to a better understanding of the geological processes that form the lower crust and Moho [*Canales et al.*, 2009; *Nedimović et al.*, 2005]. Acquiring MCS data with an 8-km-long streamer, as current *Langseth* capabilities allow, will further improve imaging of lower crustal and uppermost mantle features, as well as enabling amplitude-vs-offset studies of the physical properties of such deep targets. An added value of long-offset MCS data is their potential for conducting high-resolution waveform tomography studies to obtain the fine-scale seismic velocity structure of the upper- and mid-crust in the vicinity of a deep drill hole, thus contributing to a better integration of drilling sampling/results and regional geophysical data.

(3) 3D large-scale Ocean Bottom Seismometer (OBS) data. *Langseth* offers a superb powerful airgun array for active-source 3D wide-angle refraction/reflection OBS experiments. Using traveltime tomography techniques, these type of data allow resolving the 3D *P*- and *S*-wave velocity and anisotropy structure of the crust and uppermost mantle at scales of several kilometers, which will help interpretation of drilling results and placing them in the appropriate tectonic context.

(4) 2D high-resolution OBS data. Data acquired with a large number of densely spaced OBSs, in conjunction with *Langseth*'s excellent seismic source, can be used for high-resolution determination of the velocity structure of the Moho transition zone (MTZ) in the vicinity of a drill hole using waveform tomography approaches [e.g., *Operto et al.*, 2006]. At long source-receiver offsets (~15-40 km), the MTZ seismic signature is a high-amplitude wide-angle reflection ideal for frequency-domain waveform tomography studies [e.g., *Brenders and Pratt*, 2007].

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Appendix 3 - INVEST Meeting White Papers

A number of white papers related to drilling the oceanic lithosphere have been submitted to The IODP INVEST meeting (*IODP New Ventures in Exploring Scientific targets*, September 23-25, 2009, Bremen, Germany; http://www.marum.de/iodp-invest.html). Several of them directly or indirectly addressed scientific objectives and/or engineering/technological aspects of the MoHole project. They can be downloaded from the INVEST meeting web site :

• *Petrological nature of the oceanic Moho*, by Shoji Arai (Kanazawa University, Japan) :
http://www.marum.de/Binaries/Binary42200/Arai_MoHole.pdf

• *Integration of drilling into deep oceanic crust and seafloor geophysical observations for investigation of upper mantle structure and plate aging*, by Kiyoshi Baba (Earthquake Research Institute, University of Tokyo, Japan) et al. :
http://www.marum.de/Binaries/Binary42202/Baba_CrustMantleStructureIntergration.pdf

• *Ocean Drilling and Exploring a Heterogeneous Ocean Crust*, by Henry J.B. Dick (Dept. of Geology & Geophysics, WHOI, Woods Hole, USA) et al. :
http://www.marum.de/Binaries/Binary42446/Dick_CrustalHeterogeneity.pdf

• *Towards coordination and integration of deep marine biosphere research: the Dark Energy Biosphere Institute (DEBI)*, by Katrina J. Edwards (USC, Los Angeles, USA) et al. :
http://www.marum.de/Binaries/Binary42209/Edwards_DeepBiosphereDEBI.pdf

• *Technological challenges necessary for the new horizon of IODP*, by Hiromi Fujimoto (Graduate School of Science, Tohoku University, Japan) :
http://www.marum.de/Binaries/Binary42212/Fujimoto_TechnologicalChallenges.pdf

• *Vertical Magnetization Structure of Ocean Crust and uppermost Mantle*, by Toshiya Fujiwara (IFREE, JAMSTEC, Japan) :
http://www.marum.de/Binaries/Binary42214/Fujiwara_OceanCrustMagneticStructure.pdf

• *Evolution of Hydrothermal Circulation*, by Robert N. Harris (College of Oceanic and Atmospheric Sciences, Oregon State University, USA) et al. :
http://www.marum.de/Binaries/Binary42217/Harris_HydrothermalCirculationEvolution.pdf

• *Drilling deep through the ocean crust into the upper mantle*, by Benoît Ildefonse (Géosciences Montpellier, CNRS, Université Montpellier 2, France) et al. :
http://www.marum.de/Binaries/Binary42226/Ildefonse_MoHole.pdf

• *Technological Drivers for Future IODP Science*, by the IODP Engineering Development Panel :
http://www.marum.de/Binaries/Binary42467/IODPEngineeringDevelopmentPanel_TechnologicalDrivers.pdf

• *New World of Technology developed with "Chikyu"*, by Yoshio Isozaki (CDEX, JAMSTEC, Japan) et al. :
http://www.marum.de/Binaries/Binary42443/Isozaki_NewTechnologyChikyu.pdf

• *Technology Developments for IODP Phase 2*, by Japan Domestic INVEST Workshop Technology Development Group :
http://www.marum.de/Binaries/Binary42439/JapanDomesticINVESTWorkshopTechnologyDevelopment_Group_Technology.pdf

• *Development of high temperature drilling technologies for 21st century Mohole*, by Engineering Development Advisory Committee (J-DESC, Japan) :
http://www.marum.de/Binaries/Binary42316/JapaneseEDGroup_HighTemperatureDrilling.pdf

• *Technological development for high temperature measurement in IODP*, by Engineering Development Advisory Committee (J-DESC, Japan) :
http://www.marum.de/Binaries/Binary42317/JapaneseEDGroup_HighTemperatureMeasurements.pdf

• *Ultra deep water and ultra deep drilling technologies for 21st Century Mohole*, by Engineering Development Advisory Committee (J-DESC, Japan) :
http://www.marum.de/Binaries/Binary42283/Watanabe_UltradeepDrilling.pdf

• *Geophysical studies toward deep drilling through the oceanic crust into the upper mantle*, by Shuichi Kodaira (IFREE, JAMSTEC, Japan) et al. :
http://www.marum.de/Binaries/Binary42243/Kodaira_GeophysicsUpperMantle.pdf

• *Benefits of in-situ and well-side geochemical monitoring at riser drilling*, by Hidenori Kumagai (IFREE, JAMSTEC, Japan) et al. :
http://www.marum.de/Binaries/Binary42244/Kumagai_GeochemicalMonitoringRiser.pdf

• *MOHOLE proposal for understanding the role of water in magmatic processes of oceanic ridges*, by Hiroaki Sato (Dept. Earth and Planetary Sciences, Kobe University, Japan) :
http://www.marum.de/Binaries/Binary42262/Sato_MoHole.pdf

• *Realistic Mohole using D/V Chikyu*, By Nobukazu Seama (Kobe University, Japan) et al. :
http://www.marum.de/Binaries/Binary42463/Seama_Mohole.pdf

• *The Ocean Lithosphere: A Fundamental Component of the Earth System (encapsulating discussions of the InterRIDGE-IODP "Melting, Magma, Fluids and Life" Workshop)*, by Damon Teagle (NOC, University of Southampton, UK) et al. :
http://www.marum.de/Binaries/Binary42445/Teagle_MeltingMagmaFluidLife.pdf

• *21st Century MoHole - Researches on Magmatic Processes of the Moho Transition Zone beneath the fast-spreading ridges*, by Susumu Umino (Kanazawa University, Japan) :
http://www.marum.de/Binaries/Binary42269/Susumu_MoHole.pdf

• *Breakthrough the Discontinuity: 21st Century Mohole*, by Susumu Umino (Kanazawa University, Japan) et al. :
http://www.marum.de/Binaries/Binary42280/Umino_JapanWG_MoHole.pdf

• *Life and Ecosystem in Deep Biosphere and Subseafloor Aquifers*, by Hiroyuki Yamamoto (JAMSTEC, Japan) et al. :
http://www.marum.de/Binaries/Binary42307/Yamamoto_DeepBiosphere2.pdf

Appendix 4 - Links to Earlier Scientific Planning Documents

• COMPLEX, 1999 conference report :
http://www.iodp.org/index.php?option=com_docman&task=doc_download&gid=808

• "Opportunities in Geochemistry for Post-2003 Ocean Drilling", 2000 workshop report :
http://www.iodp.org/index.php?option=com_docman&task=doc_download&gid=784

• ODP Architecture of the lithosphere PPG, summary report, 2003 :
http://www.iodp.org/index.php?option=com_docman&task=doc_download&gid=783

• Mission Moho, 2006 Workshop Report :
http://www.iodp.org/index.php?option=com_docman&task=doc_download&gid=1309

• "Mission Moho: Formation and Evolution of Oceanic Lithosphere", EOS, 2006 :
http://www.iodp.org/index.php?option=com_docman&task=doc_download&gid=1302

• "Mission Moho Workshop: Drilling Through the Oceanic Crust to the Mantle", Scientific Drilling, 2007 :
http://www.iodp.org/iodp_journals/2_Mission_Moho_Workshop_SD4.pdf

• MissionMoho IODP proposal, 2007 :
http://www.gm.univ-montp2.fr/spip/IMG/pdf/MissionMohoProposal_April07_LowRes.pdf

• Melting, Magma, Fluids and Life, 2009 workshop report :
available at http://www.interridge.org/WG/DeepEarthSampling/workshop2009

Appendix 5 - Workshop Presentation slides

Introduction, scientific rationale for the MoHole

• **Damon A.H. Teagle & Mission Moho Proponents** - Beyond the Moho: Scientific justification for a complete penetration of intact in situ ocean crust and into the upper mantle *65*

Available Site survey data in the Pacific

• **Douglas S. Wilson** - The Trade-off of Depth and Temperature in choosing a MoHole Site *75*

• **Nobukazu Seama** - Hawaii site in comparison with IODP site 1256 .... *83*

• **Douglas S. Wilson, Alistair J. Harding, Eric Hallenborg, & Graham Kent** - Site Survey Data at ODP Site 1256 (ODP Leg 206, IODP Expeditions 309/312) *106*

• **Donna K. Blackman** - "Deep Tow" Site: ~30Myr Old Crust off Southern California ... *115*

• **Shuichi Kodaira** - IFREE seismic studies toward the Mohole project: results and future plan *120*

Current understanding of technological feasibility

• **Greg Myers** - MoHole Engineering… Seeking solutions inside and outside of IODP *134*

• **Shomei Kobayashi** - "Chikyu" Drilling Challenge for the MoHole *144*

• **Masaoki Yamao** - The CHIKYU Engineering Development *157*

• **Yuichi Shinmoto** - Technical Development of Coring System in the Quest to reach the Earth's Mantle *163*

Drilling and coring at high temperatures

• **David Mainprice & Philippe Pezard** - Drilling DEEP into HOT Oceanic Crust, Constraints and Challenges *167*

• **Alister Skinner** - Iceland Deep Drilling Project *177*

Brief !

Beyond the Moho:

Scientific justification for a complete penetration of intact *in situ* ocean crust and into the upper mantle

Damon A.H. Teagle
on behalf of the Mission Moho Proponents

Benoît Ildefonse Natsue Abe, Peter B. Kelemen, Hidenori Kumagai, Damon A.H. Teagle, Douglas S. Wilson, Gary Acton, Jeffrey C. Alt, Wolfgang Bach, Neil R. Banerjee, Mathilde Cannat, Richard L. Carlson, David M. Christie, Rosalind M. Coggon, Laurence Coogan, Robert Detrick, Henry J.B. Dick, Jeffrey S. Gee, Kathryn Gillis, Alistair Harding, Jeffrey A. Karson, Shuichi Kodaira, Juergen Koepke, John Maclennan, Jinichiro Maeda, Christopher J. MacLeod, D. Jay Miller, Sumio Miyashita, James H. Natland, Toshio Nozaka, Mladen Nedimovic, Yasuhiko Ohara, Kyoko Okino, Philippe Pezard, Eiichi Takazawa, Takeshi Tsuji, Susumu Umino

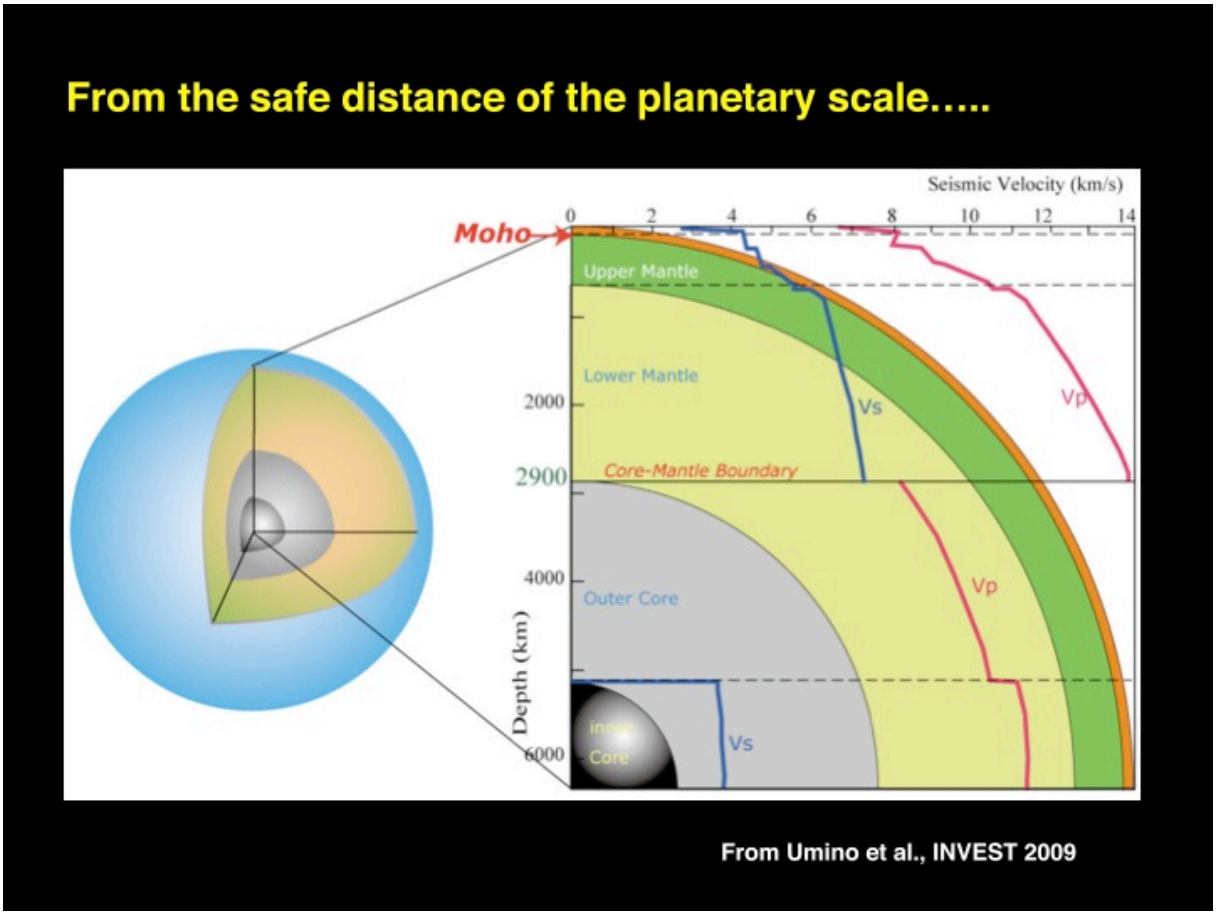
Mission Moho

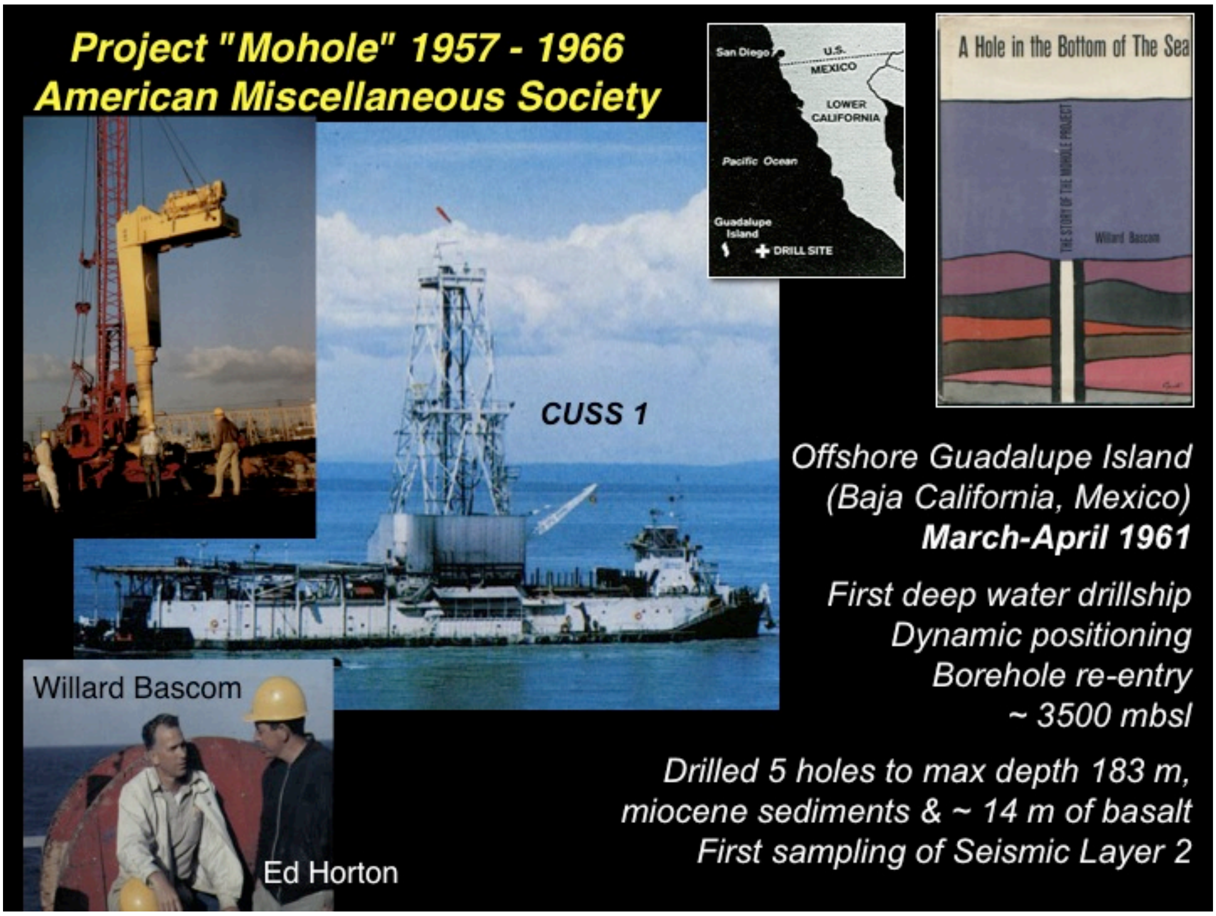
Ultimate Goal:

A complete section through intact ocean crust formed at a fast spreading rate into peridotites of the upper mantle

No longer Science Fiction!

Now within the realm of technical feasibility


From the safe distance of the planetary scale.....
Seismic Velocity (km/s)
0 2 4 6 8 10 12 14
Moho
Upper Mantle
Lower Mantle
2000
2900
Core-Mantle Boundary
Vs
Vp
4000
Outer Core
Vp
Depth (km)
6000
Inner Core
Vs
From Umino et al., INVEST 2009


Project "Mohole" 1957 - 1966
American Miscellaneous Society
San Diego
U.S.
MEXICO
LOWER CALIFORNIA
Pacific Ocean
Guadalupe Island
DRILL SITE
A Hole in the Bottom of The Sea
THE STORY OF THE MOHOLE PROJECT
Willard Bascom
CUSS 1
Offshore Guadalupe Island
(Baja California, Mexico)
March-April 1961
First deep water drillship
Dynamic positioning
Borehole re-entry
~ 3500 mbsl
Drilled 5 holes to max depth 183 m,
miocene sediments & ~ 14 m of basalt
First sampling of Seismic Layer 2
Willard Bascom
Ed Horton


Project "Mohole" 1957 - 1966
High Drama
of Bold Thrust
through Ocean Floor
EARTH'S SECOND LAYER IS TAPPED IN PRELUDE TO MOHOLE
by JOHN STEINBECK
John Steinbeck
Life
April 14, 1961
"Our expedition should destroy the old and well loved error that doers and thinkers are different breeds"


Project MoHole
back in the News
New York Times
The Sunday Times
Newsweek
Metro
BBC WORLD SERVICE
Big George's Breakfast
Daily Mail
Richard and Judy!
Inside James Wood, Michel Faber, Barbara Ehrenreich, Mark Lawson, Charlie Brooker
The Guardian
The joy of being 60
Michel Houellebecq
Journey to the centre of Earth
The search for life six miles down
Man to be charged with McCartney murder today
Police investigate religious links after witchcraft abuse of child, 8
Harry Potter and the missing gun

Unfortunately…

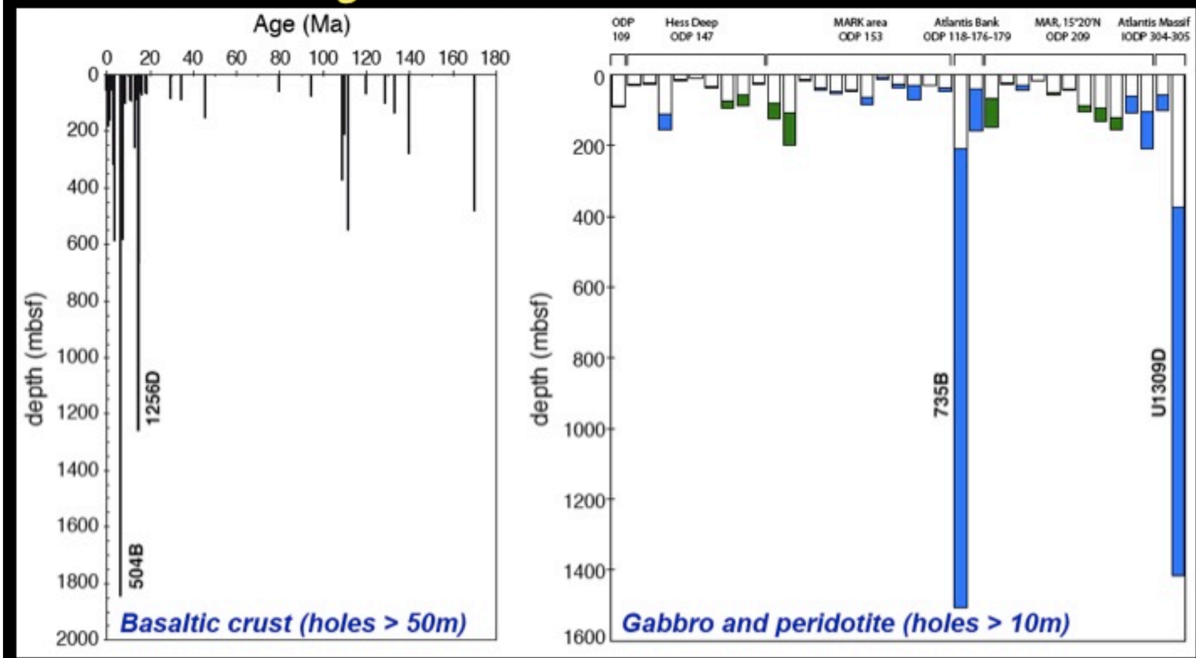
Many of the major science motivations of Project MoHole and 40 years of scientific ocean drilling still remain:

- Nature of the **Moho**
- **Seismic Layering** of the crust
- **Accretion** of the ocean crust
- Nature of **Magma Chambers**
- **Thermal Structure** of the ocean crust
- Geometry of **Hydrothermal Cooling**
- Chemical, fluid and isotopic **Fluxes**
- Ridge Axis vs **Ridge Flank Exchange**
- Origin of **Magnetic Stripes**

Primary inhibitor

Dearth of continuous sections of ocean crust

Basement drilling 1968 to 2005



Until recently: 1 penetration of lava-dikes - Hole 504B
no sampling of dikes-gabbros

Drilling Hard Rocks in the Oceans is Hard!

Mission Moho

Ultimate Goal:

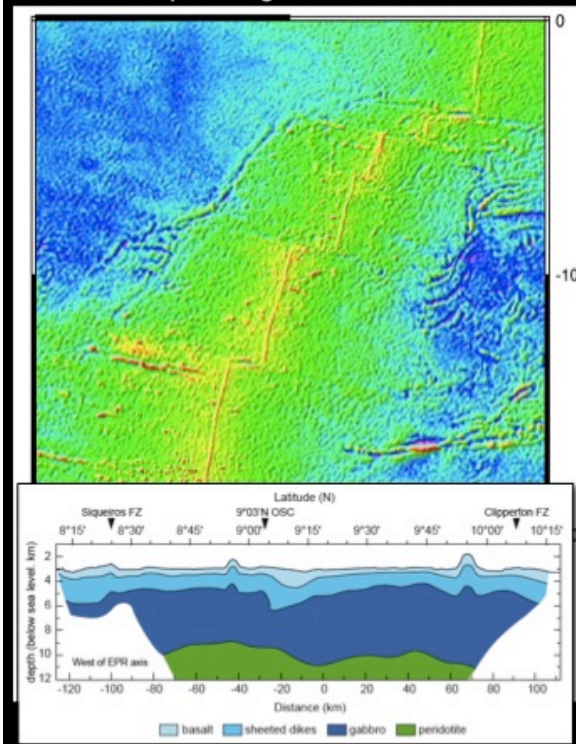
A complete section through intact ocean crust formed at a fast spreading rate into peridotites of the upper mantle

Scientific objectives:

- Geological nature of the **Mohorovicic Seismic Discontinuity**
- ***In situ* composition** and physical properties of the **Uppermost Mantle**
- Upper **Mantle Dynamics** and **Melt Migration** processes
- **Bulk Composition** of the oceanic crust
- **Magmatic accretion** at mid-ocean ridges
- **Extent, location, and intensity of hydrothermal exchanges**
  - global chemical budgets, seawater chemistry, subduction fluxes
- Calibrate regional **Seismic Layering** against borehole and samples
- **Marine magnetic anomalies**
- **Limits of Life** in the Oceanic Lithosphere

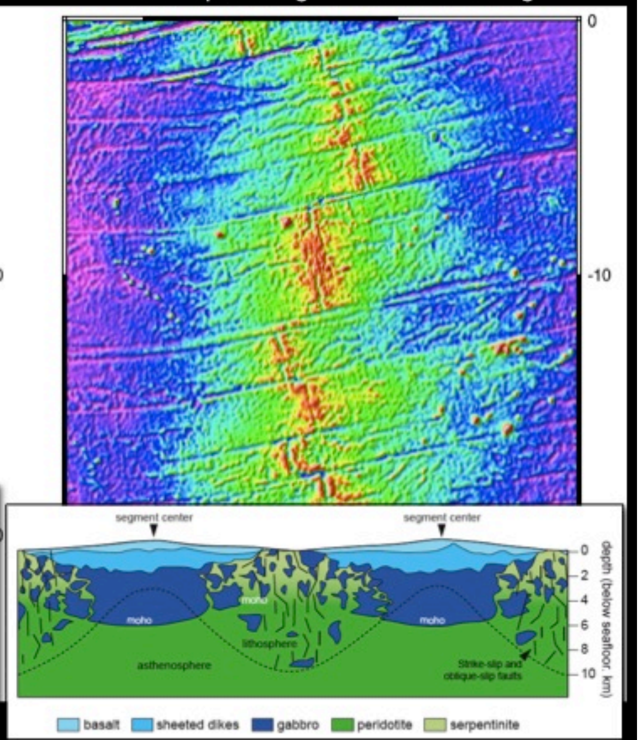
Ocean crust architecture is variable

Fast-spreading : East Pacific Rise

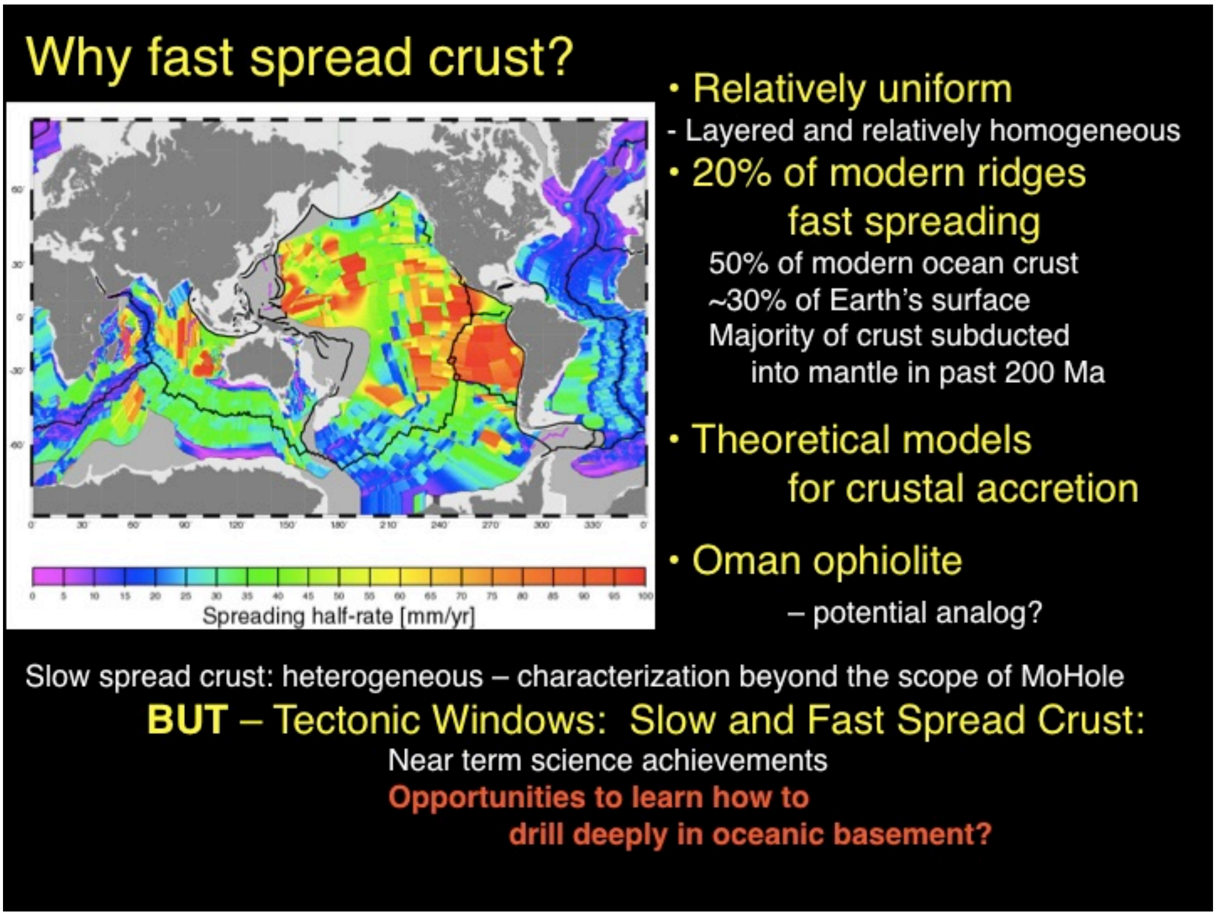


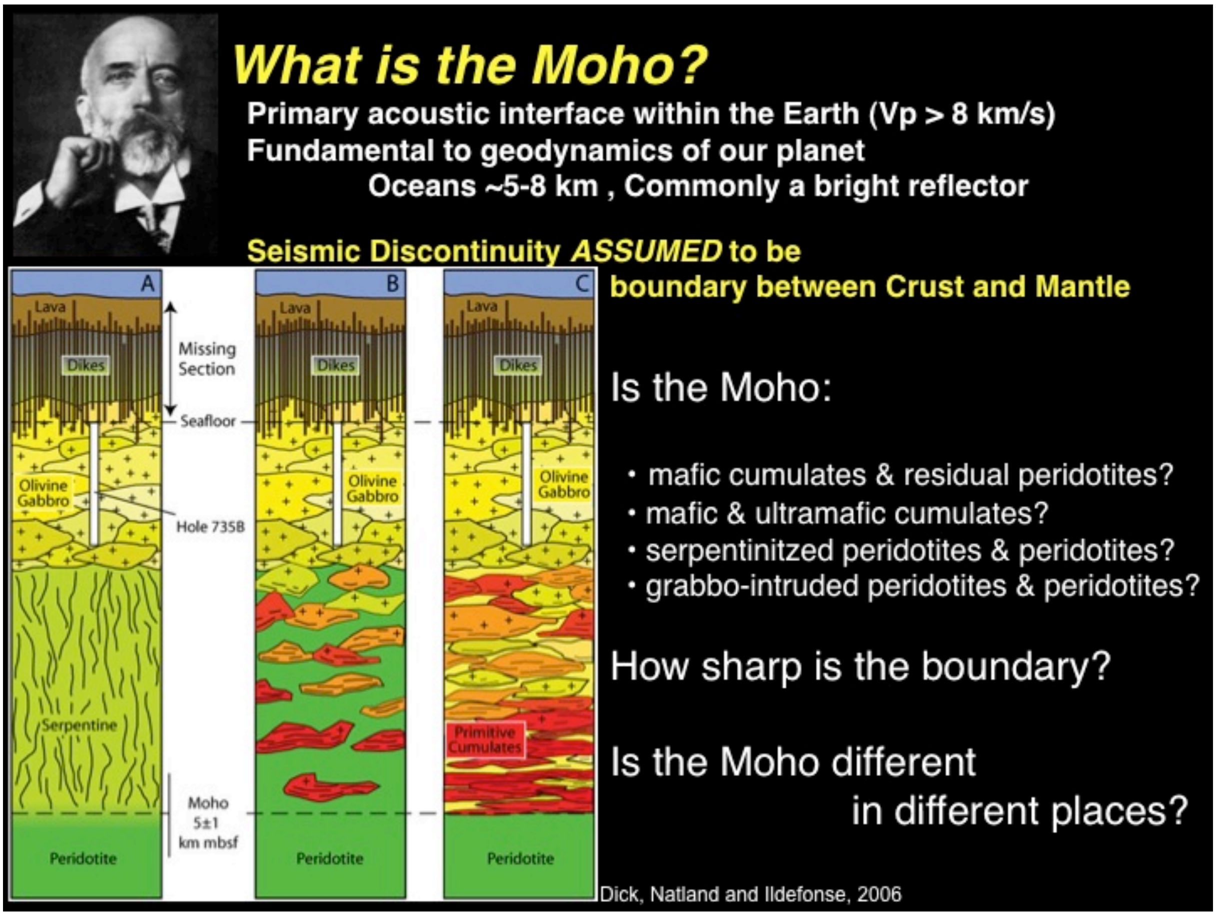
After Canales et al. (2003)

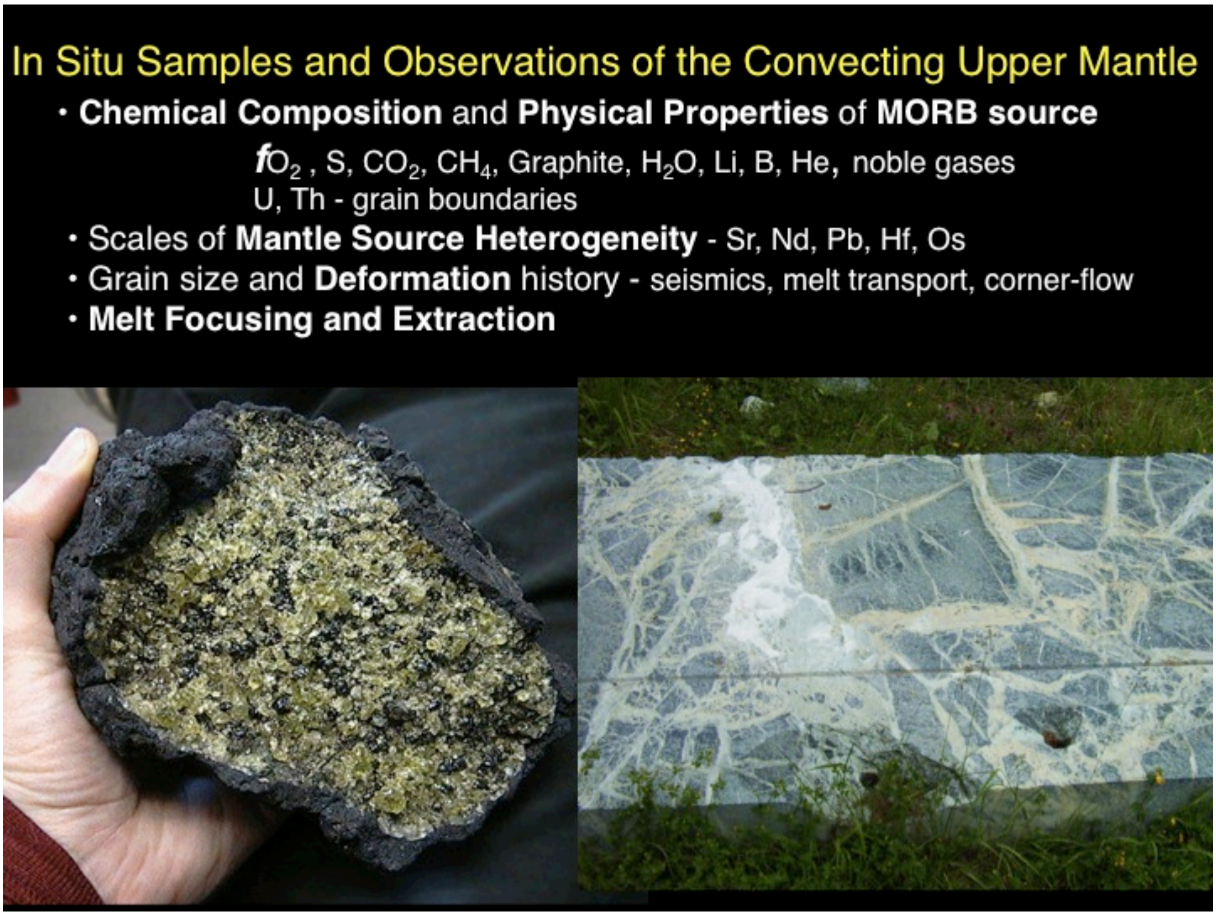
Slow-spreading : Mid-Atlantic Ridge

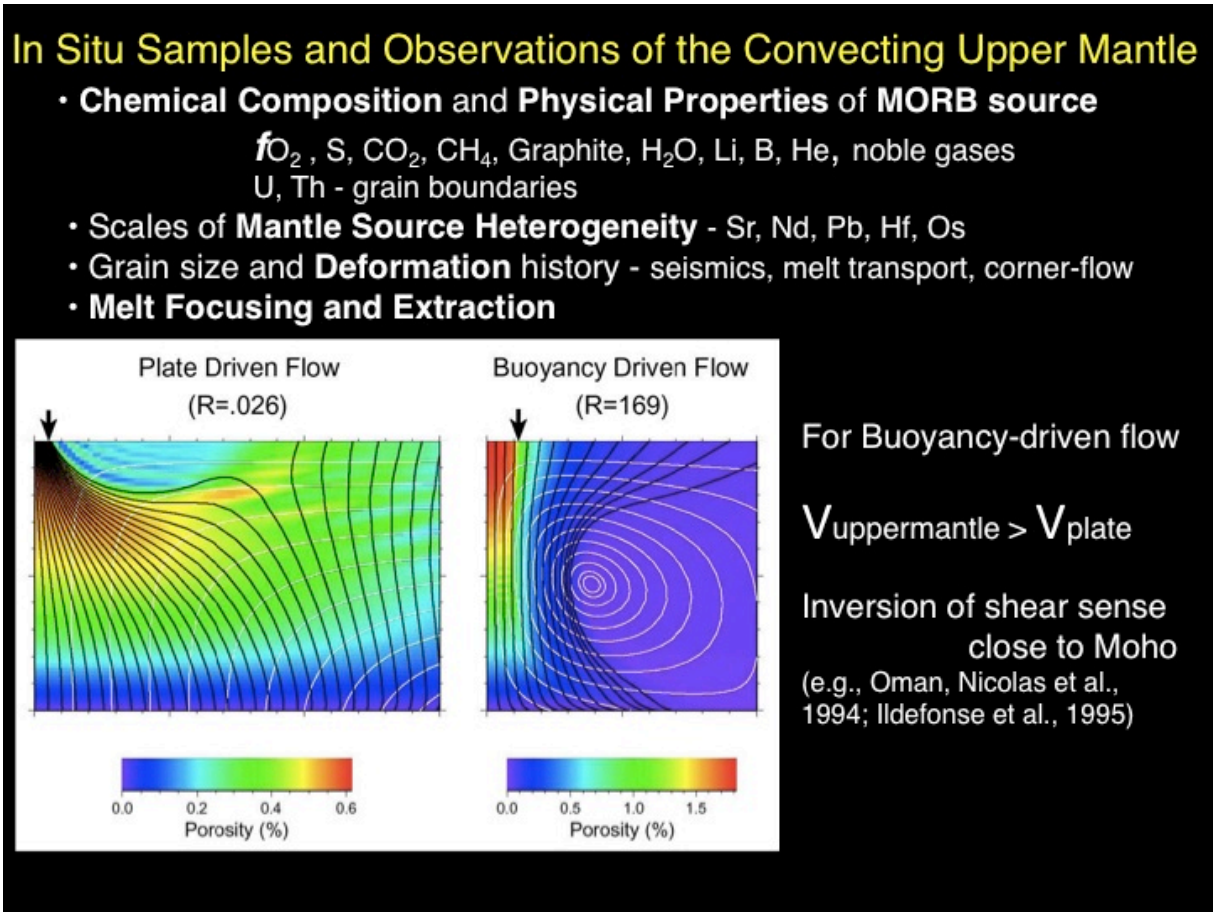


After Cannat et al. (1995)


Why fast spread crust?
Spreading half-rate [mm/yr]
• Relatively uniform
- Layered and relatively homogeneous
• 20% of modern ridges fast spreading
50% of modern ocean crust
~30% of Earth's surface
Majority of crust subducted into mantle in past 200 Ma
• Theoretical models for crustal accretion
• Oman ophiolite
– potential analog?
Slow spread crust: heterogeneous – characterization beyond the scope of MoHole
BUT – Tectonic Windows: Slow and Fast Spread Crust:
Near term science achievements
Opportunities to learn how to drill deeply in oceanic basement?


What is the Moho?
Primary acoustic interface within the Earth (Vp > 8 km/s)
Fundamental to geodynamics of our planet
Oceans ~5-8 km , Commonly a bright reflector
Seismic Discontinuity ASSUMED to be boundary between Crust and Mantle
A
B
C
Lava
Dikes
Missing Section
Seafloor
Olivine Gabbro
Hole 735B
Serpentine
Primitive Cumulates
Moho 5±1 km mbsf
Peridotite
Is the Moho:
• mafic cumulates & residual peridotites?
• mafic & ultramafic cumulates?
• serpentinitzed peridotites & peridotites?
• grabbo-intruded peridotites & peridotites?
How sharp is the boundary?
Is the Moho different in different places?
Dick, Natland and Ildefonse, 2006


In Situ Samples and Observations of the Convecting Upper Mantle
• **Chemical Composition** and **Physical Properties** of **MORB source**
fO_2 , S, CO_2, CH_4, Graphite, H_2O, Li, B, He, noble gases
U, Th - grain boundaries
• Scales of **Mantle Source Heterogeneity** - Sr, Nd, Pb, Hf, Os
• Grain size and **Deformation** history - seismics, melt transport, corner-flow
• **Melt Focusing and Extraction**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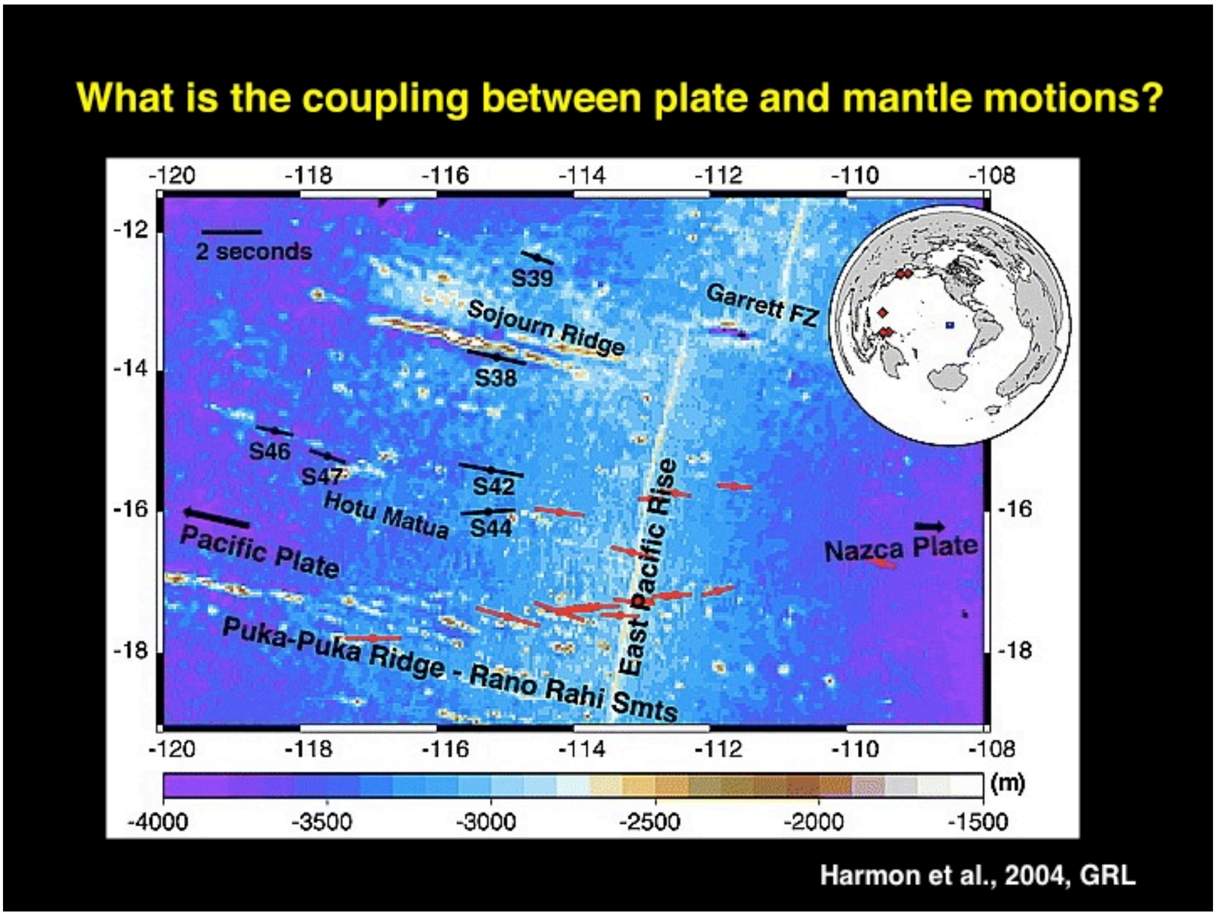
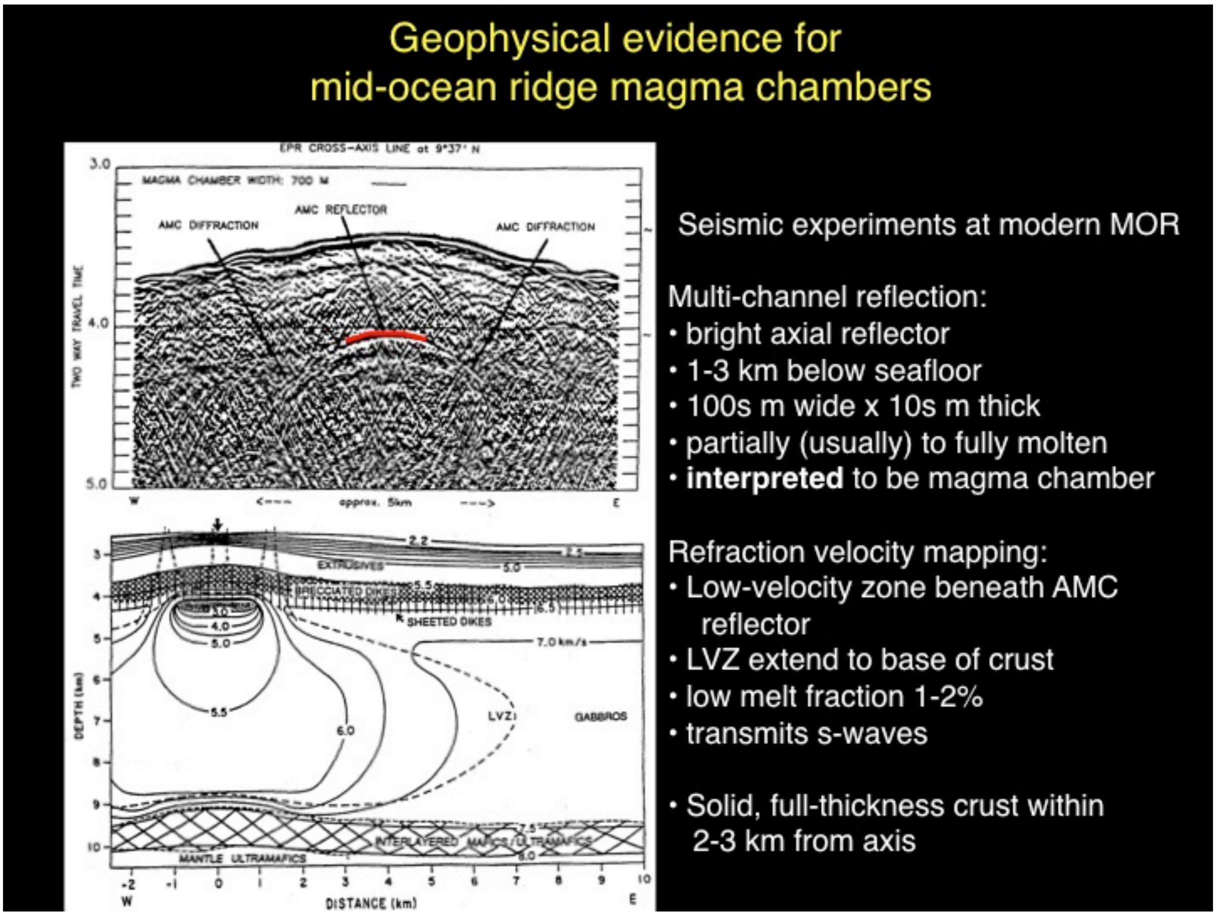
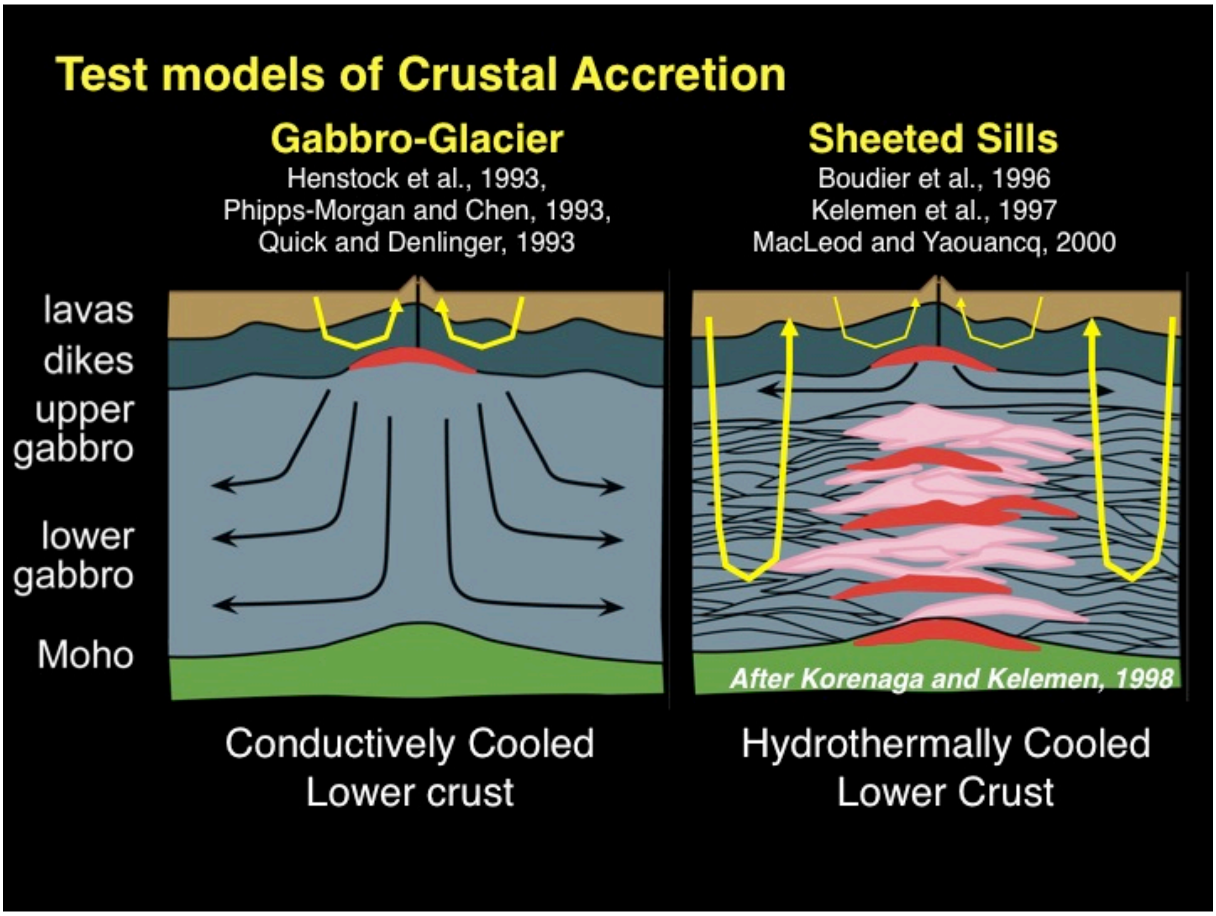
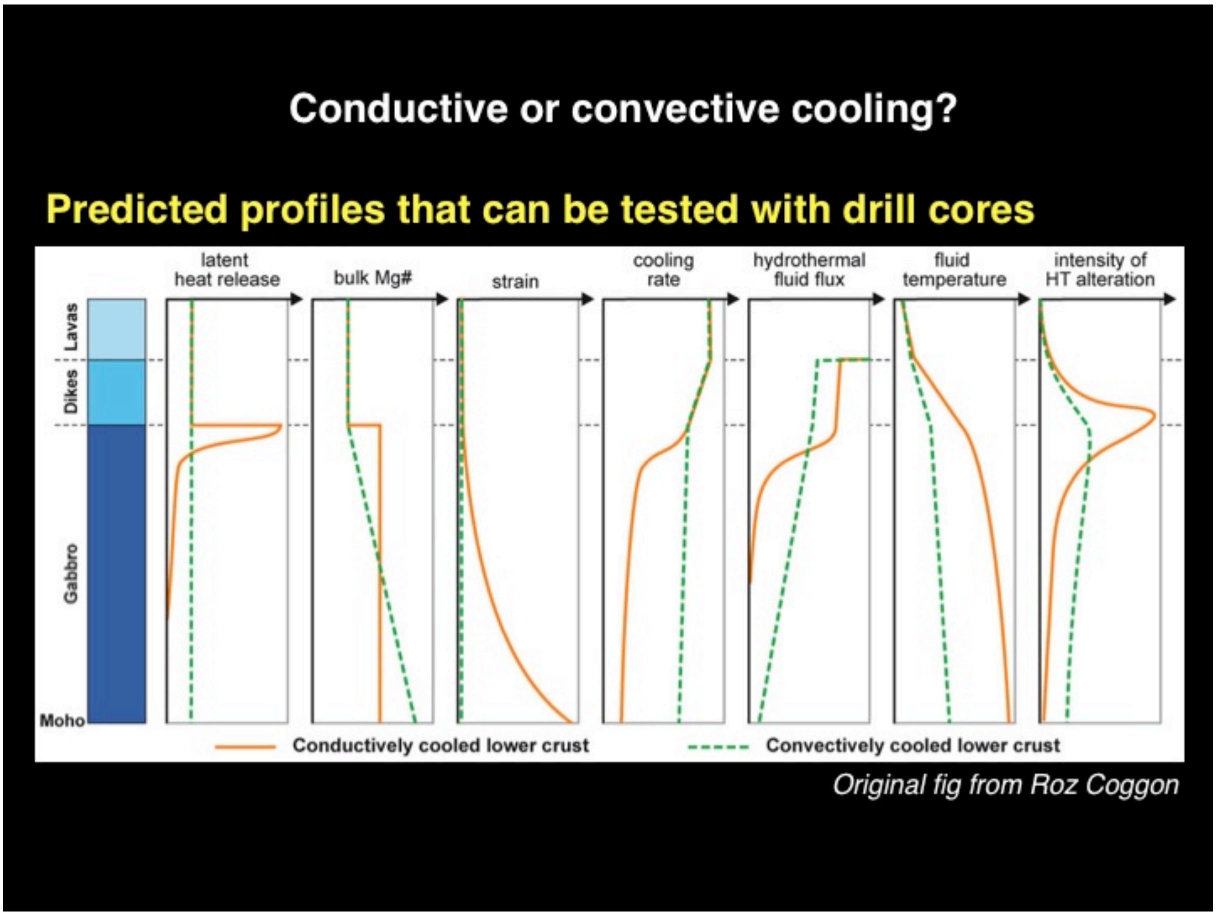
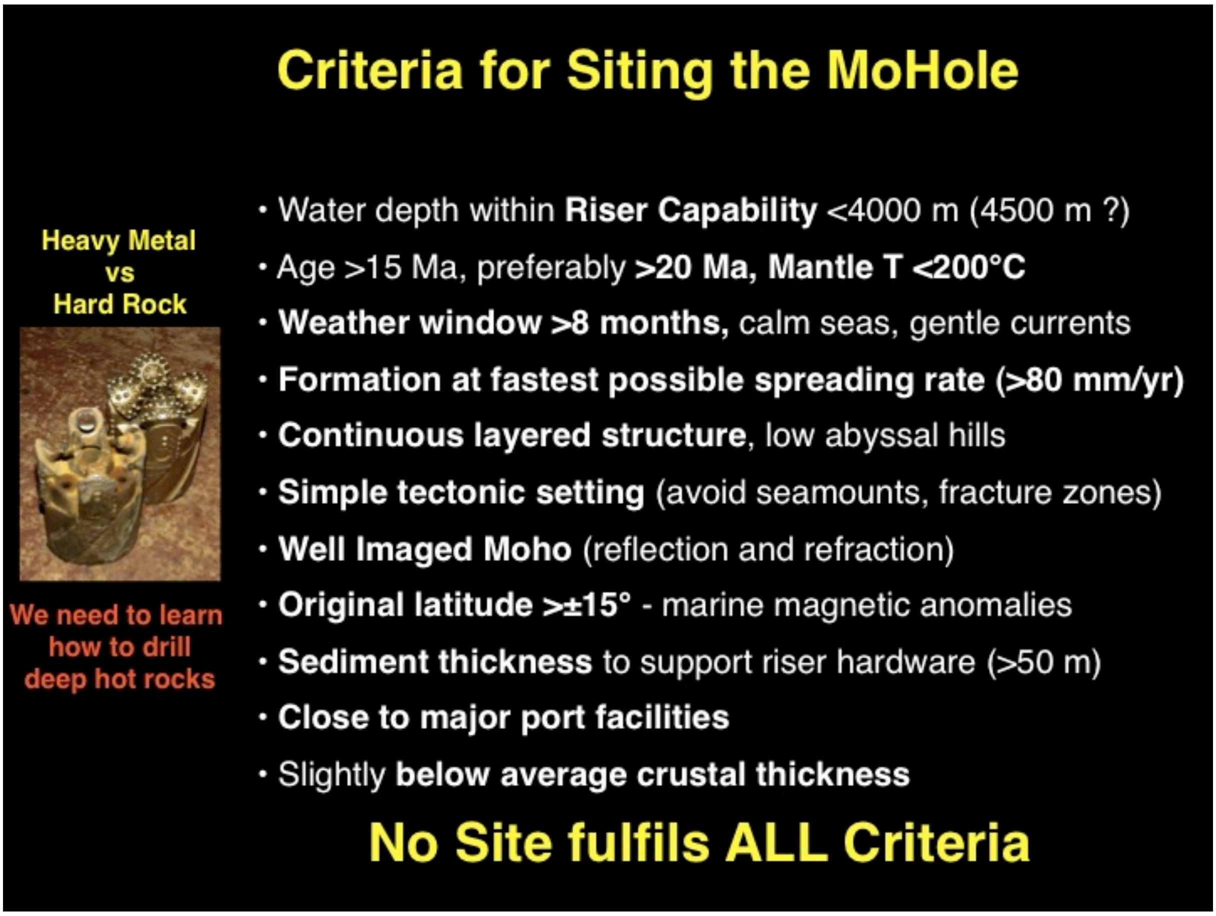
U, Th - grain boundaries
• Scales of **Mantle Source Heterogeneity** - Sr, Nd, Pb, Hf, Os
• Grain size and **Deformation** history - seismics, melt transport, corner-flow
• **Melt Focusing and Extraction**
Plate Driven Flow
(R=.026)
Buoyancy Driven Flow
(R=169)
0.0 0.2 0.4 0.6
Porosity (%)
0.0 0.5 1.0 1.5
Porosity (%)
For Buoyancy-driven flow
$V_{uppermantle} > V_{plate}$
Inversion of shear sense close to Moho
(e.g., Oman, Nicolas et al., 1994; Ildefonse et al., 1995)


What is the coupling between plate and mantle motions?
2 seconds
S39
Sojourn Ridge
S38
Garrett FZ
S46
S47
S42
Hotu Matua
S44
Pacific Plate
East Pacific Rise
Nazca Plate
Puka-Puka Ridge - Rano Rahi Smts
-120 -118 -116 -114 -112 -110 -108
-12 -14 -16 -18
(m)
-4000 -3500 -3000 -2500 -2000 -1500
Harmon et al., 2004, GRL


Geophysical evidence for
mid-ocean ridge magma chambers
EPR CROSS-AXIS LINE at 9°37' N
MAGMA CHAMBER WIDTH: 700 M
AMC DIFFRACTION
AMC REFLECTOR
AMC DIFFRACTION
TWO WAY TRAVEL TIME
W approx. 5km E
EXTRUSIVES
BRECCIATED DIKES
SHEETED DIKES
LVZ
GABBROS
INTERLAYERED MAFICS / ULTRAMAFICS
MANTLE ULTRAMAFICS
DEPTH (km)
DISTANCE (km)
Seismic experiments at modern MOR
Multi-channel reflection:
• bright axial reflector
• 1-3 km below seafloor
• 100s m wide x 10s m thick
• partially (usually) to fully molten
• **interpreted** to be magma chamber
Refraction velocity mapping:
• Low-velocity zone beneath AMC reflector
• LVZ extend to base of crust
• low melt fraction 1-2%
• transmits s-waves
• Solid, full-thickness crust within 2-3 km from axis


Test models of Crustal Accretion
Gabbro-Glacier
Henstock et al., 1993,
Phipps-Morgan and Chen, 1993,
Quick and Denlinger, 1993
Sheeted Sills
Boudier et al., 1996
Kelemen et al., 1997
MacLeod and Yaouancq, 2000
lavas
dikes
upper gabbro
lower gabbro
Moho
After Korenaga and Kelemen, 1998
Conductively Cooled Lower crust
Hydrothermally Cooled Lower Crust


Conductive or convective cooling?
Predicted profiles that can be tested with drill cores
latent heat release
bulk Mg#
strain
cooling rate
hydrothermal fluid flux
fluid temperature
intensity of HT alteration
Lavas
Dikes
Gabbro
Moho
Conductively cooled lower crust
Convectively cooled lower crust
Original fig from Roz Coggon


Criteria for Siting the MoHole
Heavy Metal
vs
Hard Rock
We need to learn
how to drill
deep hot rocks
• Water depth within Riser Capability <4000 m (4500 m ?)
• Age >15 Ma, preferably >20 Ma, Mantle T <200°C
• Weather window >8 months, calm seas, gentle currents
• Formation at fastest possible spreading rate (>80 mm/yr)
• Continuous layered structure, low abyssal hills
• Simple tectonic setting (avoid seamounts, fracture zones)
• Well Imaged Moho (reflection and refraction)
• Original latitude >±15° - marine magnetic anomalies
• Sediment thickness to support riser hardware (>50 m)
• Close to major port facilities
• Slightly below average crustal thickness
No Site fulfils ALL Criteria

The Trade-off of Depth and Temperature in choosing a MoHole Site

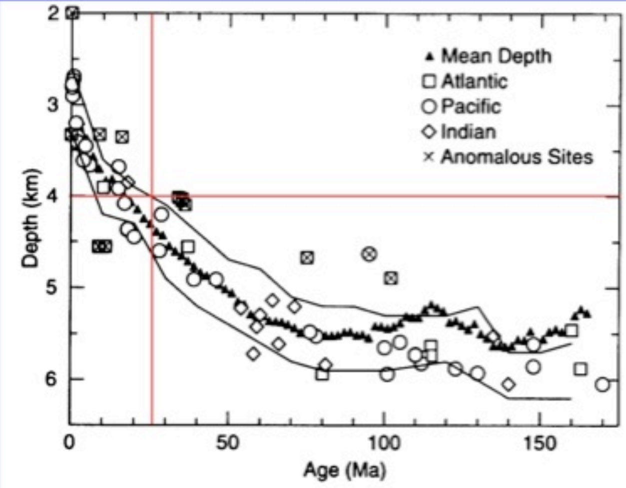
Doug Wilson, UCSB

Desired Site Properties:

- Not too deep (<~4 km: riser, pipe weight, etc.)
- Not too hot at Moho (< ~200°C)
- Nearly normal ocean crust

- Need to settle for 2 out of 3

Observed Sea Floor Depth vs Age

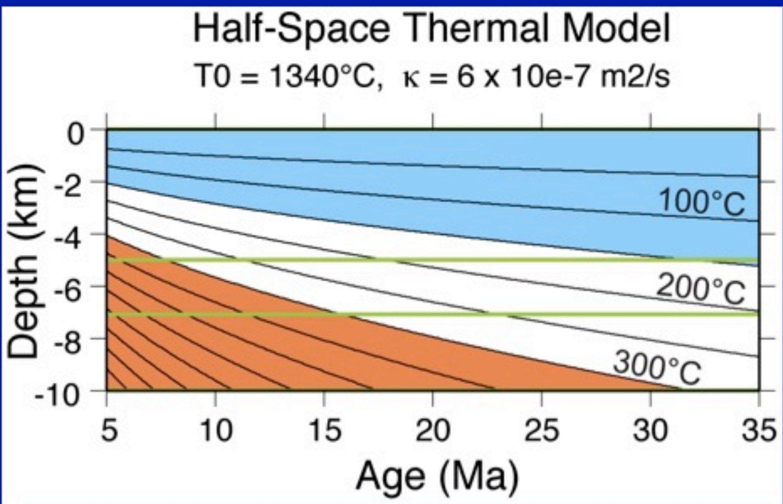


Carlson and Johnson [1994]

Fig. 2. Summary of depth and age data. Mean depth data are from *Stein and Stein* [1993]. Open symbols denote basement depth data from DSDP/ODP sites; the anomalous sites were dropped from the drilling data set for this study (see Figure 1 and Table 1a). Data pertaining to the remaining sites are summarized in Tables 1b and 2. Solid line indicates the envelope of the 67% contour about the modal depth for the North Pacific [*Renkin and Sclater*, 1988].

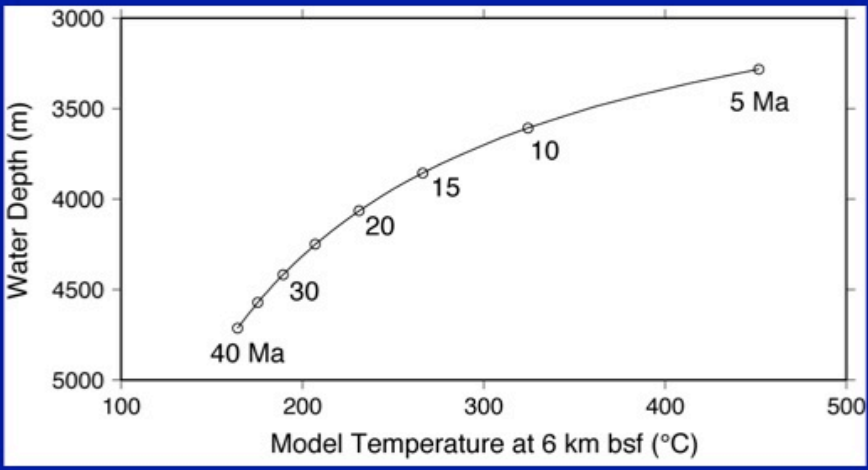
Most sites subside deeper than 4000 m by 25 Ma

Predicted Temperature as a Function of Age and Depth



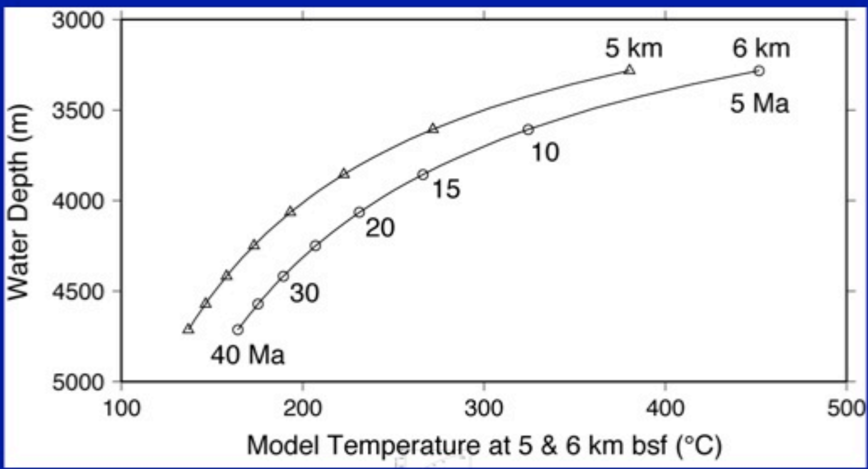
At 6 km, cooling below 200°C occurs after 25 Ma

Temp. vs. Water Depth, Average Crust

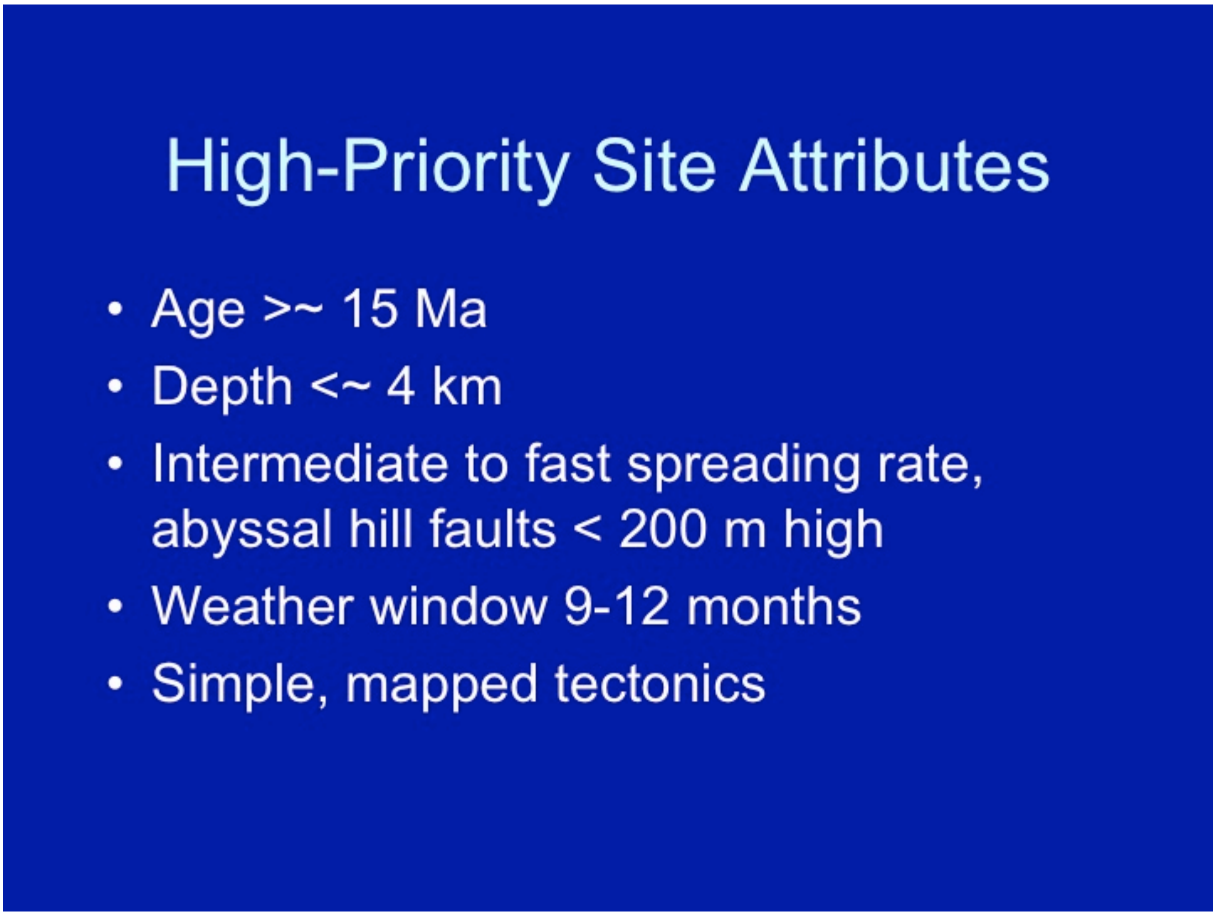


Depth from Sclater curve, temperature from half-space model

Temp. vs. Water Depth, Average Crust



Depth from Sclater curve, temperature from half-space model

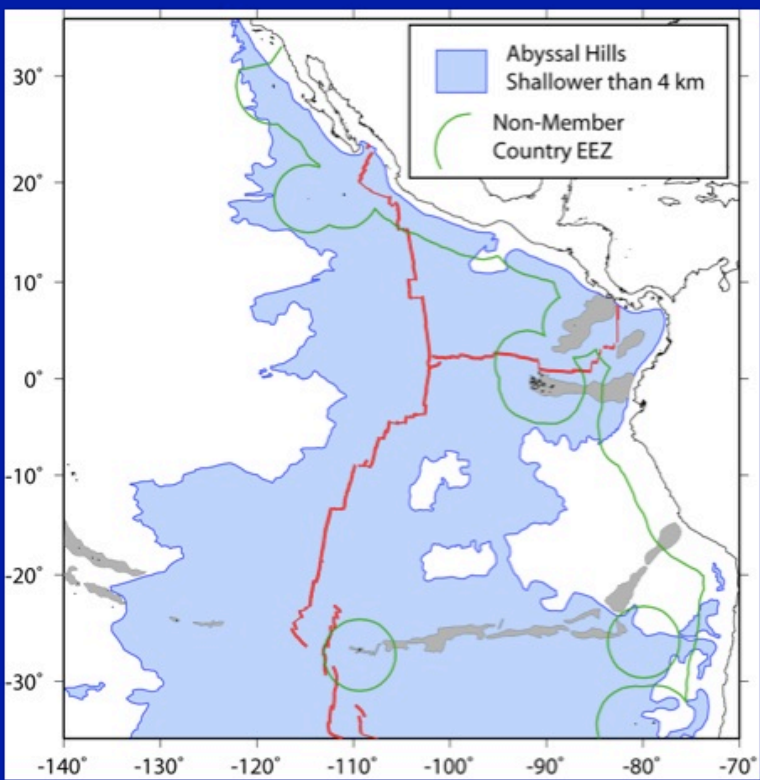

High-Priority Site Attributes
• Age >~ 15 Ma
• Depth <~ 4 km
• Intermediate to fast spreading rate, abyssal hill faults < 200 m high
• Weather window 9-12 months
• Simple, mapped tectonics

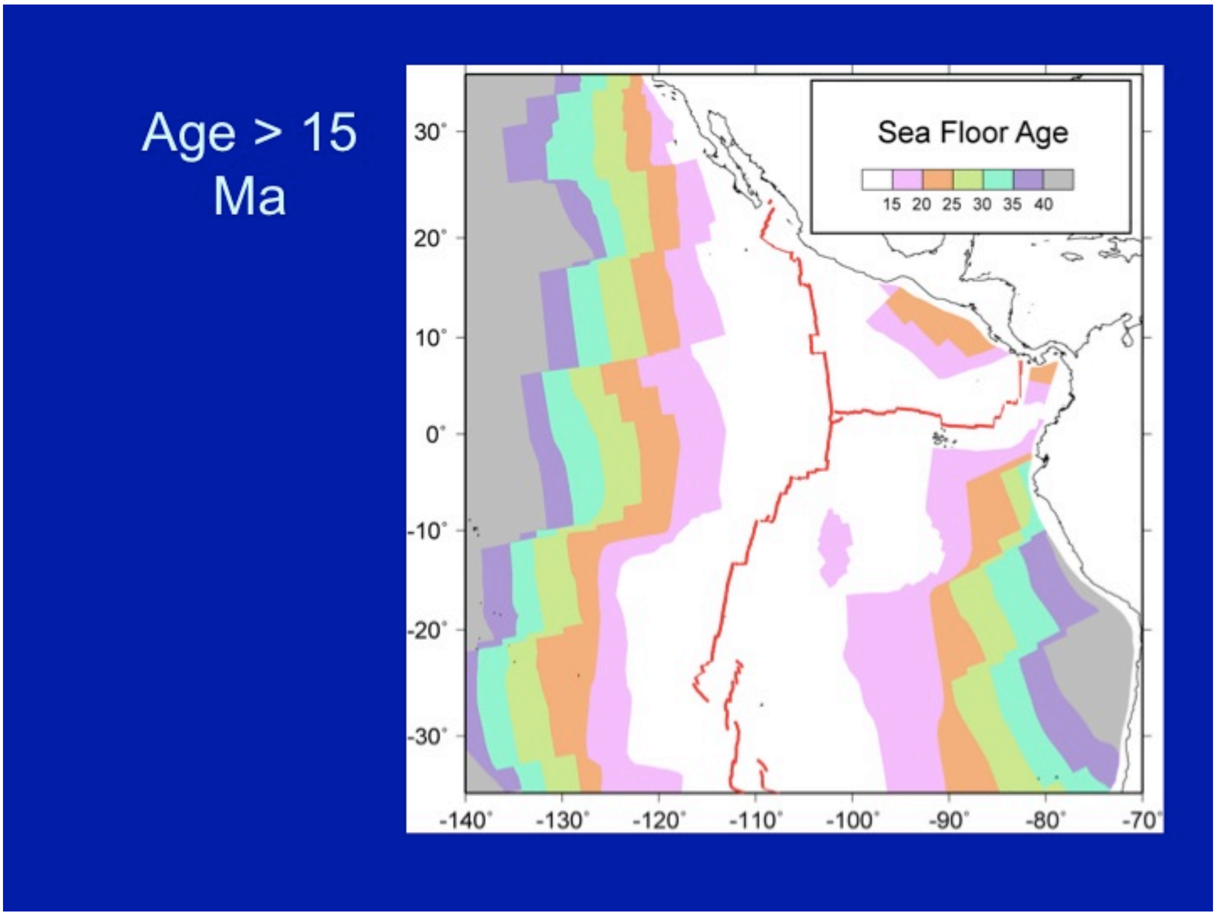

High-Priority Site Attributes
• Age >~ 15 Ma
• Depth <~ 4 km
• Eastern Pacific, 35°N–35°S
• Simple, mapped tectonics

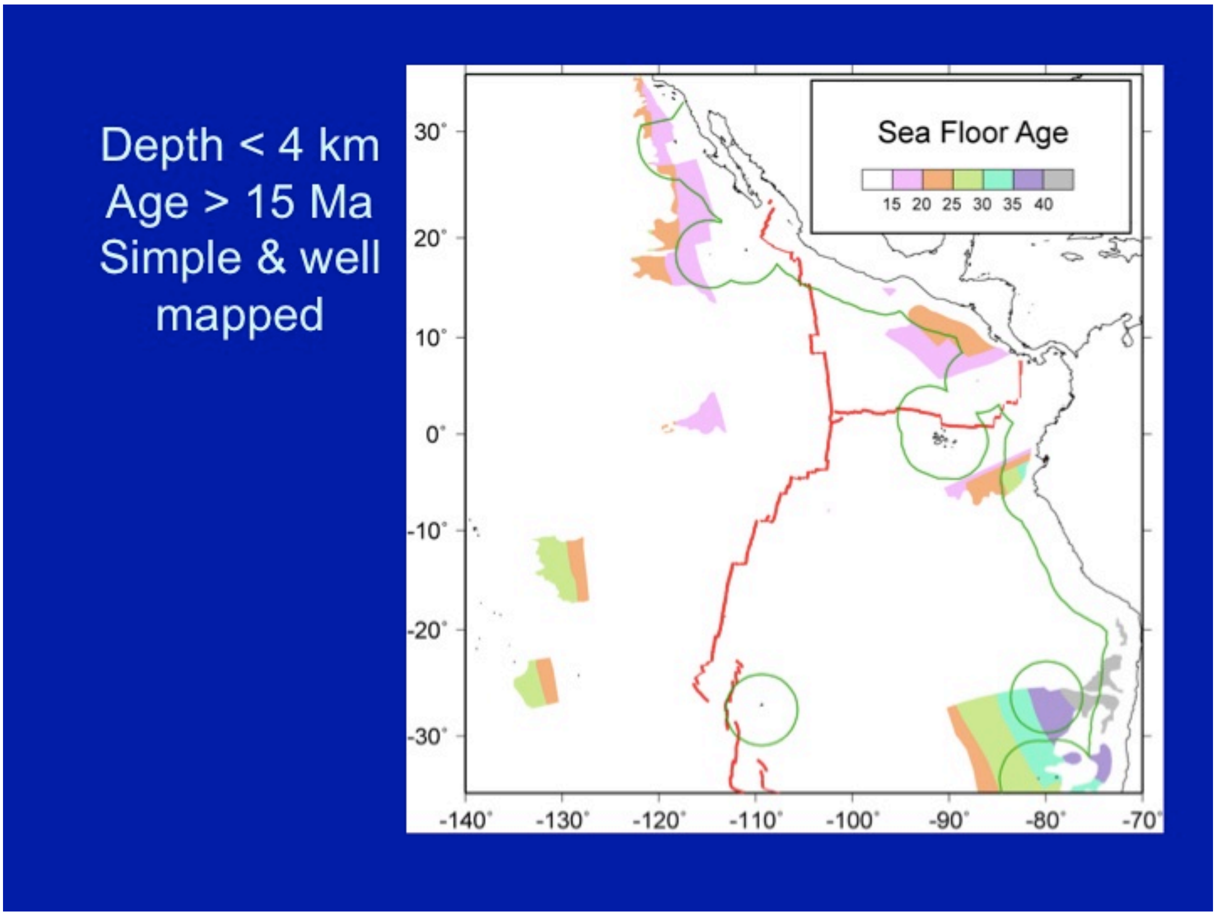
Desirable Site Attributes

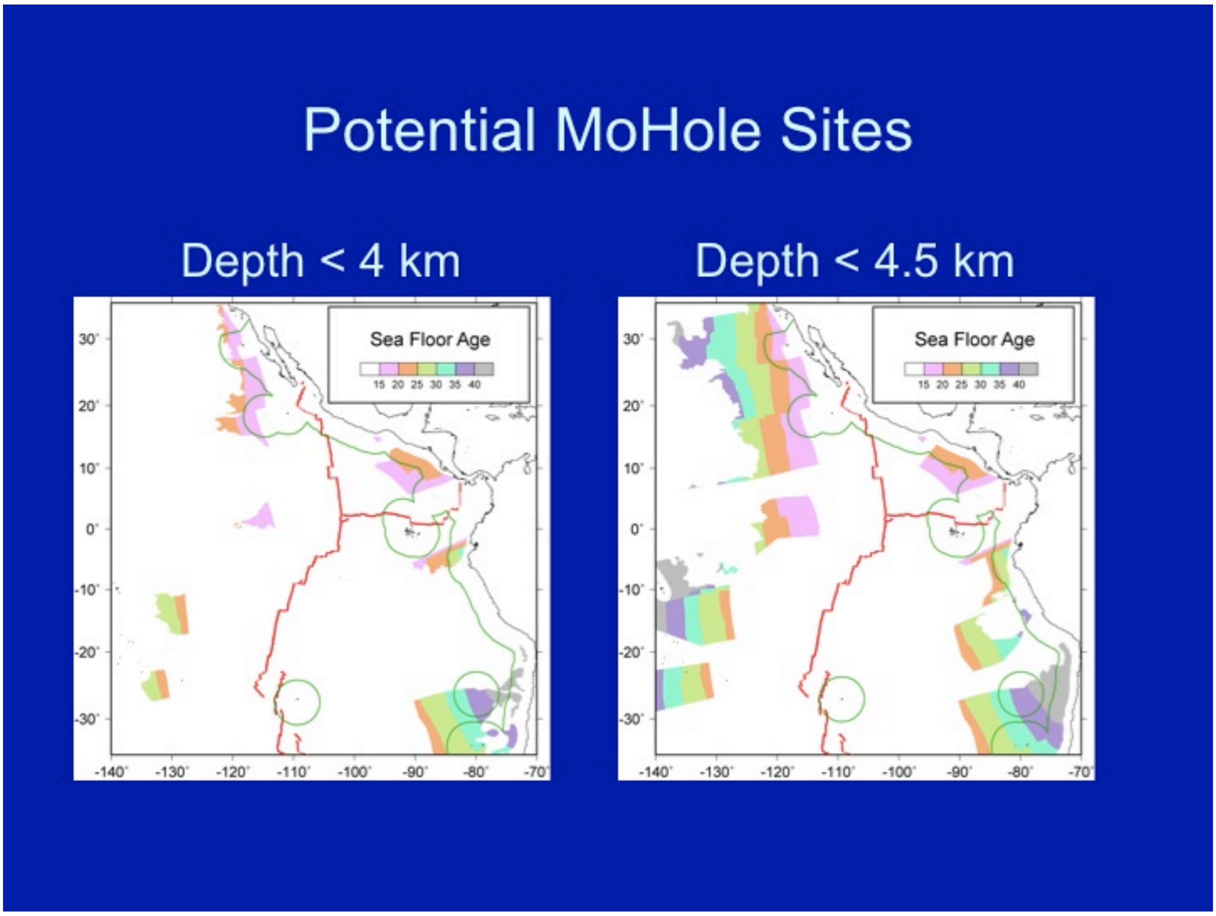
- Age > 20 Ma
- Close to major port(s)
- International waters or member EEZ
- Crustal thickness 5.0–5.5 km
- 12-month weather window
- Original latitude > ±15°
- Fastest available spreading rate

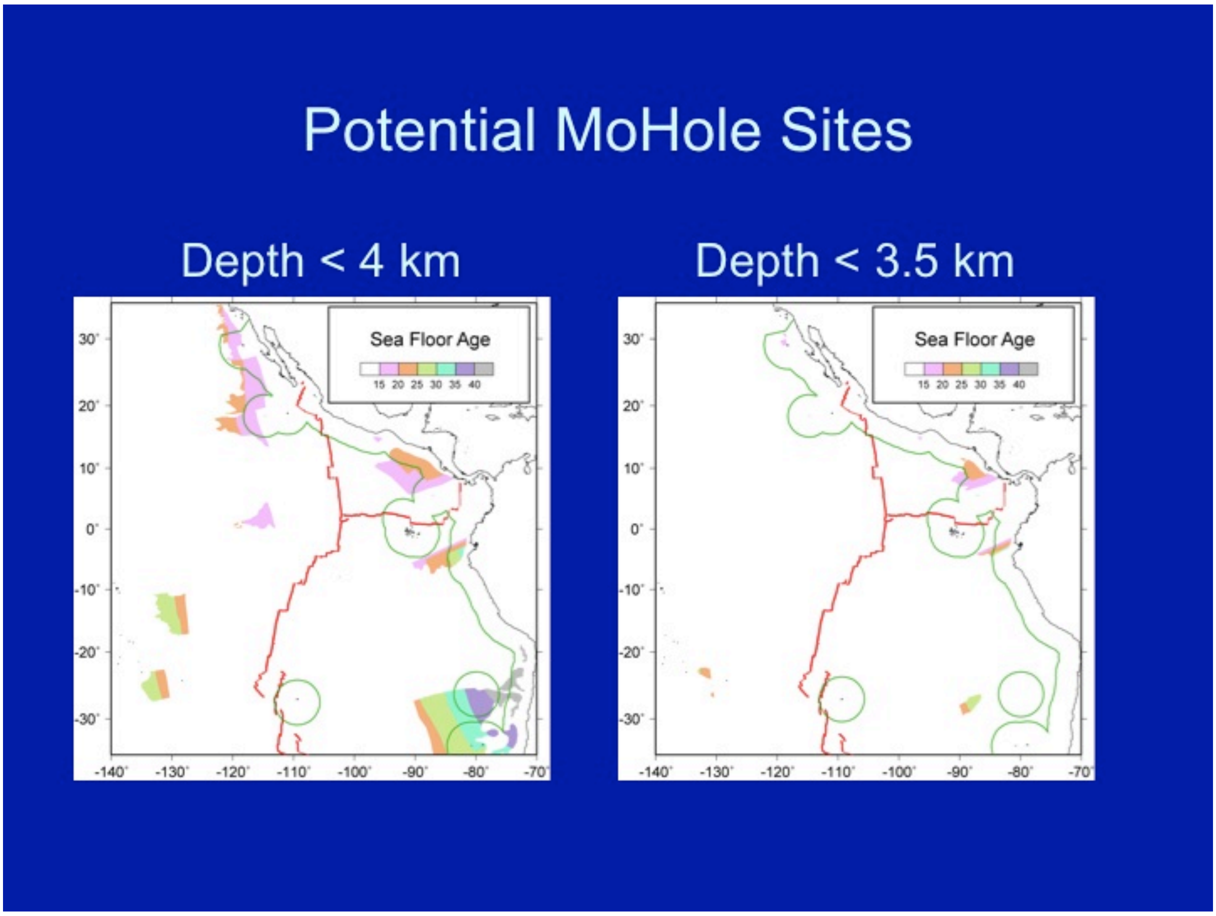
Depth limited by 4-km riser



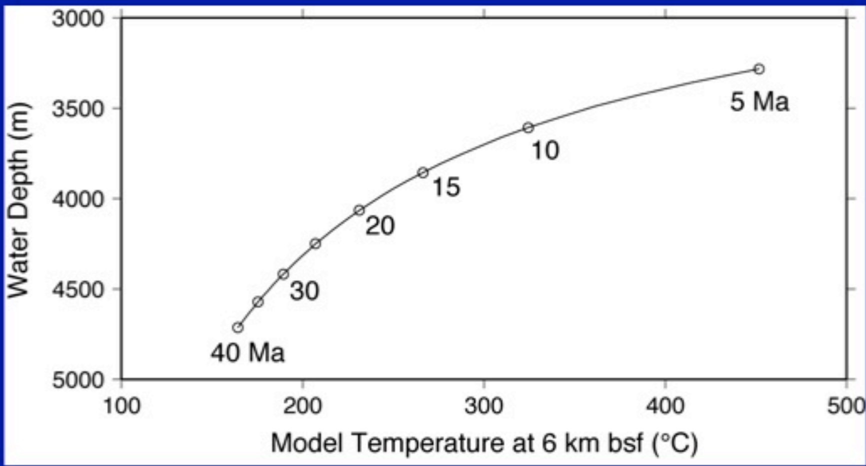

Age > 15 Ma
Sea Floor Age
15 20 25 30 35 40
30° 20° 10° 0° -10° -20° -30°
-140° -130° -120° -110° -100° -90° -80° -70°


Depth < 4 km
Age > 15 Ma
Simple & well mapped
Sea Floor Age
15 20 25 30 35 40
30° 20° 10° 0° -10° -20° -30°
-140° -130° -120° -110° -100° -90° -80° -70°


Potential MoHole Sites
Depth < 4 km
Depth < 4.5 km
Sea Floor Age
15 20 25 30 35 40
30°
20°
10°
0°
-10°
-20°
-30°
-140° -130° -120° -110° -100° -90° -80° -70°


Potential MoHole Sites
Depth < 4 km
Depth < 3.5 km
Sea Floor Age
15 20 25 30 35 40
30°
20°
10°
0°
-10°
-20°
-30°
-140° -130° -120° -110° -100° -90° -80° -70°

Temp. vs. Water Depth, Average Crust



Depth from Sclater curve, temperature from half-space model

Concluding Remarks

- Many potential sites are available for ~30 Ma at water depths 4000-4300 m, probable Moho temperature ~180°C.
- A few potential sites are available for 15-20 Ma at water depths 3400-3700 m, probable Moho temperature ~200-250°C.
- Which is a bigger engineering challenge: 4200 m water depth or 240°C formation?

Hawaii site in comparison with IODP site 1256

Nobukazu Seama
Kobe University

How should we decide a Mohole site?

→ Recent high quality seismic surveys in the western Pacific using air-gun, multi-channel streamers, and ocean-bottom seismometers, indicate that velocity structure of ocean crust and of uppermost mantle has variety even if it was formed at a fast spreading rate ridge system.

→ The Mohole drilling provides a deep reference hole for the ocean crust and the uppermost mantle.

→ to properly interpret the velocity structure
→ to point out the similarity and/or the difference in velocity structure in space (or crustal age)

How should we decide a Mohole site?

→ Detailed seismic velocity structure and its characters below are especially important.

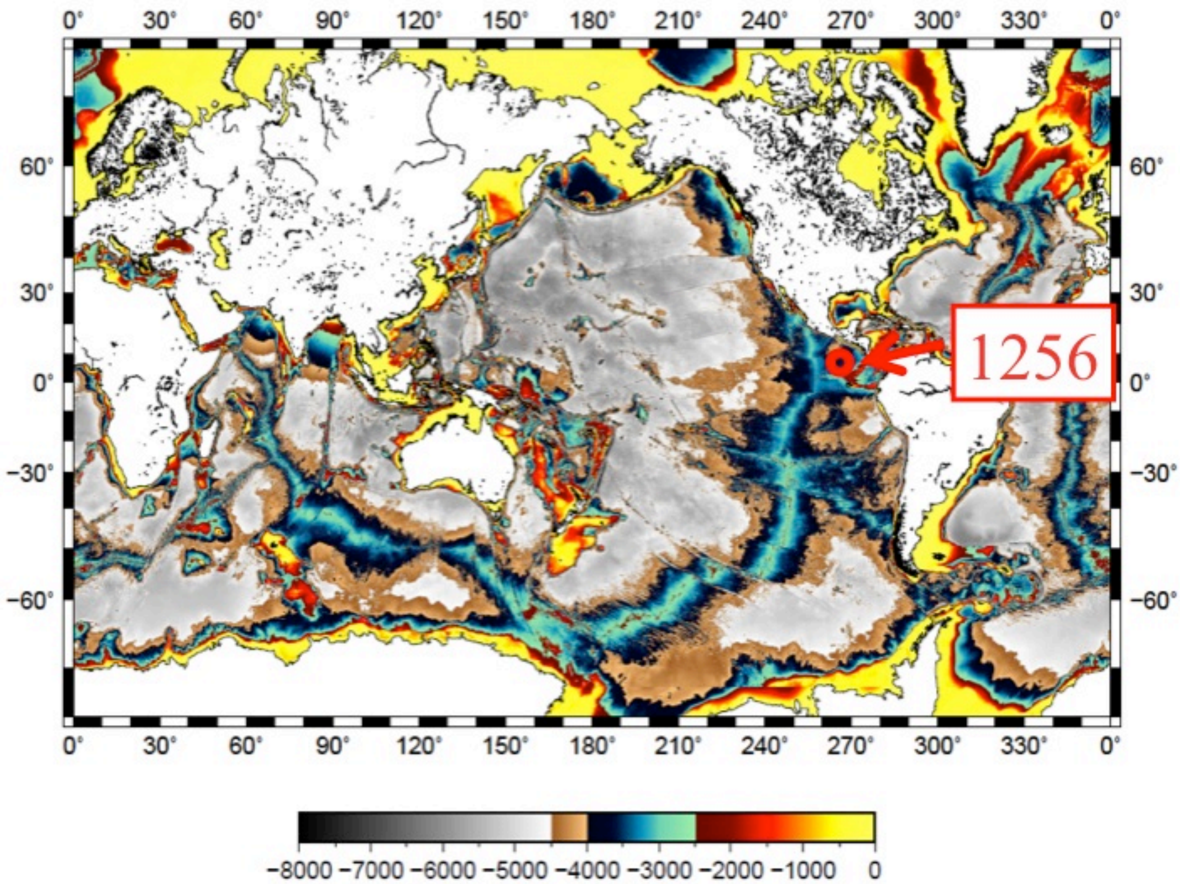
- Crustal velocity structure (velocity value, etc.)
- Moho discontinuity (amplitude of reflector; single or multiple reflectors, etc.)
- Uppermost mantle velocity structure (velocity value and degree of anisotropy, etc.)

→ The final Mohole site should be decided after discussions among the international community with enough geophysical data for all candidates.

If technology allows us to drill wherever we like,

Then, we discuss where show best seismic velocity structure as a deep reference hole for the ocean crust and the uppermost mantle.

→ Technology limitation forces us to discuss feasible drilling sites with near future technology, where we should do high quality seismic surveys in a few years.



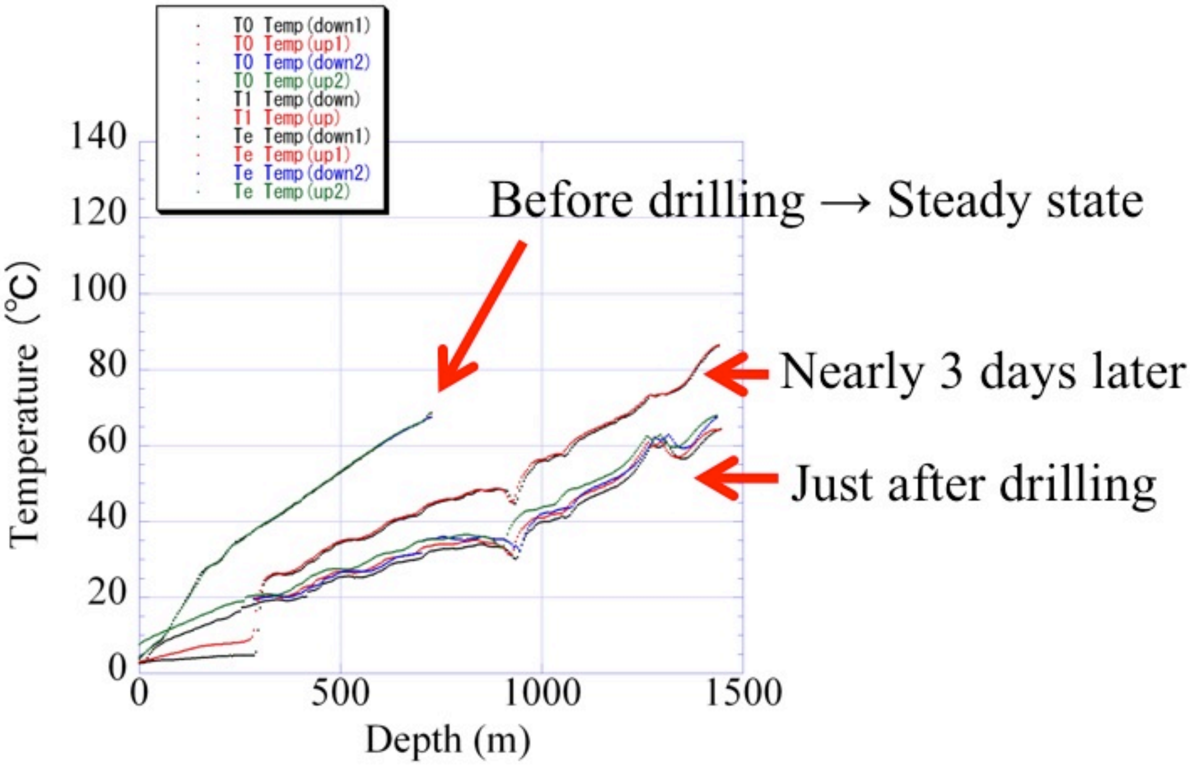
Site 1256

In Mission Moho WS full report,

- Current primary site
- The greatest currently perceived threat at Site 1256 is from potentially high down-hole temperatures. For this reason, the alternate site should be on older (colder) crust.

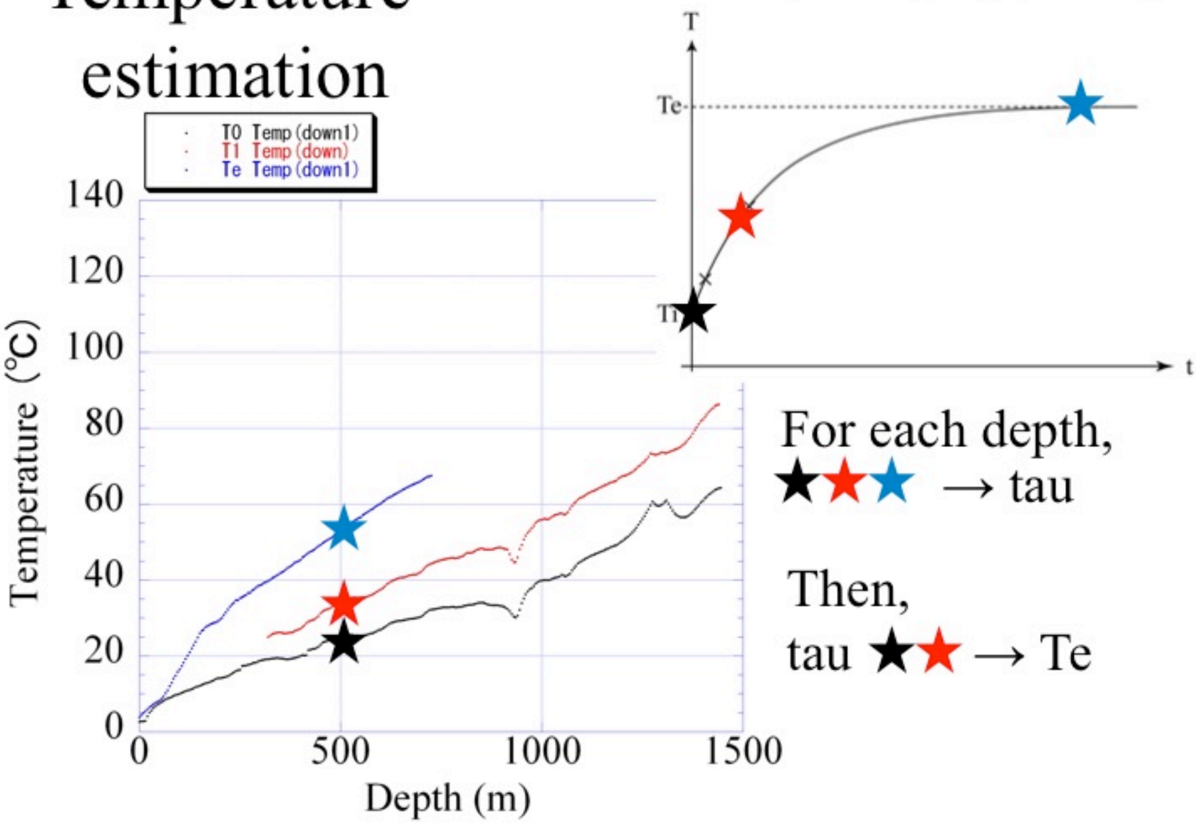
→ Bench mark for the alternate sites

Temperature in 1256D

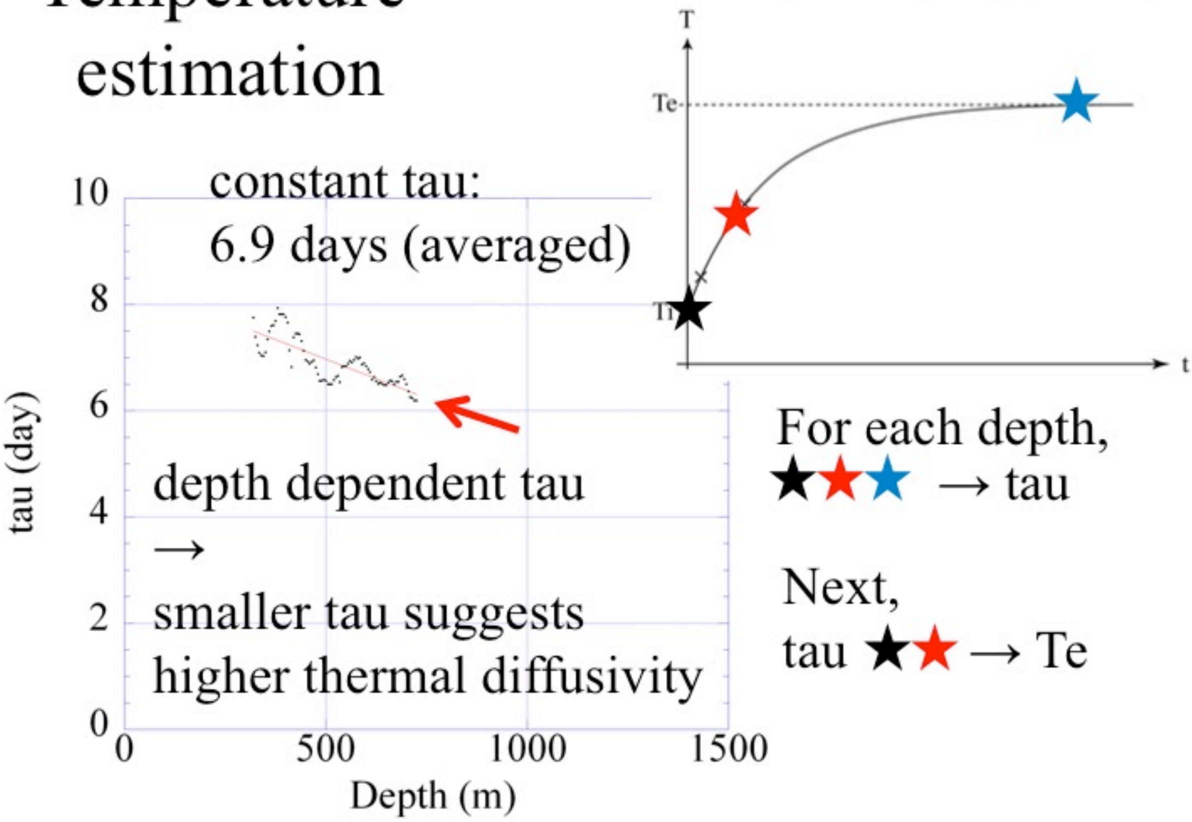


Temperature estimation

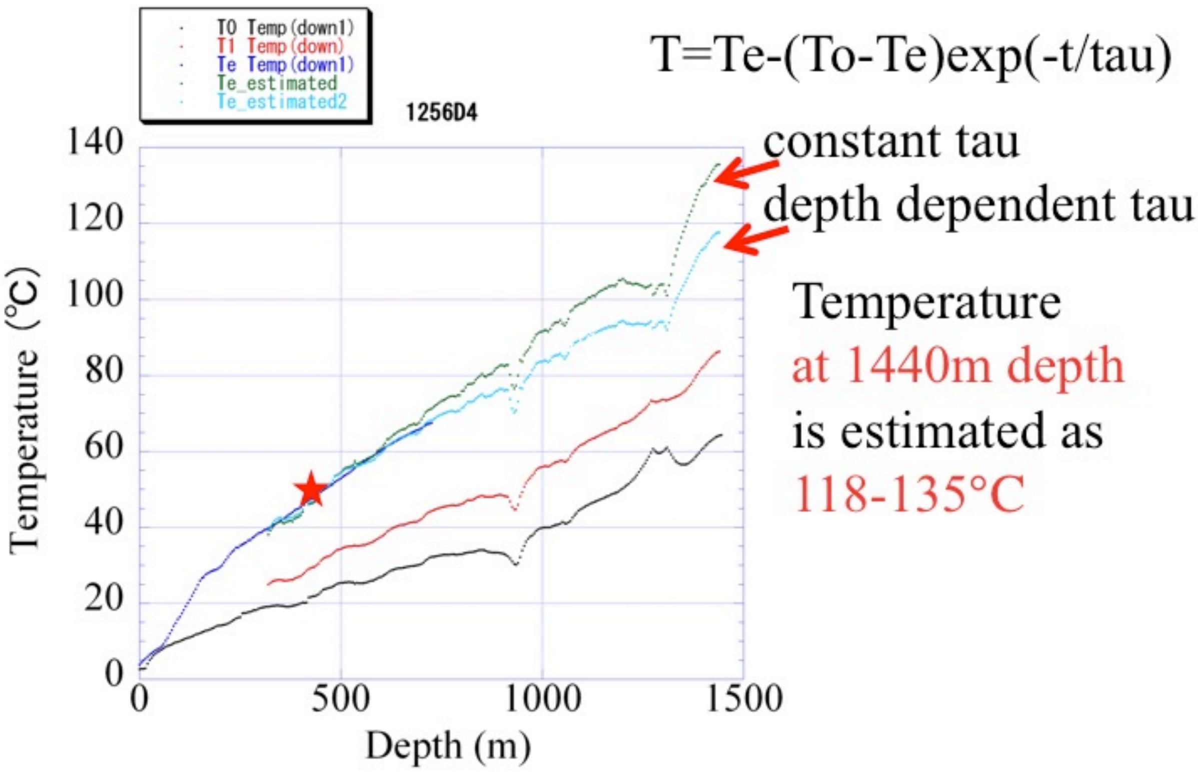
$$T=Te-(Ti-Te)\exp(-t/tau)$$



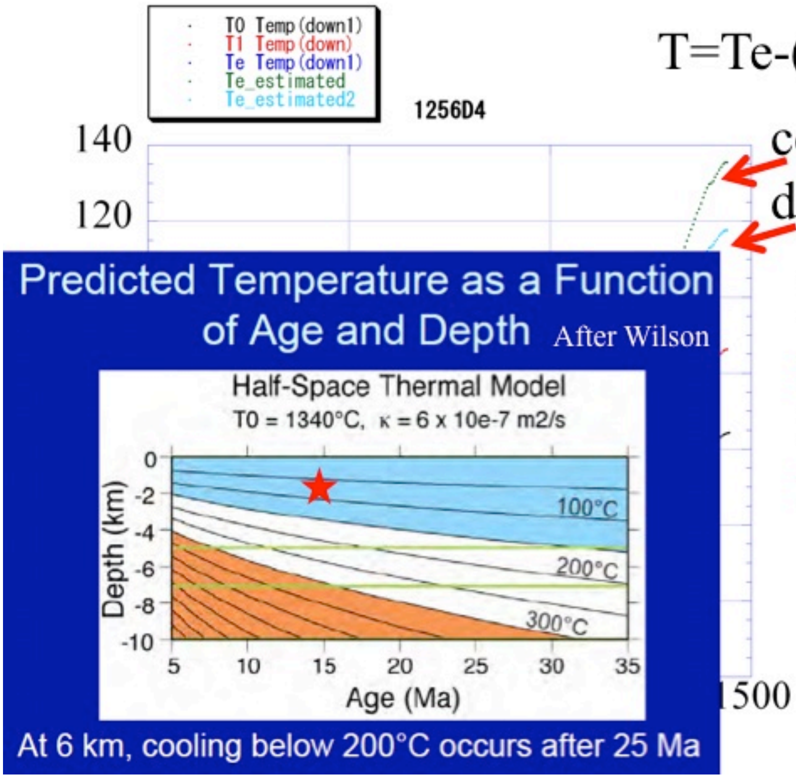
Temperature estimation



Temperature estimation



Temperature estimation



T=Te-(To-Te)exp(-t/tau)

constant tau

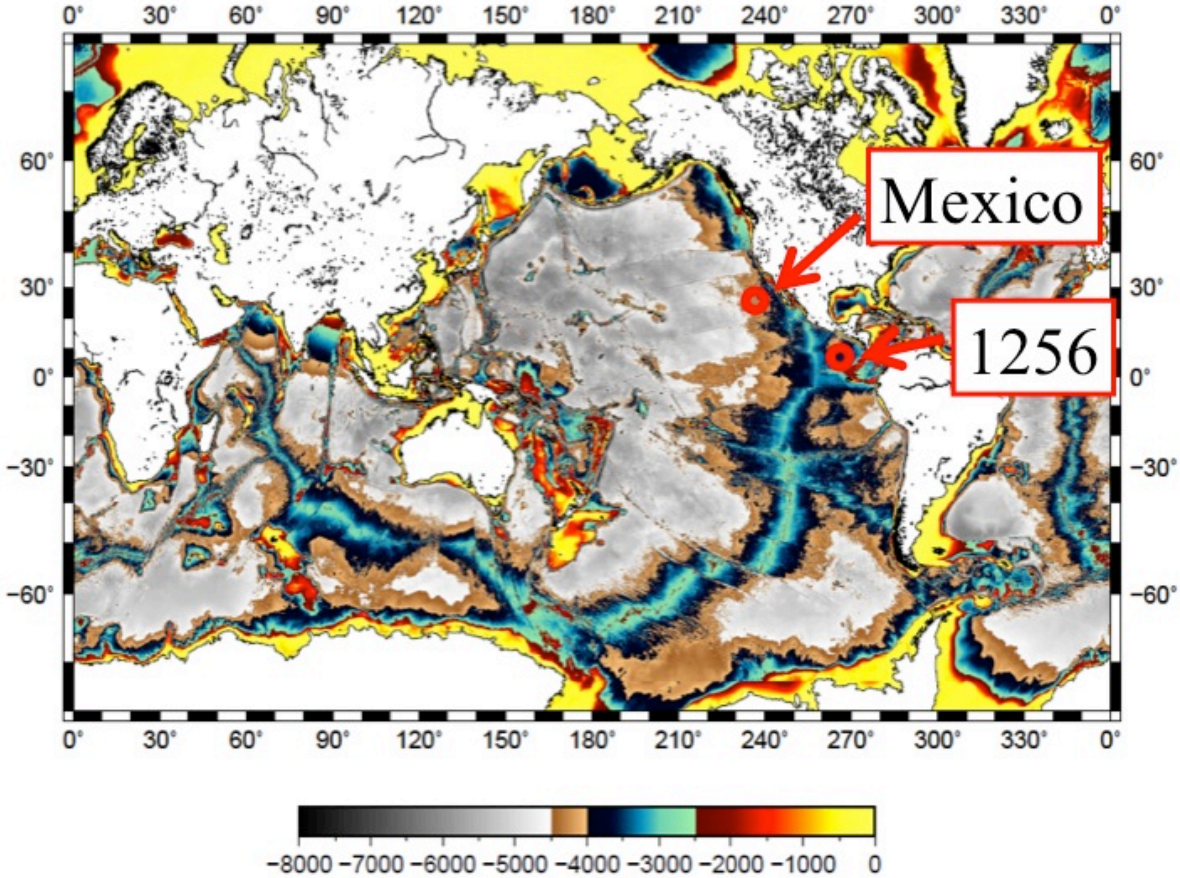
depth dependent tau

Temperature at 1440m depth is estimated as 118-135°C

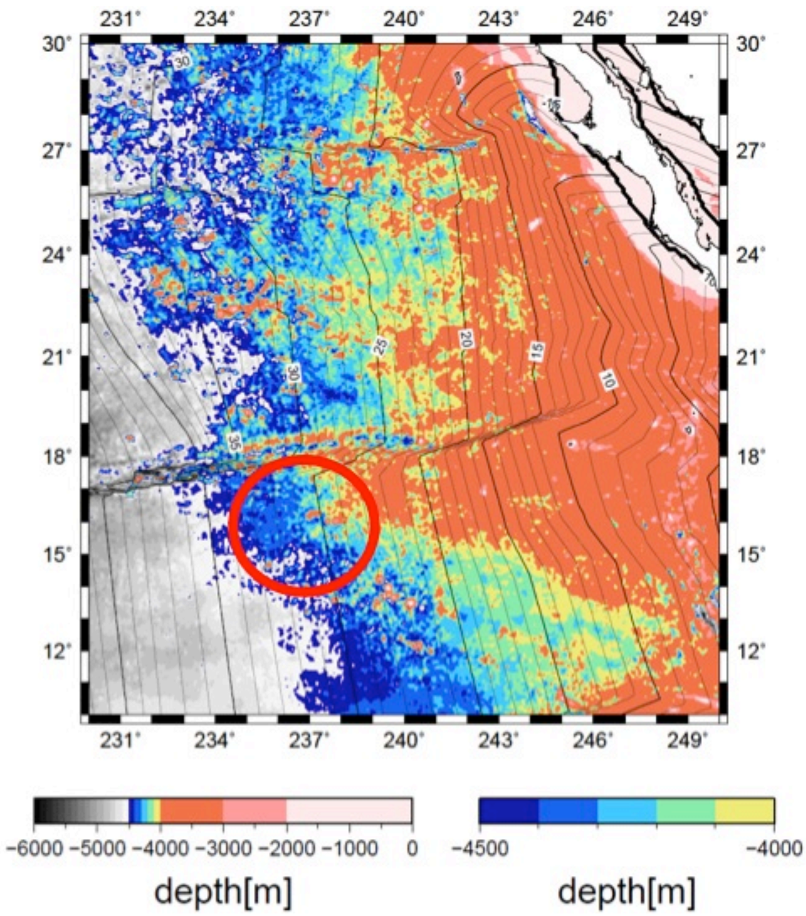
→ much higher than that from the half space thermal model

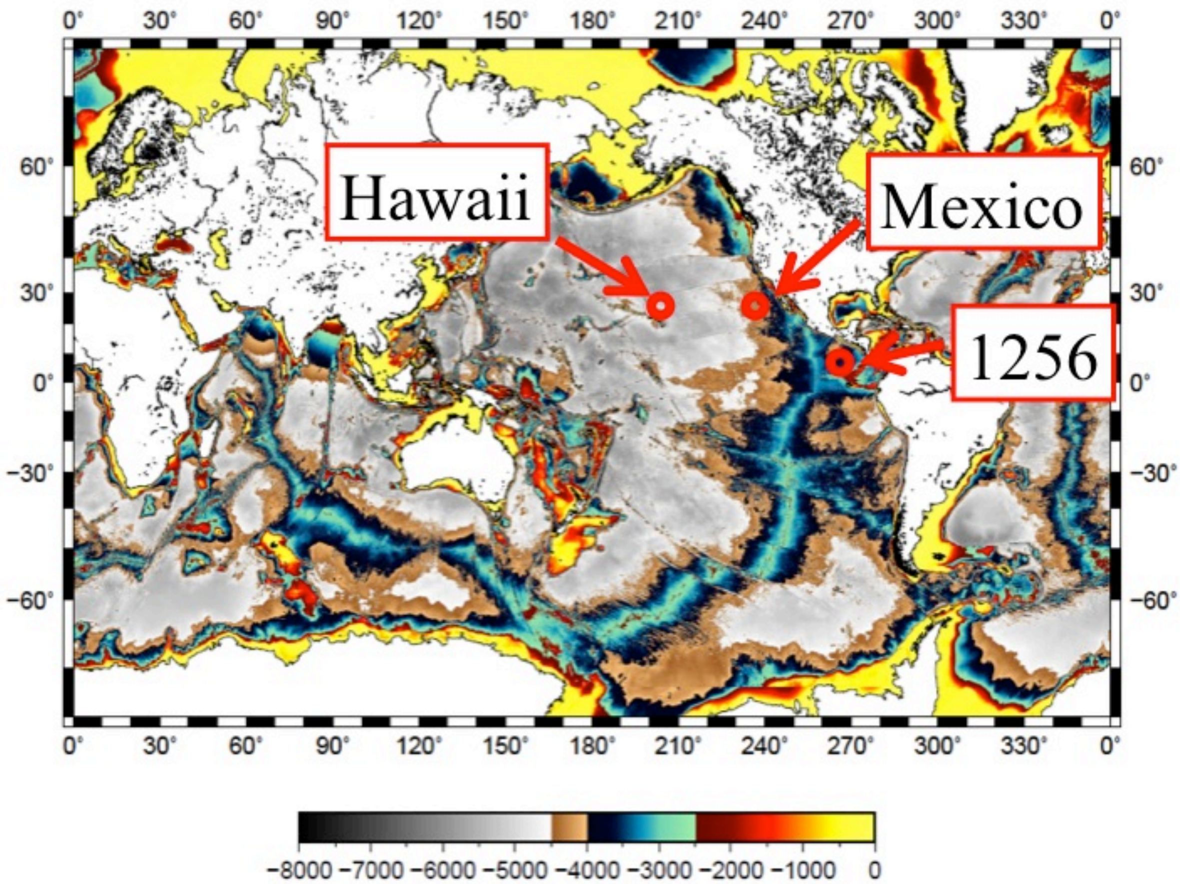
Site 1256 summary

- For the coming next drilling, temperature measurements are essential before and after the drilling.
- The alternate sites should be on older crust, because potentially high down-hole temperatures in Site 1256.
- Site 1256 is a bench mark for the alternate sites

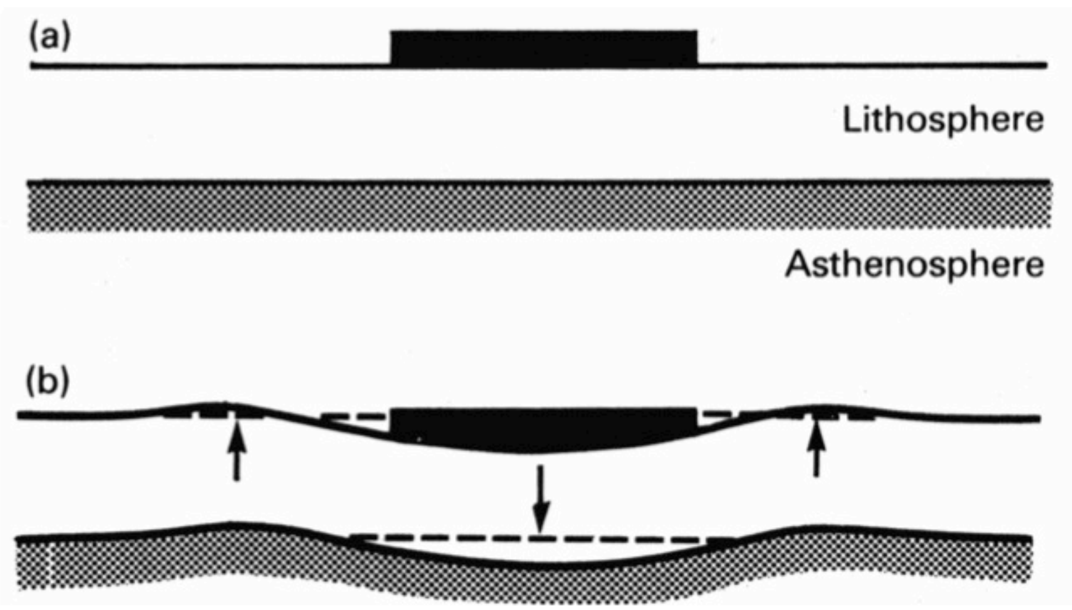

Mexico
1256
0° 30° 60° 90° 120° 150° 180° 210° 240° 270° 300° 330° 0°
60° 30° 0° −30° −60°
−8000 −7000 −6000 −5000 −4000 −3000 −2000 −1000 0

Off Mexico

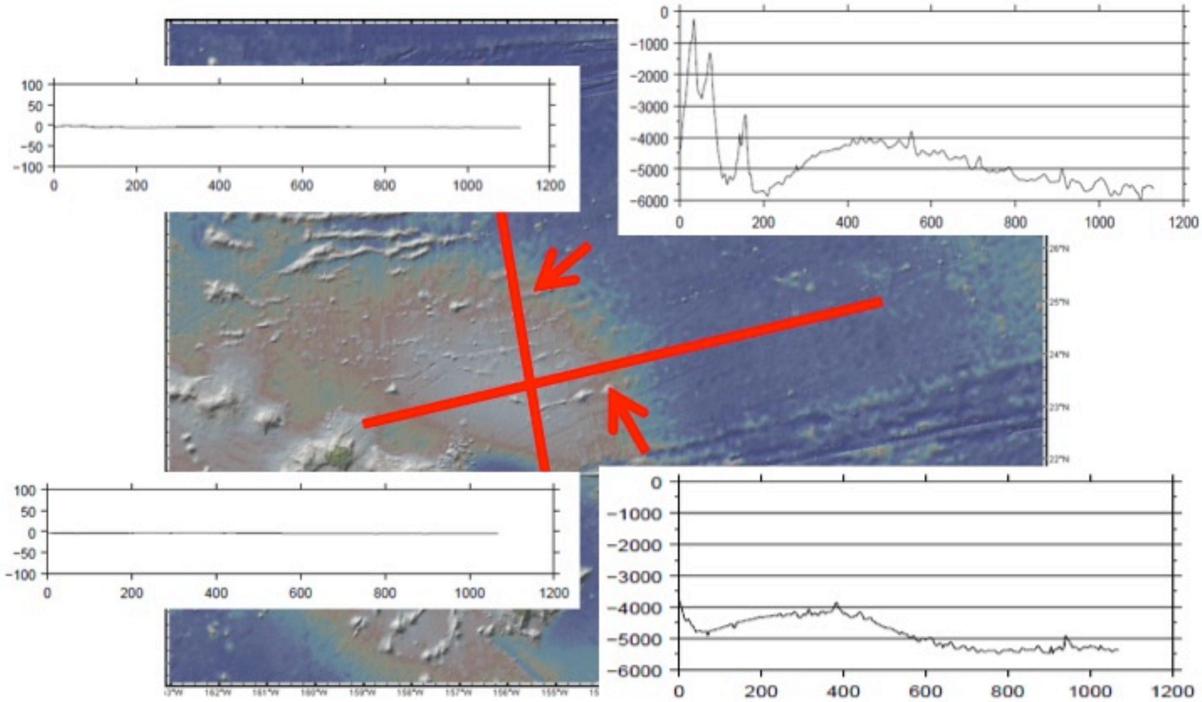

231° 234° 237° 240° 243° 246° 249°
30° 27° 24° 21° 18° 15° 12°
−6000 −5000 −4000 −3000 −2000 −1000 0
depth[m]
−4500 −4000
depth[m]



Load of Hawaii island chains bends the lithosphere



Lithosphere bending



JOURNAL OF GEOPHYSICAL RESEARCH VOL. 69, No. 8 APRIL 15, 1964

Mohole Site Selection Studies North of Maui[1]

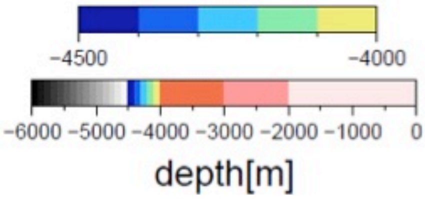
GEORGE G. SHOR, JR., AND DWIGHT D. POLLARD[2]

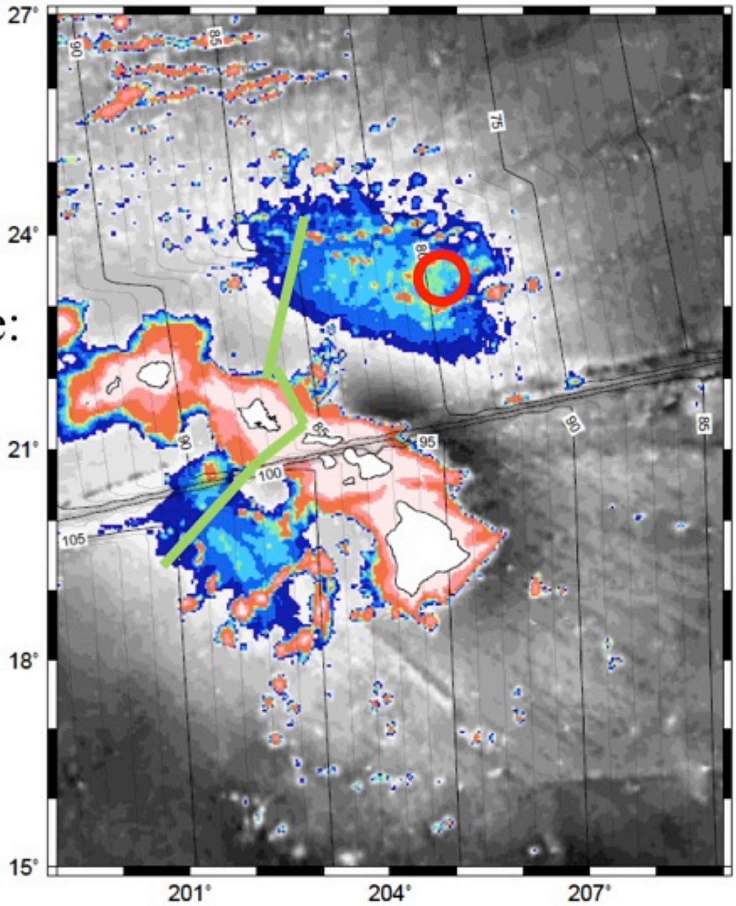
Scripps Institution of Oceanography, University of California, San Diego

Abstract. Seismic refraction profiles made across the Hawaiian arch, the Hawaiian deep, and onto the Hawaiian ridge north of the island of Maui indicate that the Mohorovicic discontinuity lies at a depth of about 10.5 km beneath the arch and dips to 13 km beneath the deep and the ridge. The variation in depth to the mantle from arch to deep is caused principally by variations in the thickness of the sediments and volcanics; the material having velocities between 5 and 7 km/sec has almost constant thickness. The hypothesis of Vening Meinesz that the Hawaiian deep is caused by down-warping of the crust under the load of the Hawaiian ridge, and that the Hawaiian arch is a side bulge caused by elastic yielding, is substantiated by the data obtained off Maui. Menard's hypothesis that the smooth sea floor on the Hawaiian arch is caused by extensive lava flows rather than by sedimentation is also supported: material having a velocity near 4 km/sec at or just beneath the sea floor was found under the deep and under the south side of the arch. This material has apparently filled the original deep in part. Some evidence exists for lateral variation of the velocity of compressional waves in the mantle. This, plus variations of velocity in the shallower layers and possible changes of dip of layers within the length of individual refraction profiles, makes the computed depth to mantle at individual stations depend somewhat on the form of solution and pairing of stations. Depths to the discontinuity as shallow as 9 km may exist at some points on the arch. A small area in which high-velocity material occurs within 7 km of sea level was found under the shelf northwest of Kahului, Maui; this may be material brought up from the mantle either in a volcanic pipe or by faulting.

Hawaii site

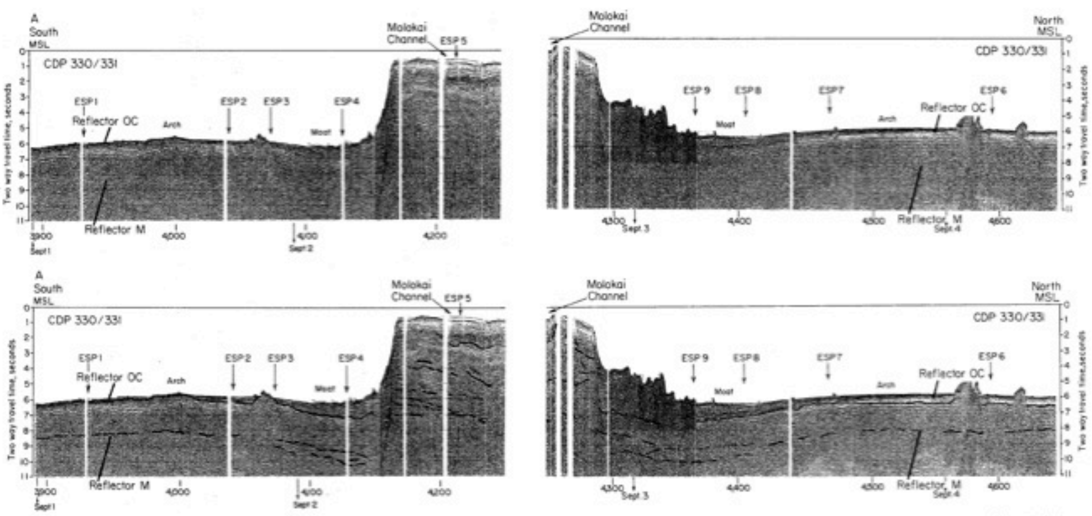
- Crustal Age:
  80Ma
- Half spreading rate:
  35-40 mm/yr
- Original latitude:
  near equator
- Water depth:
  4050-4300 m





Previous seismic survey results

- Clear Moho discontinuity



Watts et al., 1985

Previous seismic survey results

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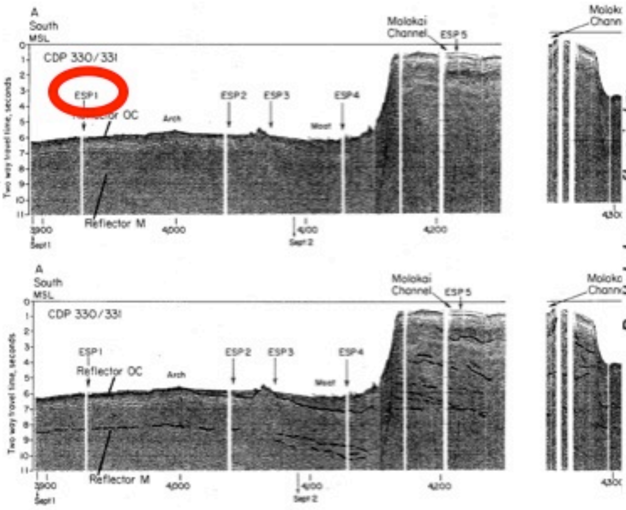
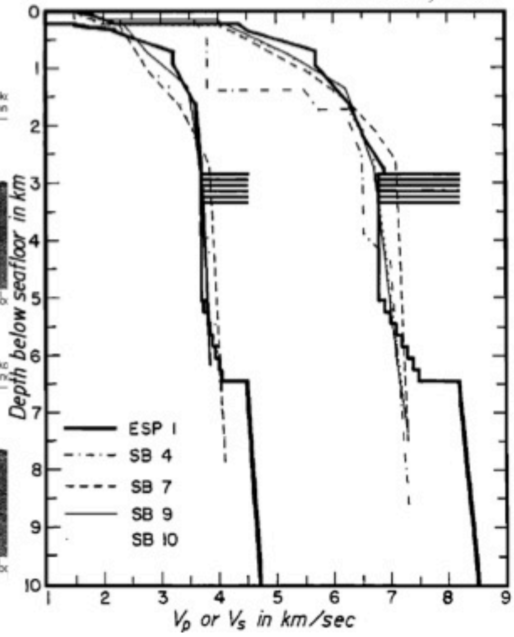
Lindwall, 1991

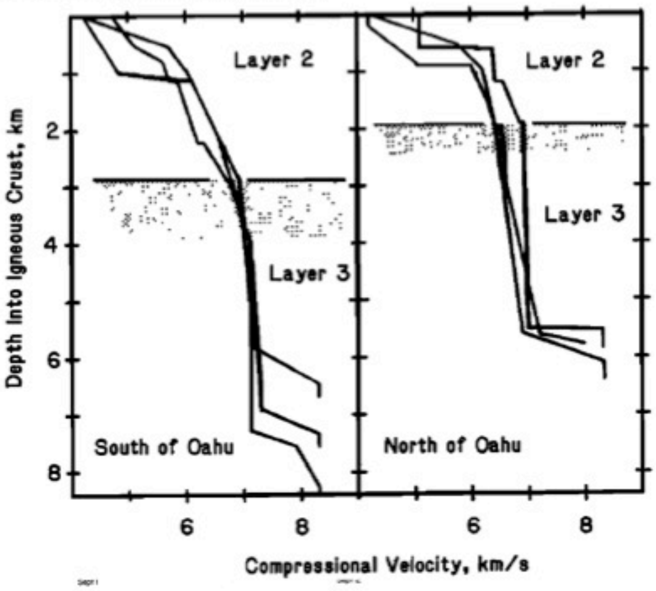




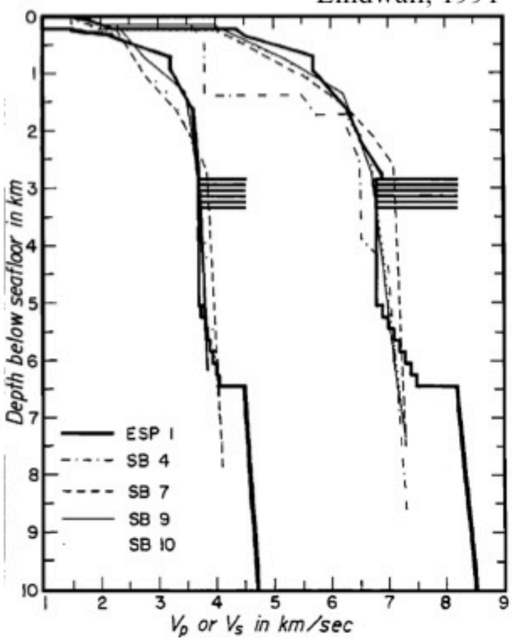
Previous seismic survey results

- Clear Moho discontinuity

ten Brink and Brocher, 1988

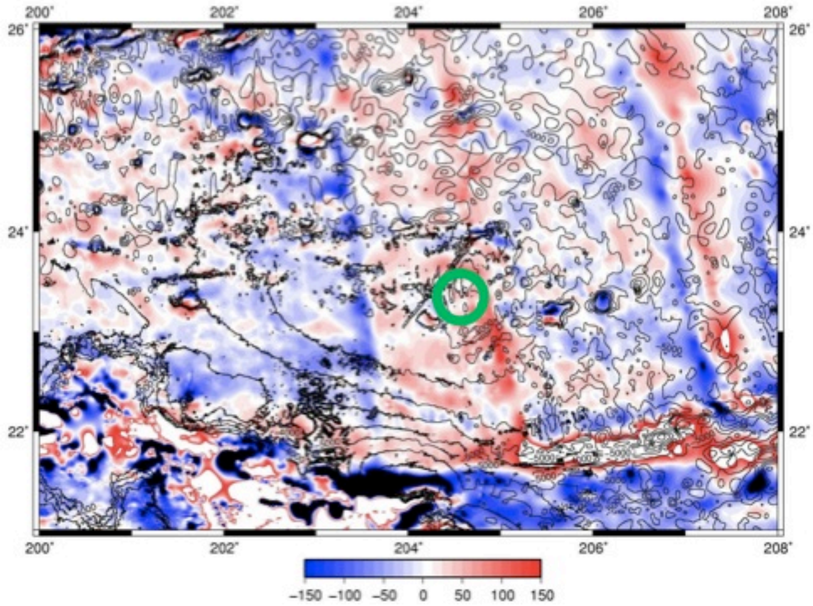


Lindwall, 1991



Geomagnetic Anomaly

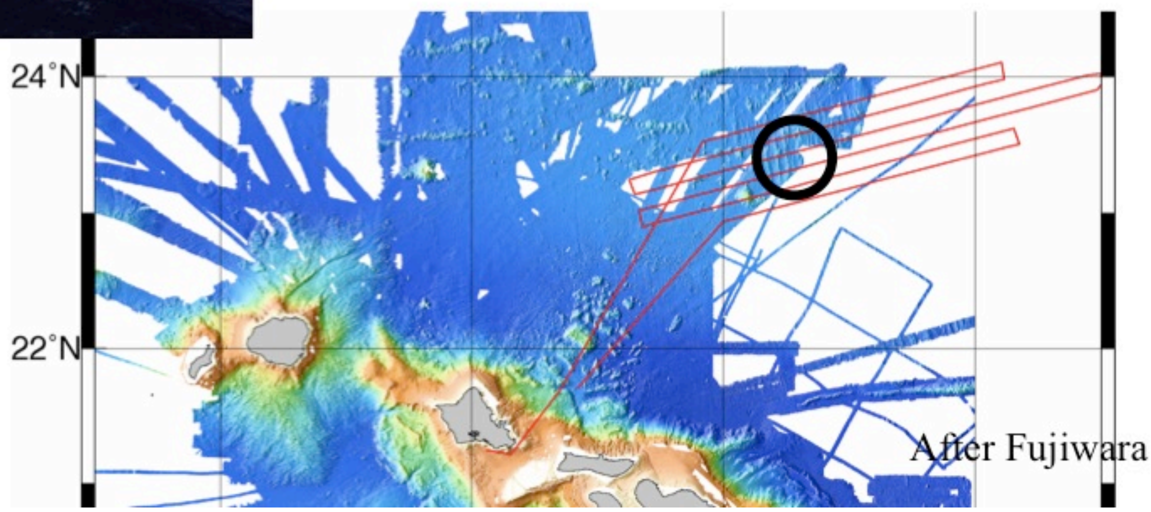
- Clear 2D Normal/Reverse patterns
- Crustal age is well constrained ~80Ma
- Half spreading rate 35-40 km/Myr



R/V Kilo Moana KM1003 Cruise

B. Taylor, G. Moore, G. Ito, 1 post doc, 6 students (SOEST, Univ. Hawaii), N. Abe, T. Fujiwara (IFREE, JAMSTEC)

- 20 Feb ~ 25 Feb 2010 (6 days)



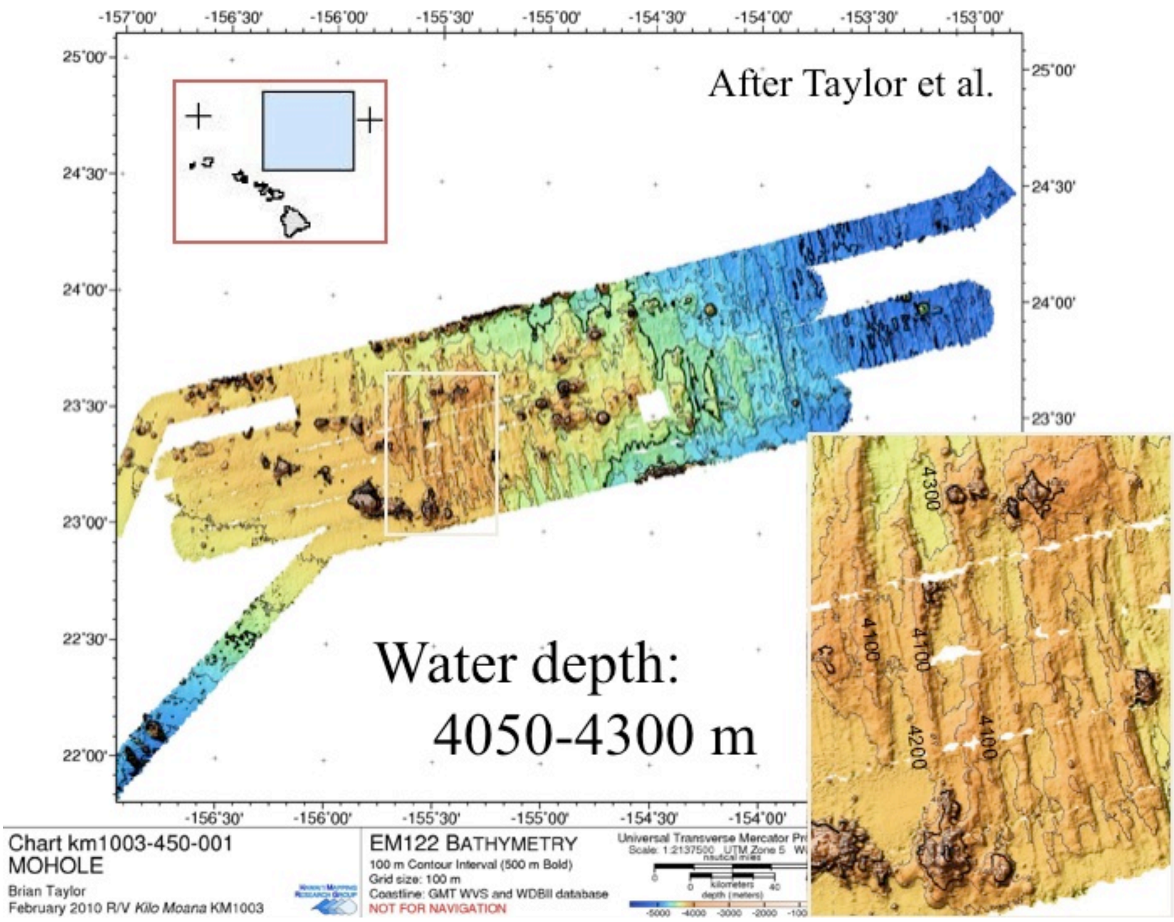
KM1003 with R/V Kilo Moana

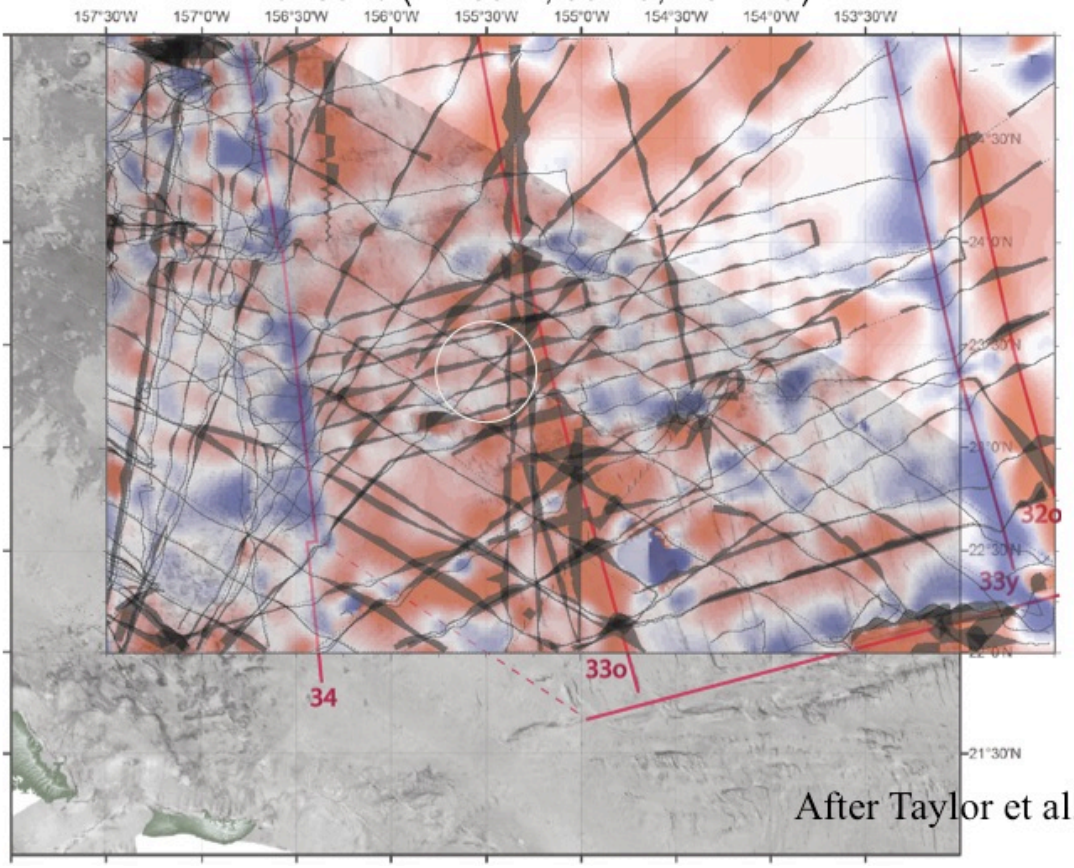
- Swath bathymetry (Simrad EM120)
- Sub-bottom profiler (Knudsen 320)
- Gravity (LaCoste-Romberg S-33)
- Magnetics (Geometrics G-882 Cesium)

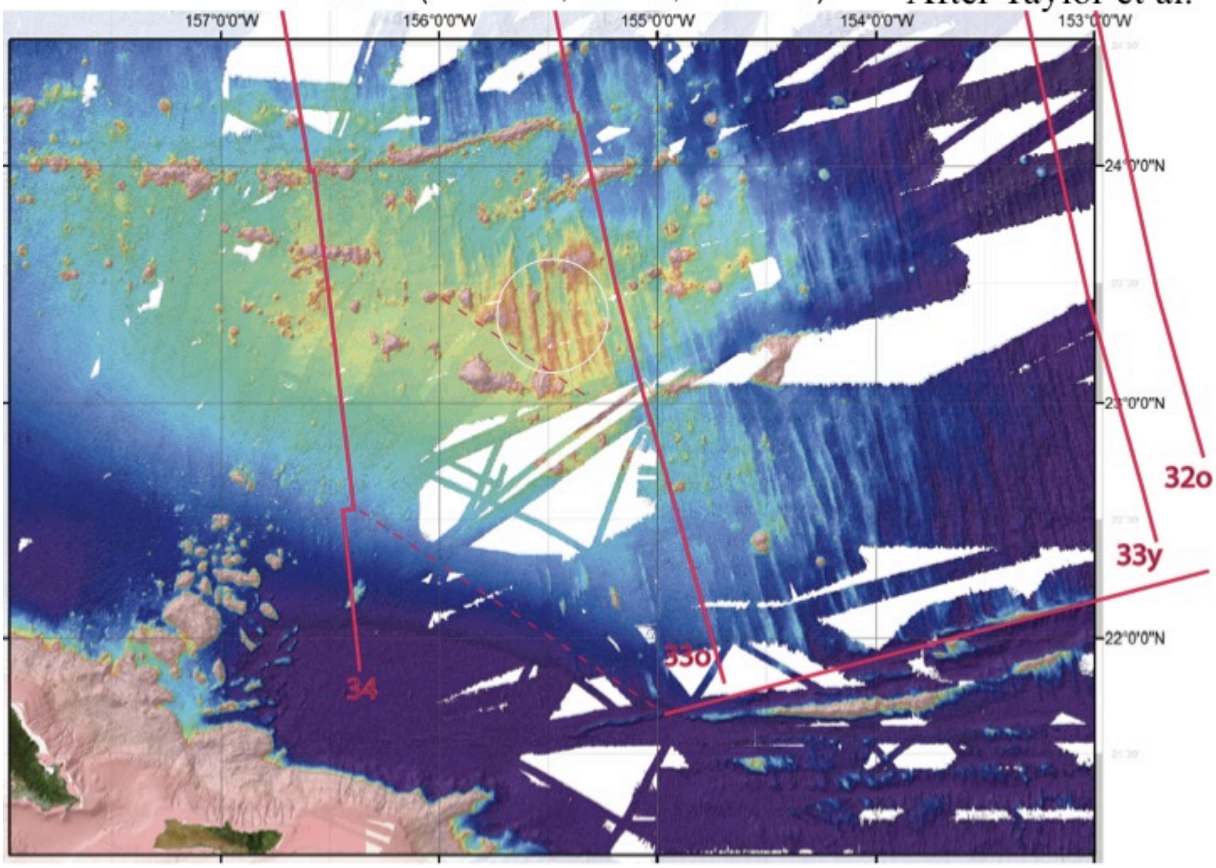
Gravitymeter


Magnetometer

After Fujiwara

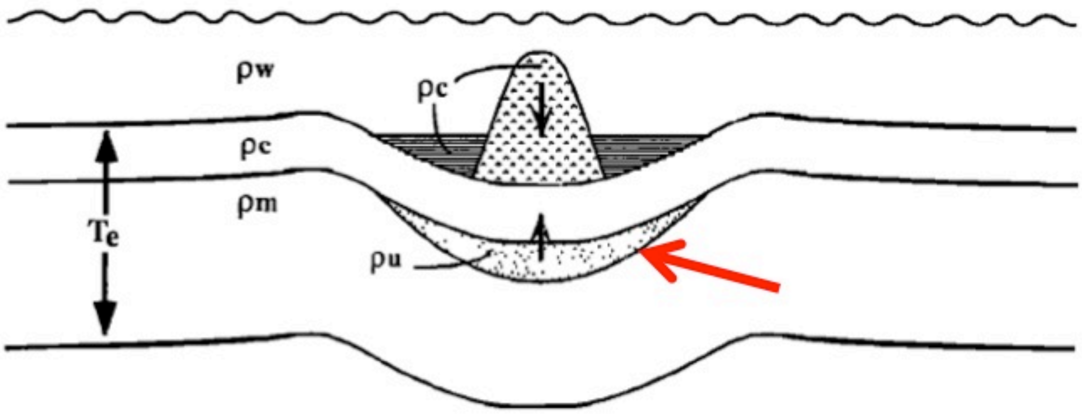



NE of Oahu (<4100 m, 80 Ma, 1.3 HFU)
157°30'W
157°0'W
156°30'W
156°0'W
155°30'W
155°0'W
154°30'W
154°0'W
153°30'W
24°0'N
22°30'N
22°0'N
21°30'N
34
33o
33y
32o
After Taylor et al.


NE of Oahu (<4100 m, 80 Ma, 1.3 HFU)
After Taylor et al.
157°0'0"W
156°0'0"W
155°0'0"W
154°0'0"W
153°0'0"W
24°0'0"N
23°0'0"N
22°0'0"N
34
33o
33y
32o

Could Hawaiian Plume modify the crust and uppermost mantle?

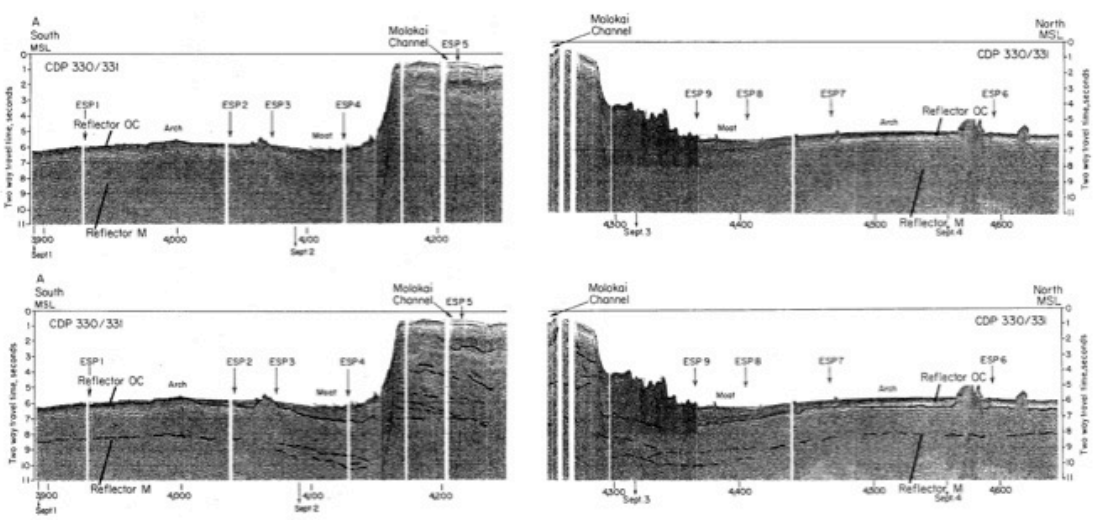
1) Infill material
2) Arch Volcanoes



Wolfe et al., 1994

Previous seismic survey results

- Deep crustal sill complex



Watts et al., 1985

Previous seismic survey results

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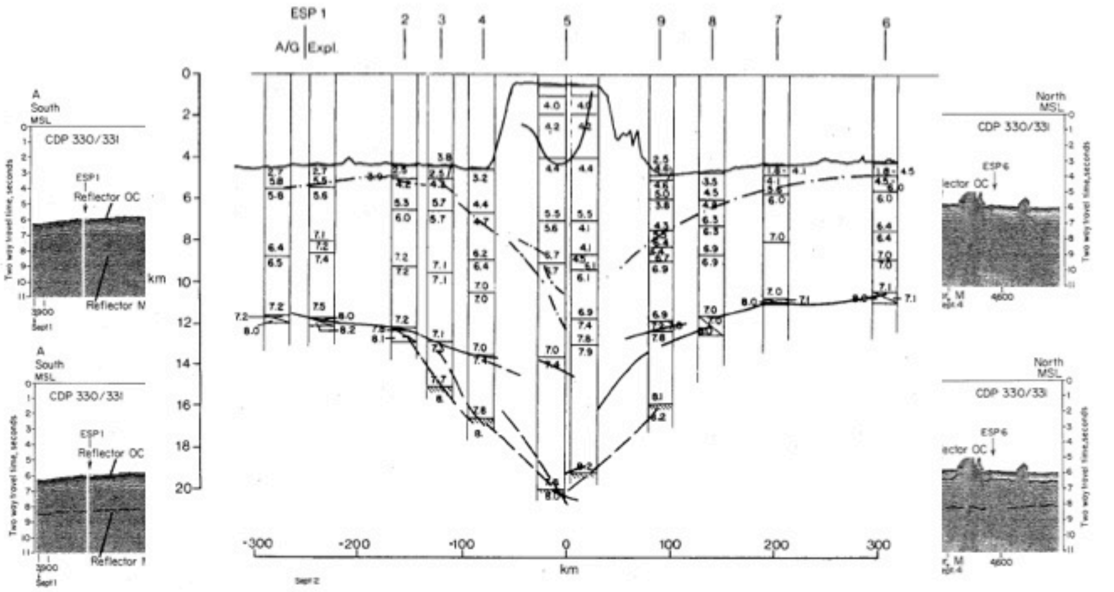

Watts et al., 1985

Could Hawaiian Plume modify the crust and uppermost mantle?

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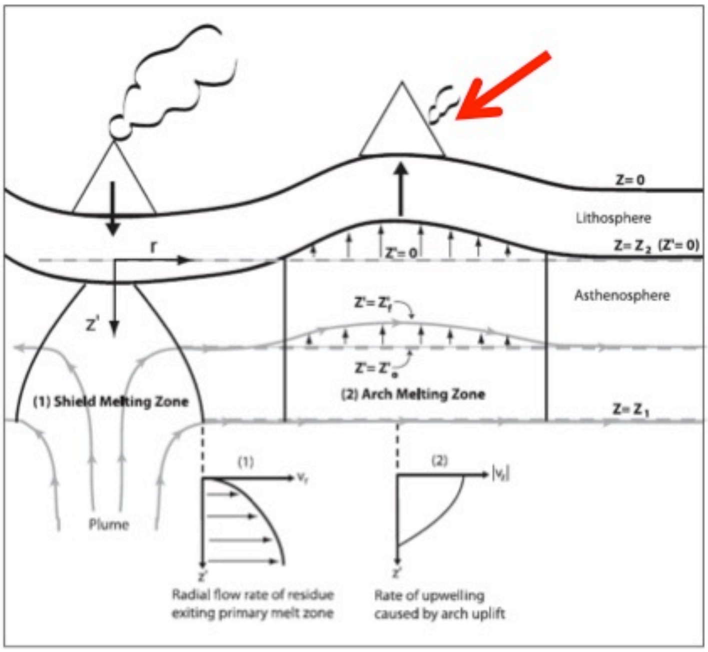
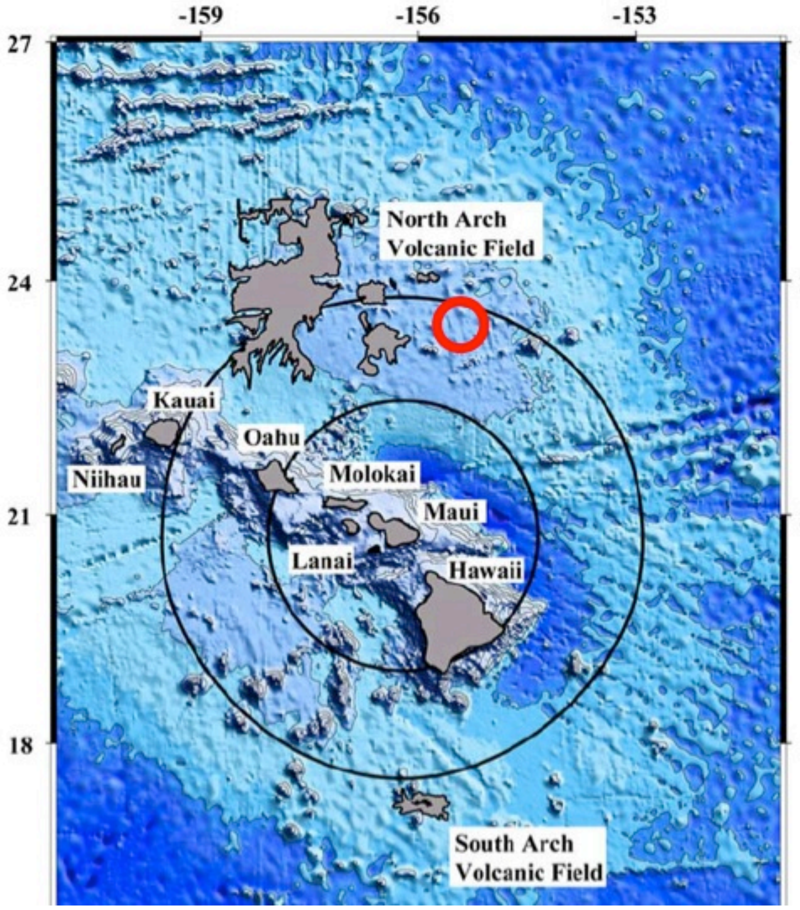
2) Arch Volcanoes



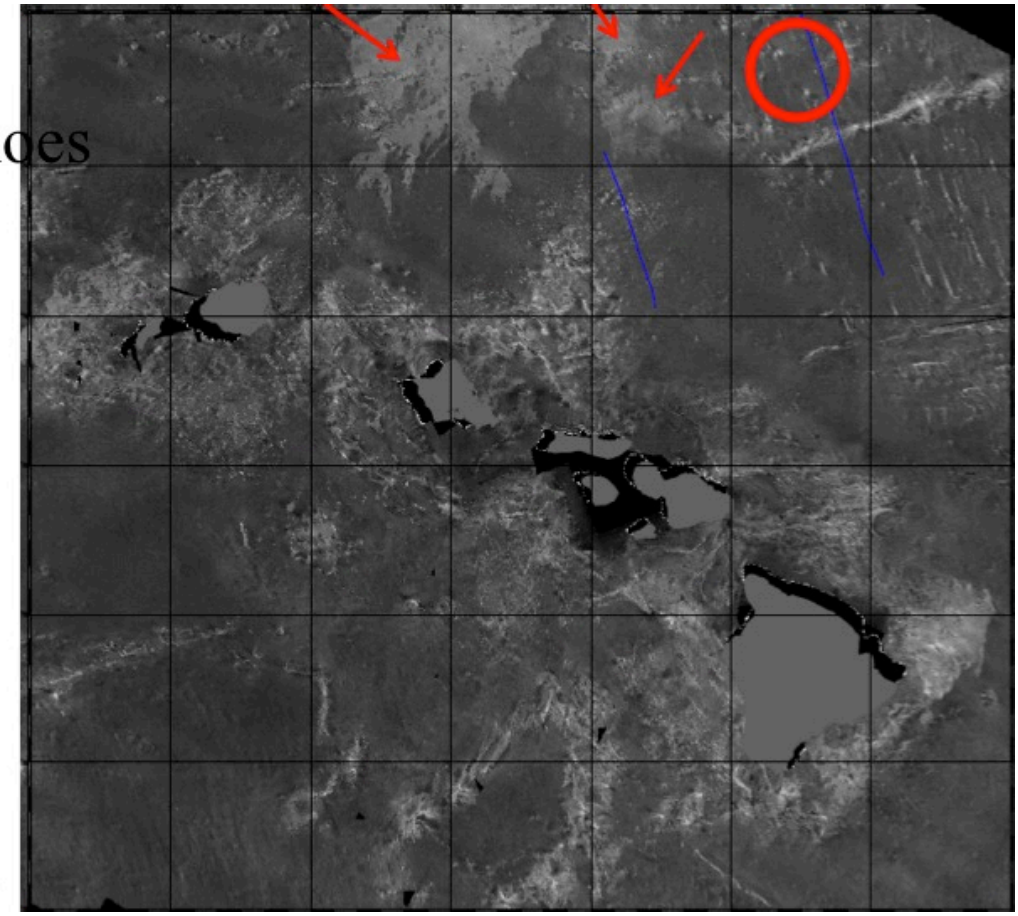
Bianco et al., 2005

Arch Volcanic Fields

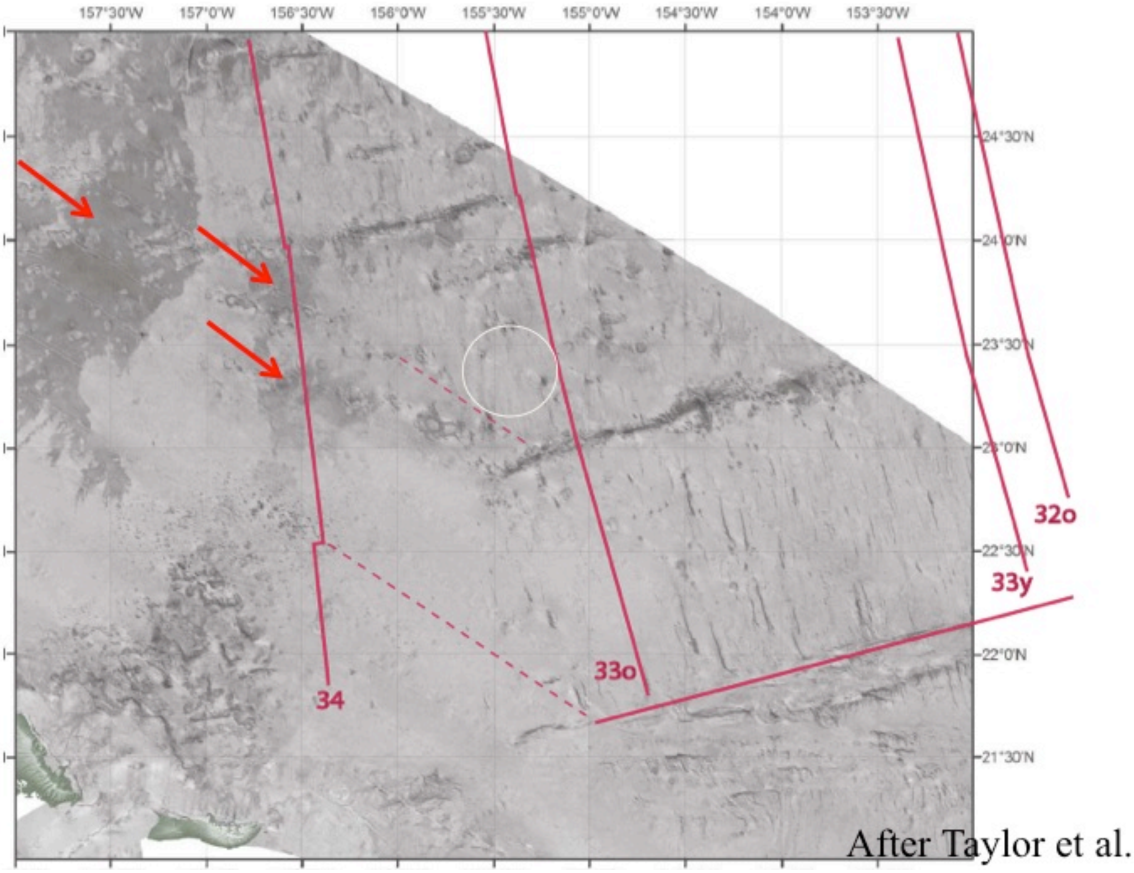


Bianco et al., 2005

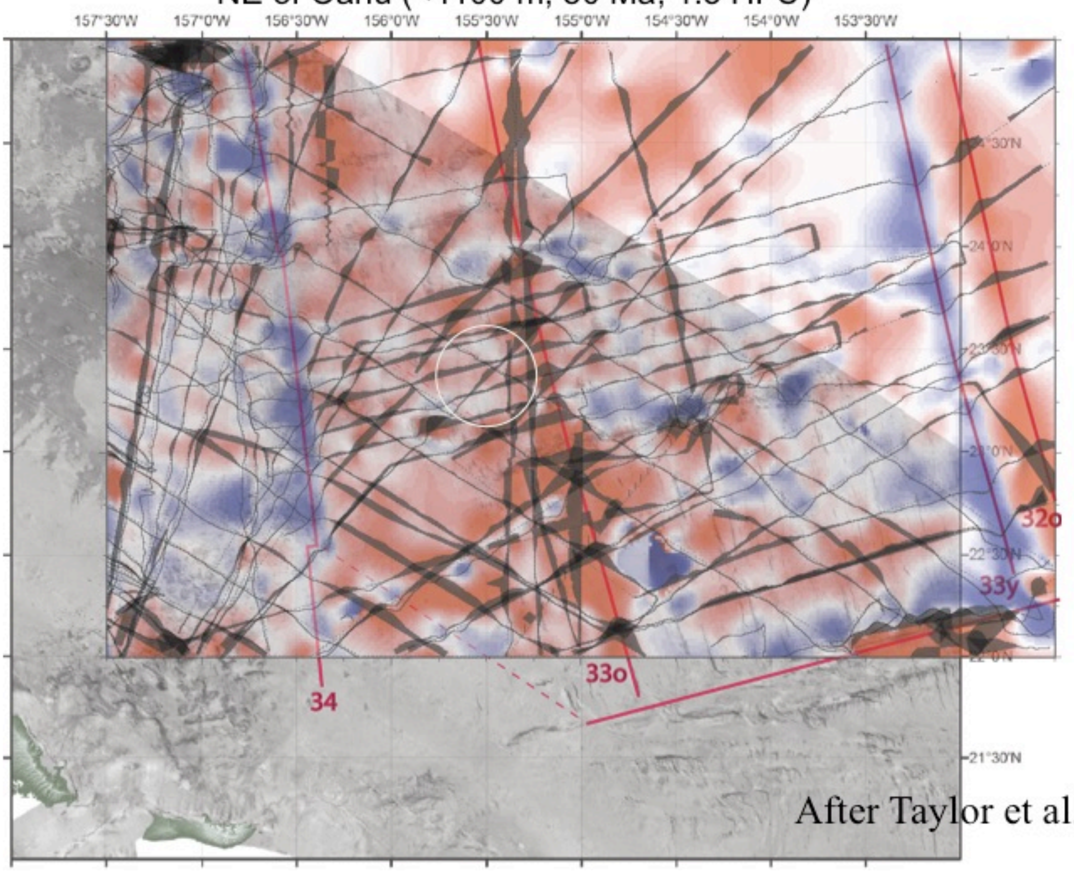
Arch Volcanoes



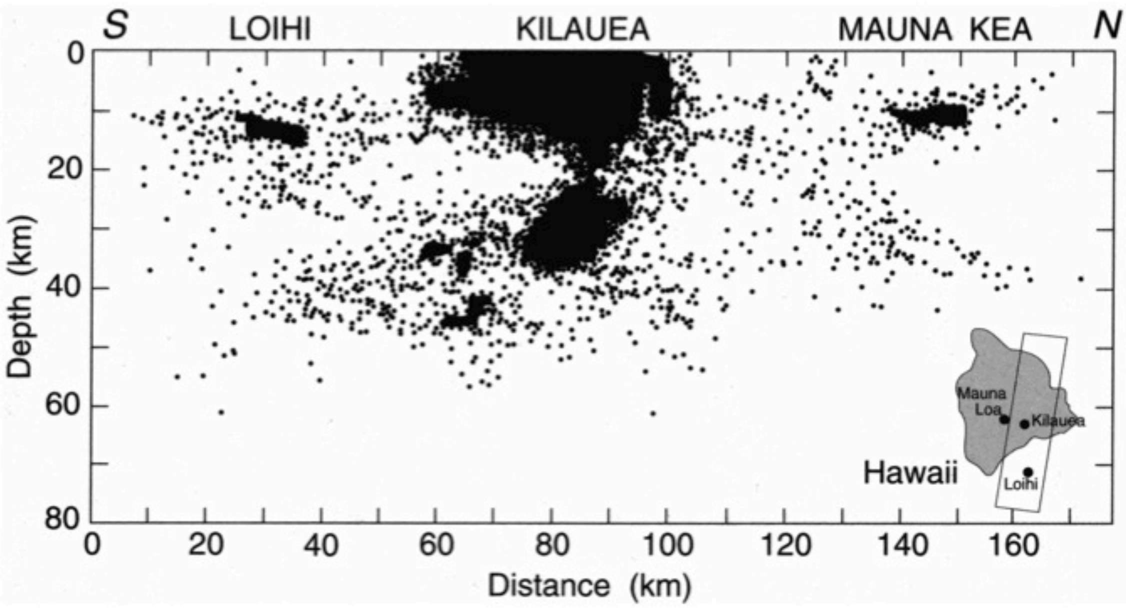
Normark et al., 1989



NE of Oahu (<4100 m, 80 Ma, 1.3 HFU)

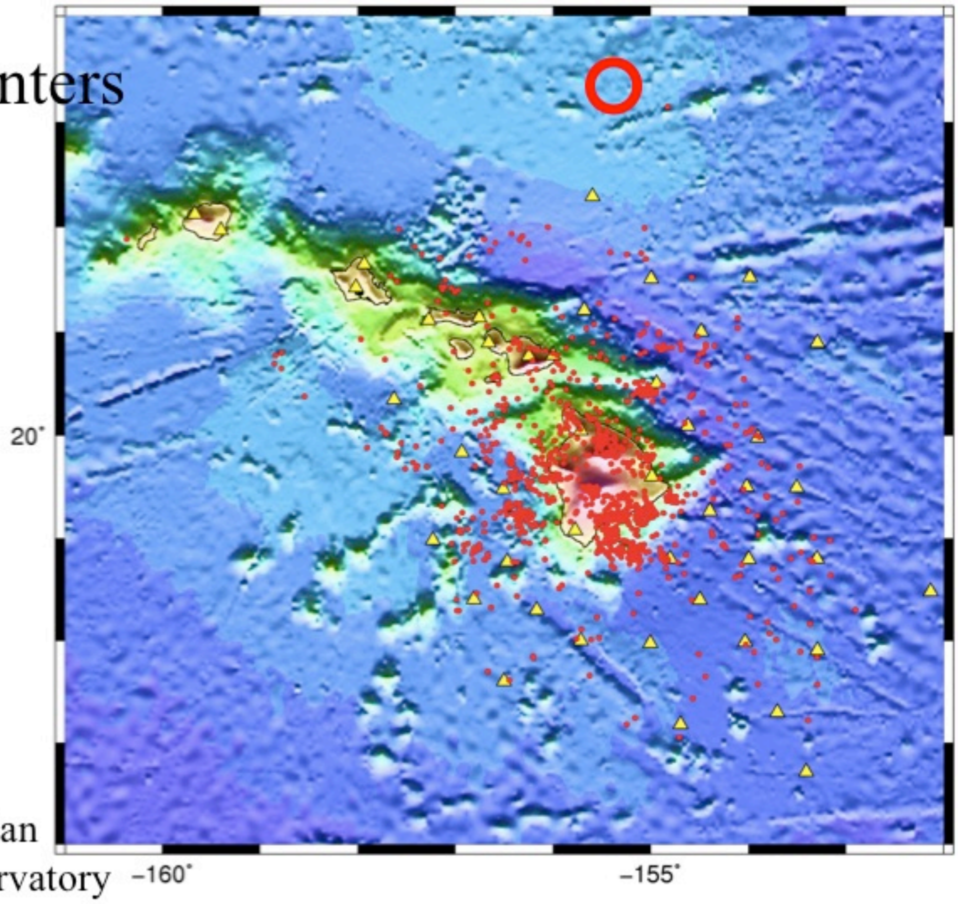


Seismicity could be indicator for magma reservoirs an conduits



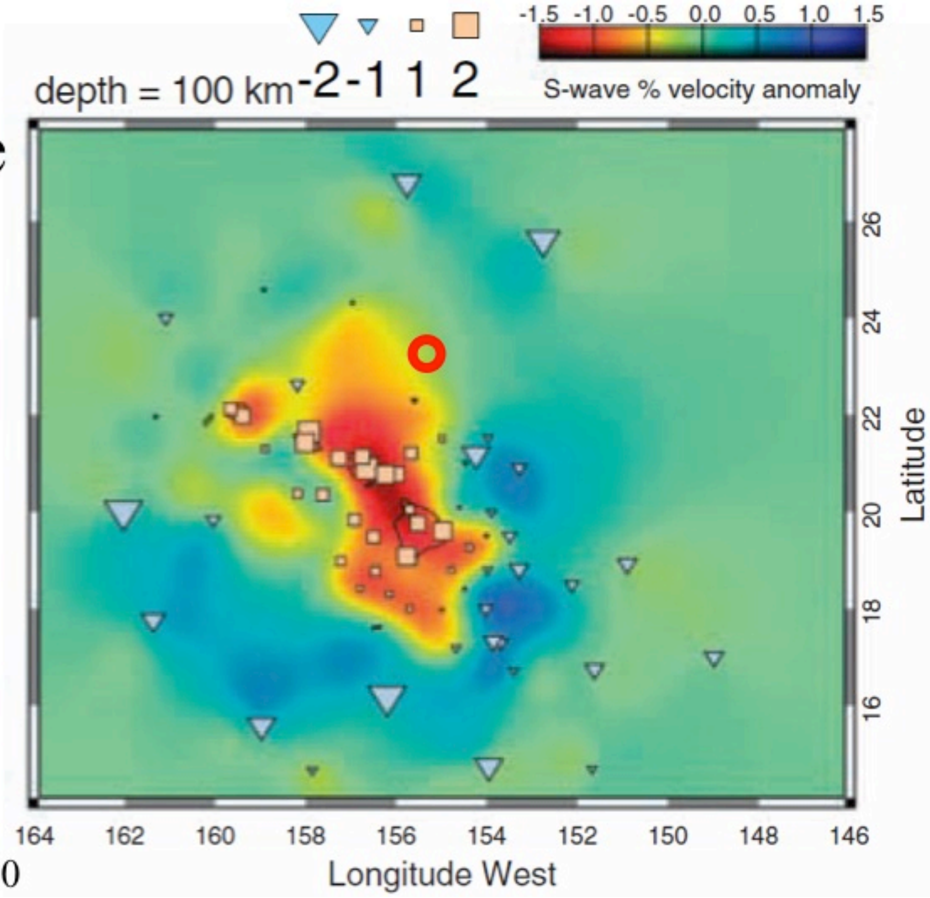
Klein et al., 1987

Hypocenters



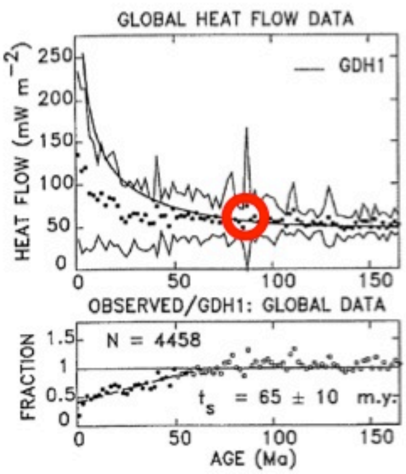
USGS Hawaiian Volcano Observatory

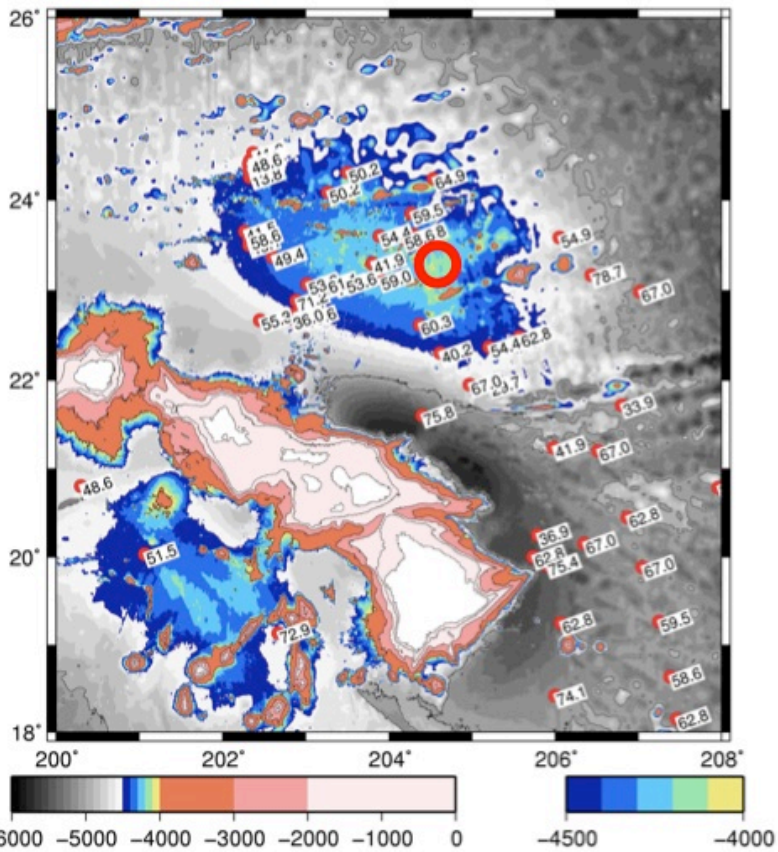
Deep S structure



Wolfe et al., 2010

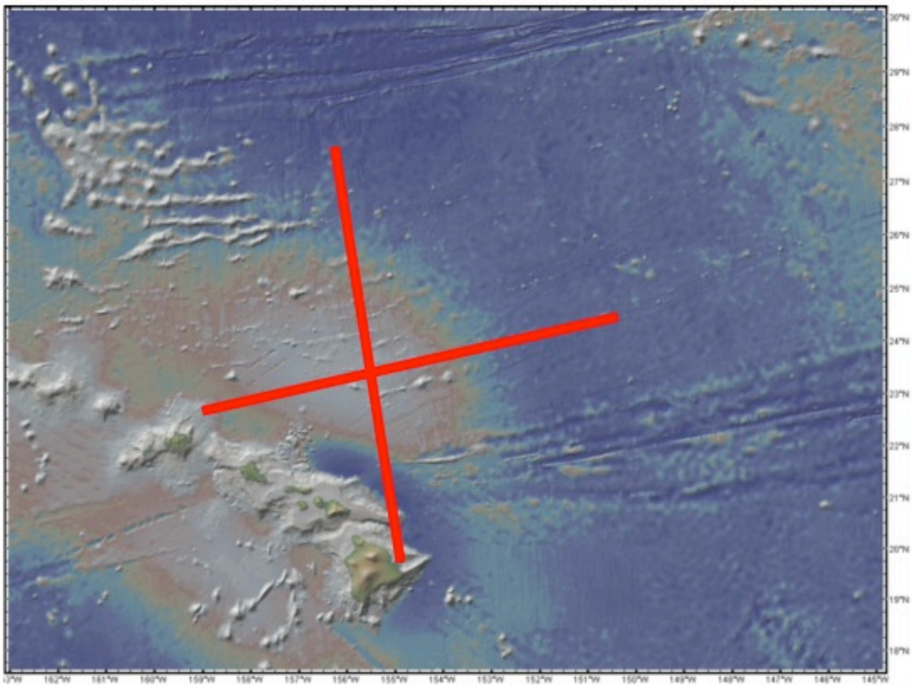
Heat Flow





Stein and Stein, 1992

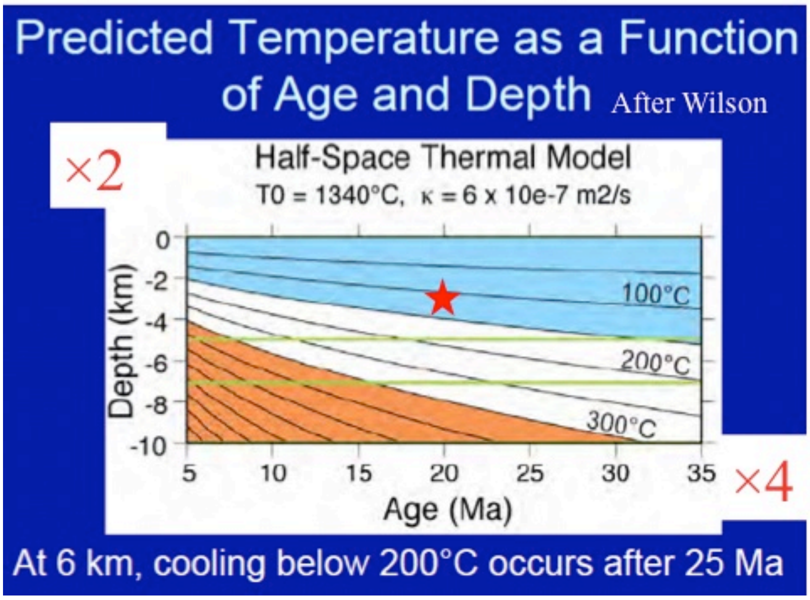
Proposed seismic survey lines



Temperature estimation for Hawaii site

Half space thermal model + Square root t low

→ slightly higher than 100°C at 6km→ <150°C



Good for

- Drilling
- LWD

(Logging-While-Drilling)

- Microbiology

(Temperature for amino acid surviving)

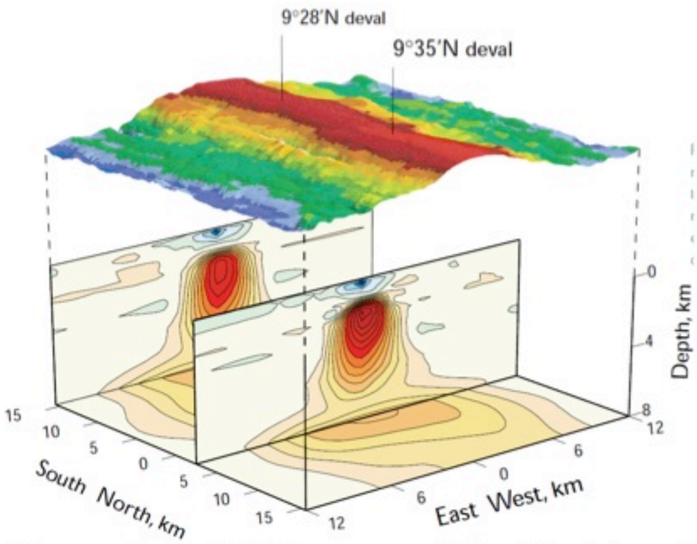
Hawaii site shows desirable site attributes?

・Nearly normal ocean crust → Need to avoid Arch volcanoes
・Age > 20Ma ← Not too hot at Moho (<~200°C) ○<150°C
・Not too deep (4-km riser) → 4050-4300 m
・Close to major port(s) ○
・International waters or member EEZ ○
・Crustal thickness 5.0-5.5 km → ~ 6 km?
・12-month weather window ○
・Original latitude > ±15 → nearly equator

・High quality seismic survey → We need to do it
・Slower spreading rate than current fastest ridge system

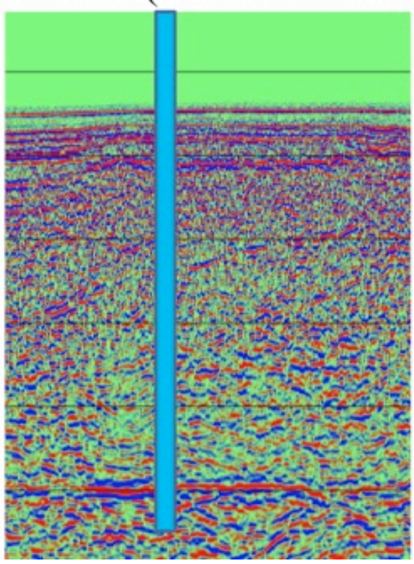
Desirable item: Slower spreading rate than current fastest ridge system

<~80mm/yr half spreading rate



Dunn et al., 2000

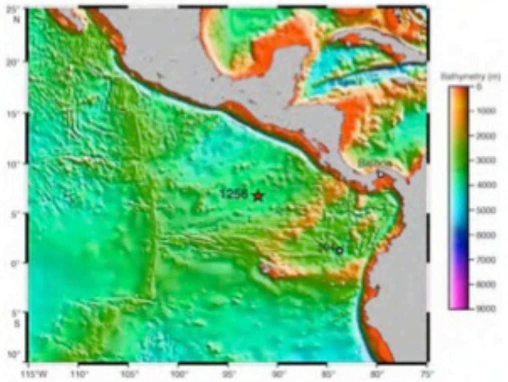
Mohole (reference hole)



After Kodaira et al.

Weak points of Site 1256

- Too hot at Moho?
- Faster spreading rate than current fastest ridge system (~110mm/yr half spreading rate)
- Clear Moho? → High quality seismic survey



How should we decide a Mohole site?

→ Detailed seismic velocity structure and its characters below are especially important.

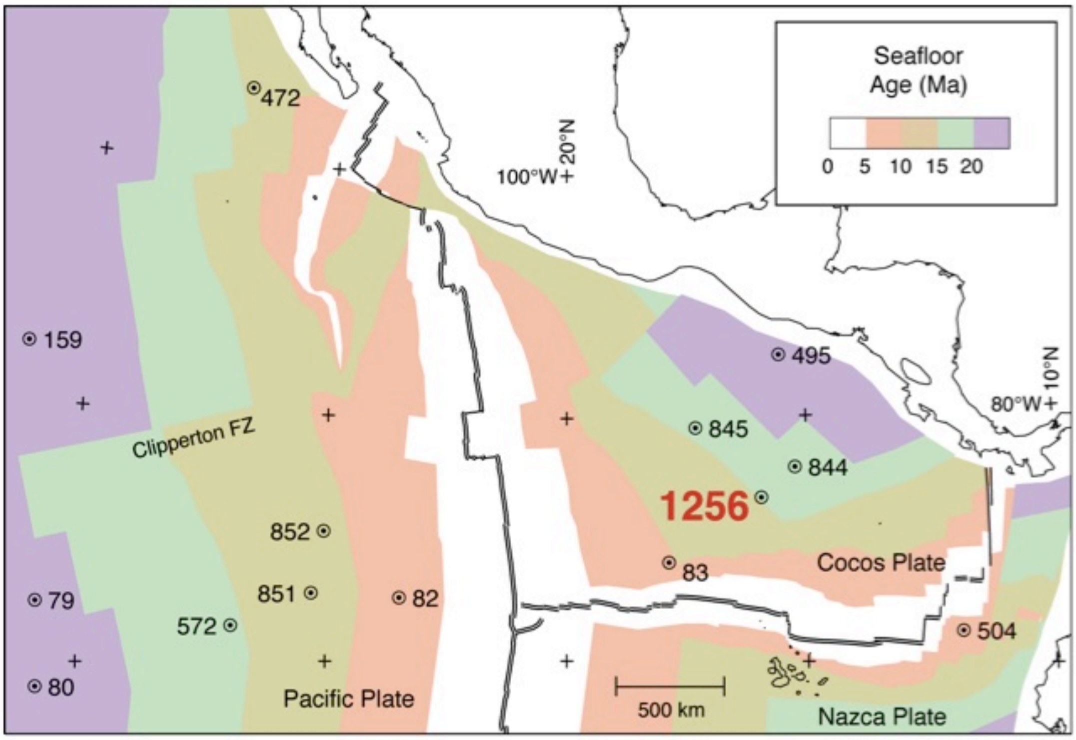
- Crustal velocity structure (velocity value, etc.)
- Moho discontinuity (amplitude of reflector; single or multiple reflectors, etc.)
- Uppermost mantle velocity structure (velocity value and degree of anisotropy, etc.)

→ The final Mohole site should be decided after discussions among the international community with enough geophysical data for all candidates.

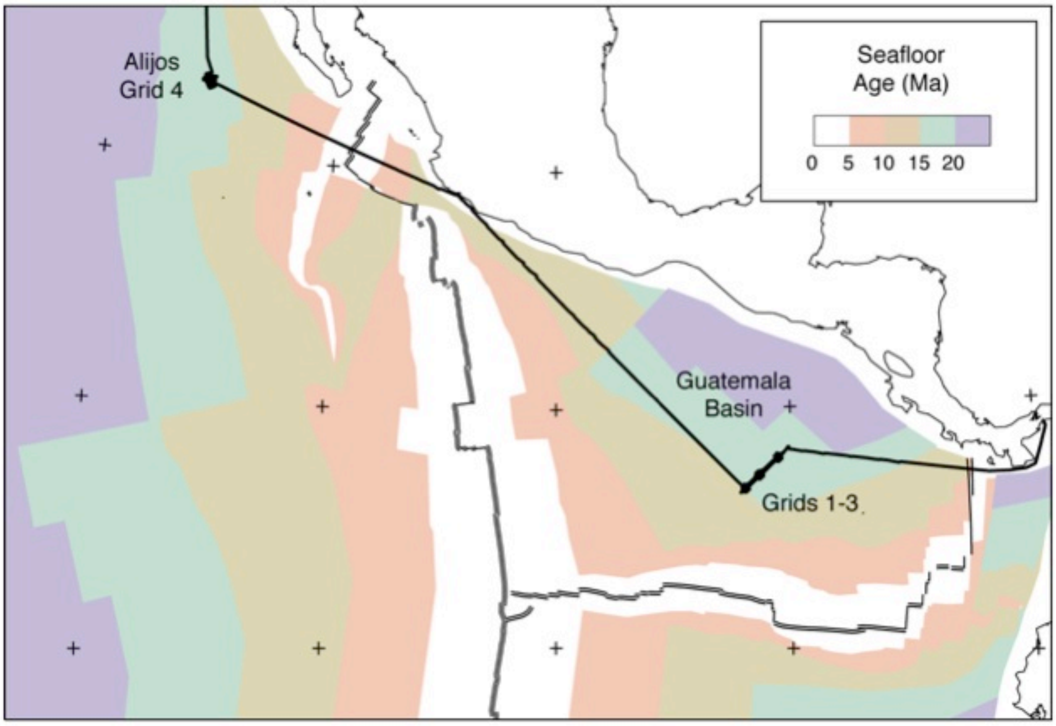
Site Survey Data at ODP Site 1256

ODP Leg 206, IODP Expeditions 309/312

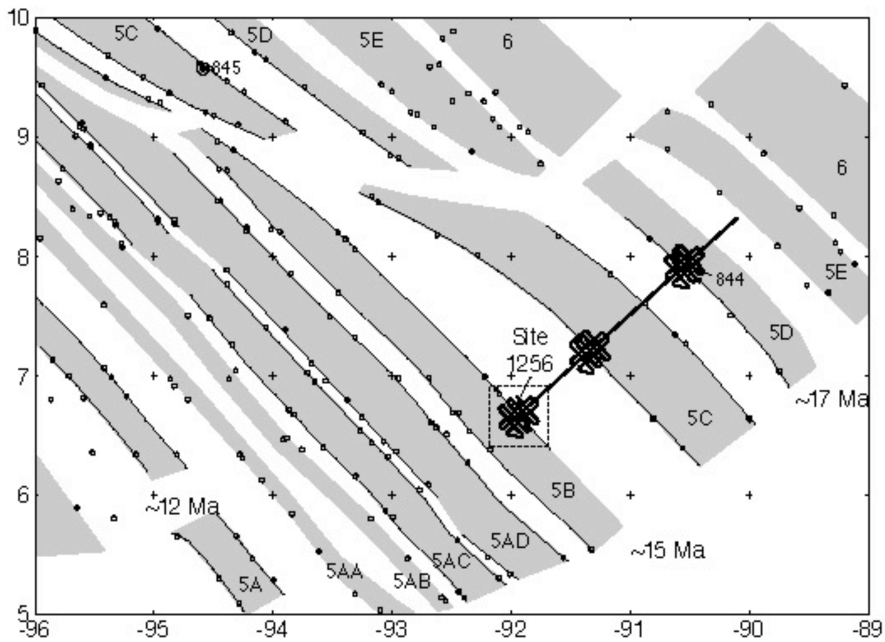
Douglas S. Wilson, Alistair J. Harding, Eric Hallenborg, Graham Kent

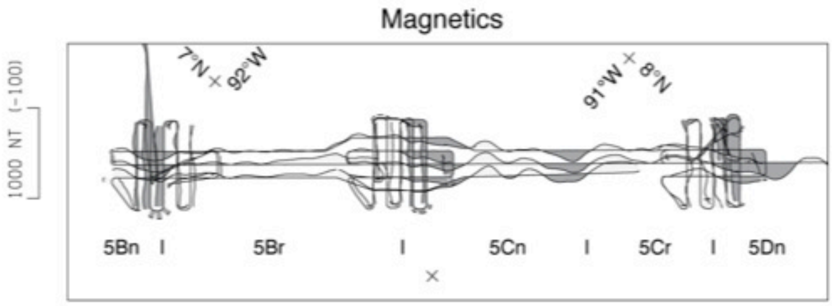


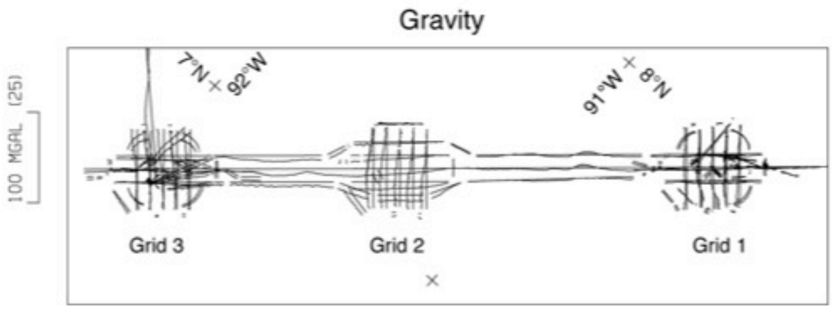
EW9903 Trackline

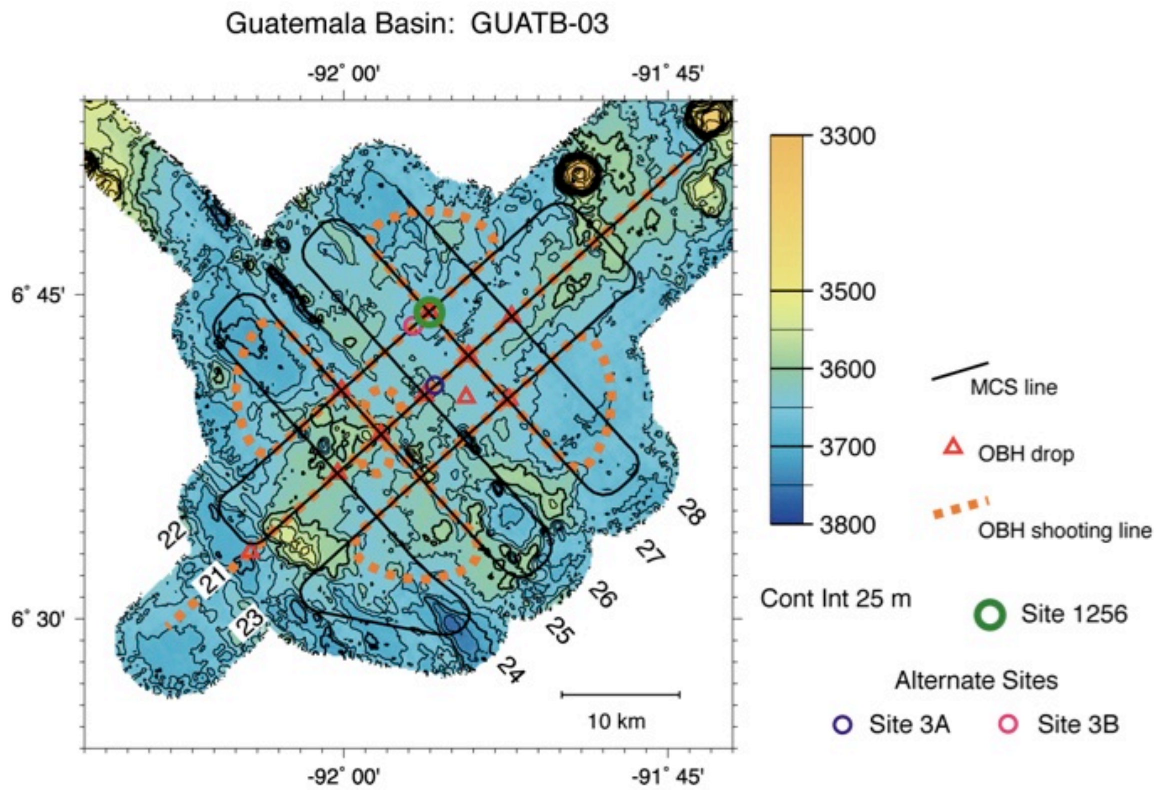


Isochrons and site-survey track

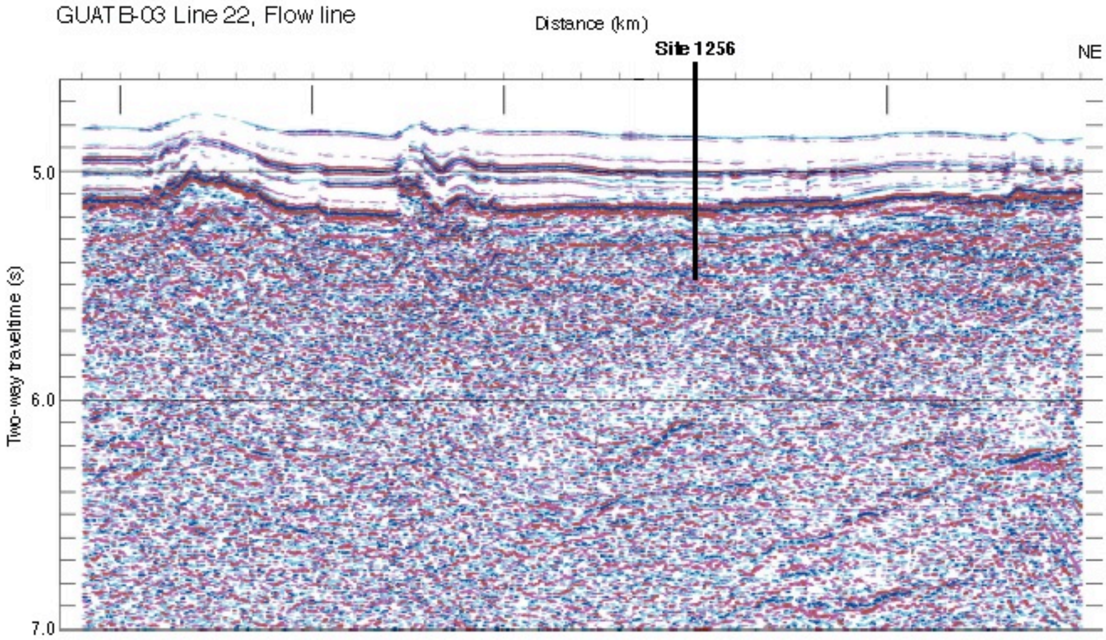


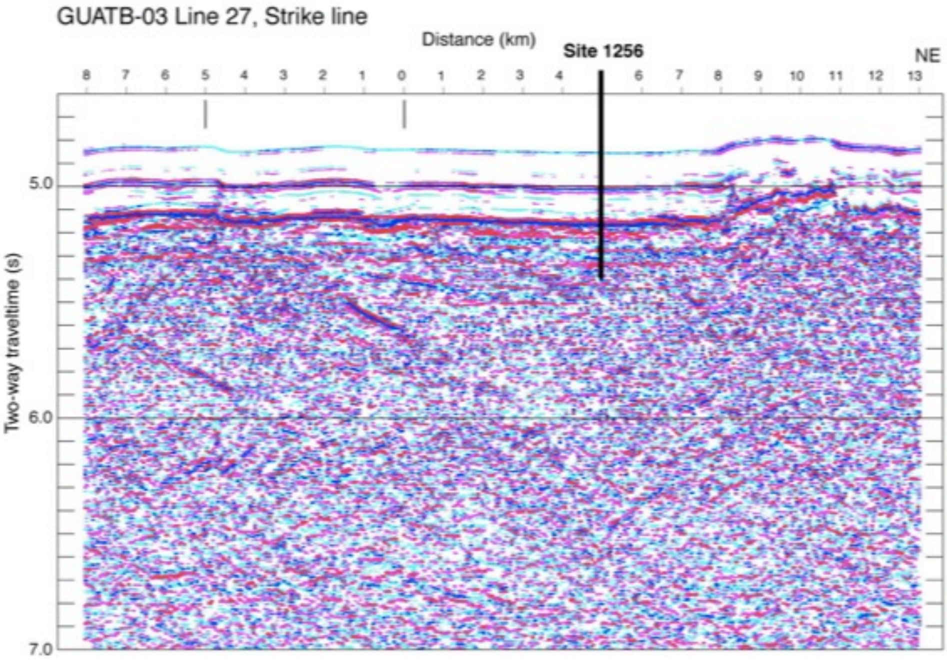

Magnetics
7°N × 92°W
91°W × 8°N
1000 NT (-100)
5Bn
5Br
5Cn
5Cr
5Dn

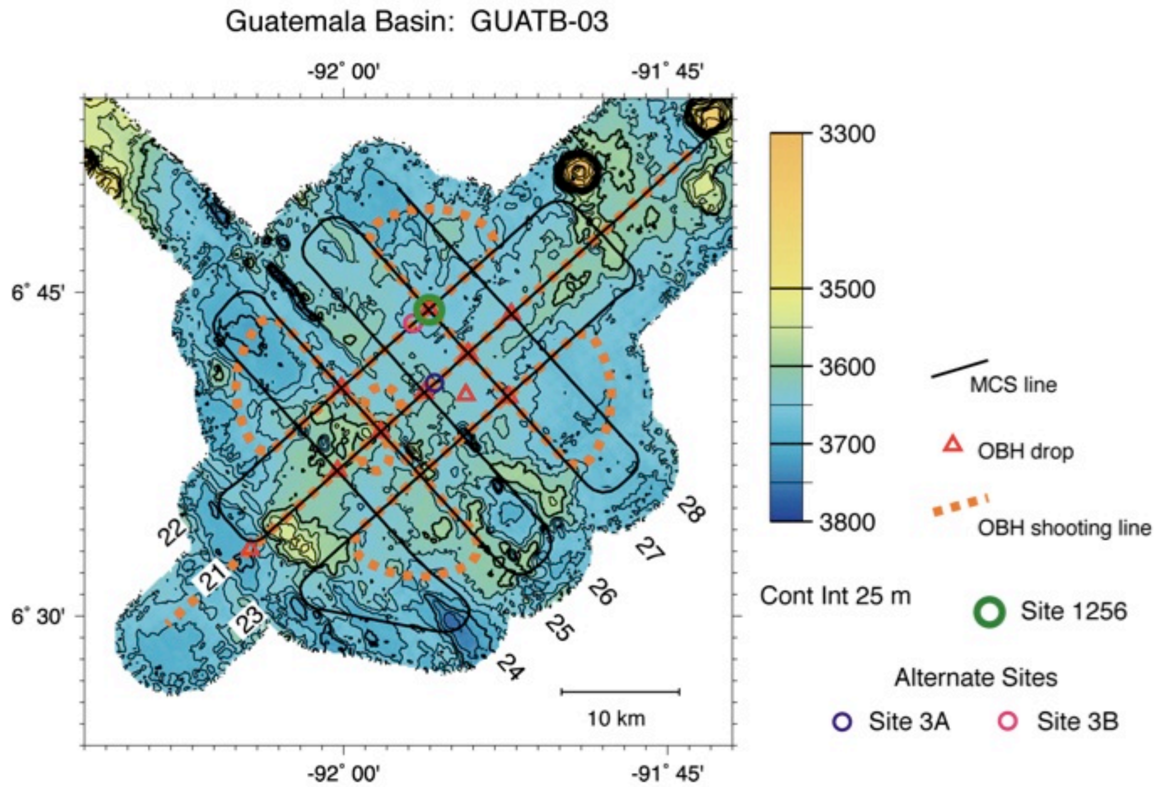

Gravity
7°N × 92°W
91°W × 8°N
100 MGAL (25)
Grid 3
Grid 2
Grid 1


Guatemala Basin: GUATB-03
-92° 00'
-91° 45'
6° 45'
6° 30'
3300
3500
3600
3700
3800
MCS line
OBH drop
OBH shooting line
Cont Int 25 m
Site 1256
Alternate Sites
Site 3A
Site 3B
10 km
21
22
23
24
25
26
27
28

Seismic reflection section






Guatemala Basin: GUATB-03
-92° 00'
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6° 45'
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3300
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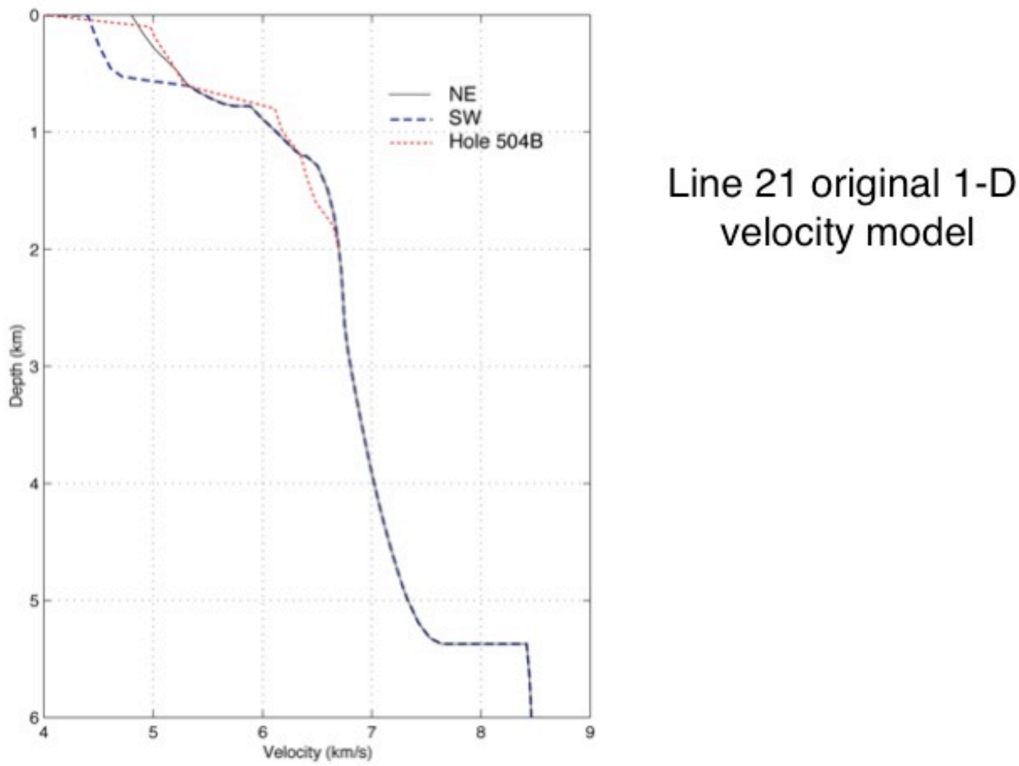
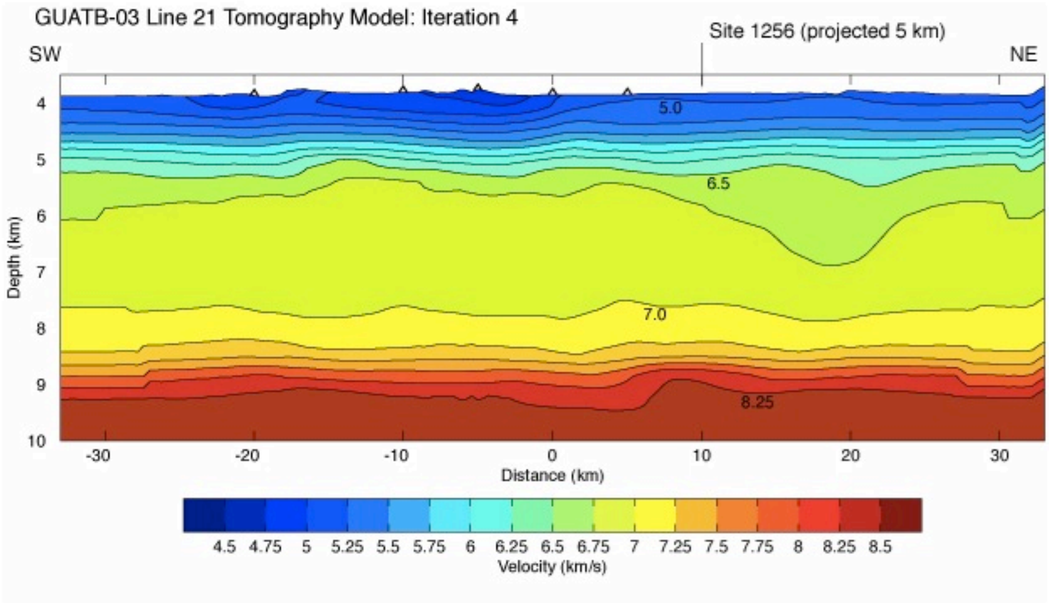
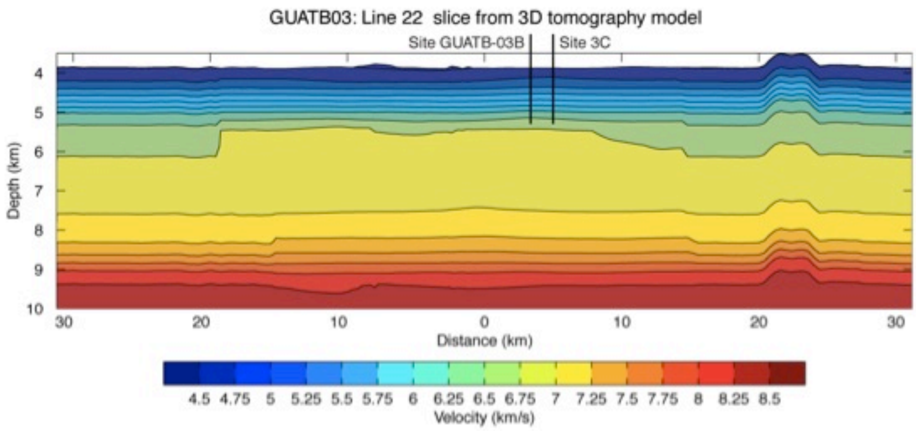
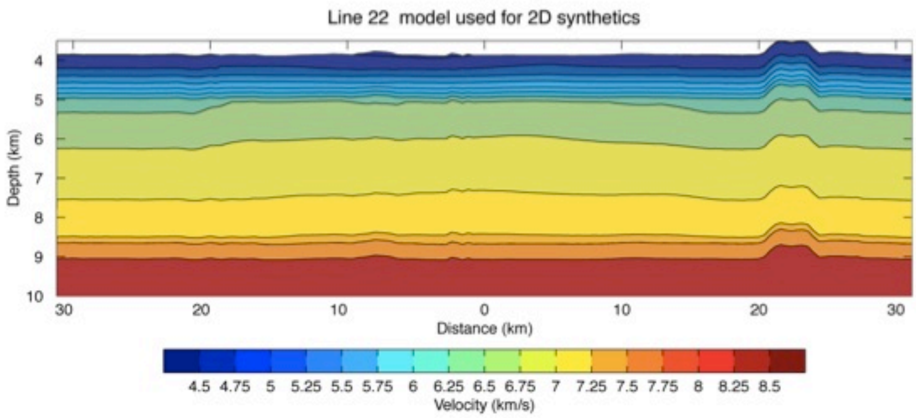
Cont Int 25 m
MCS line
OBH drop
OBH shooting line
Site 1256
Alternate Sites
Site 3A
Site 3B
10 km
21
22
23
24
25
26
27
28

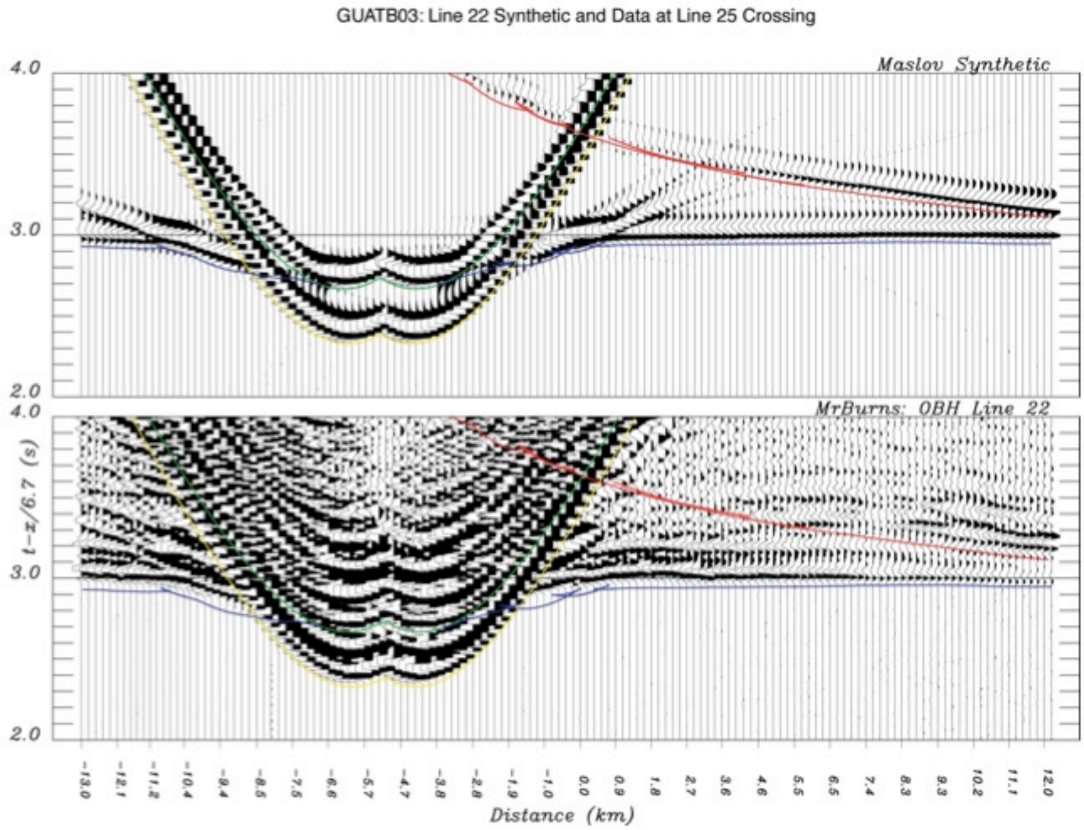

NE
SW
Hole 504B
Depth (km)
Velocity (km/s)
Line 21 original 1-D velocity model

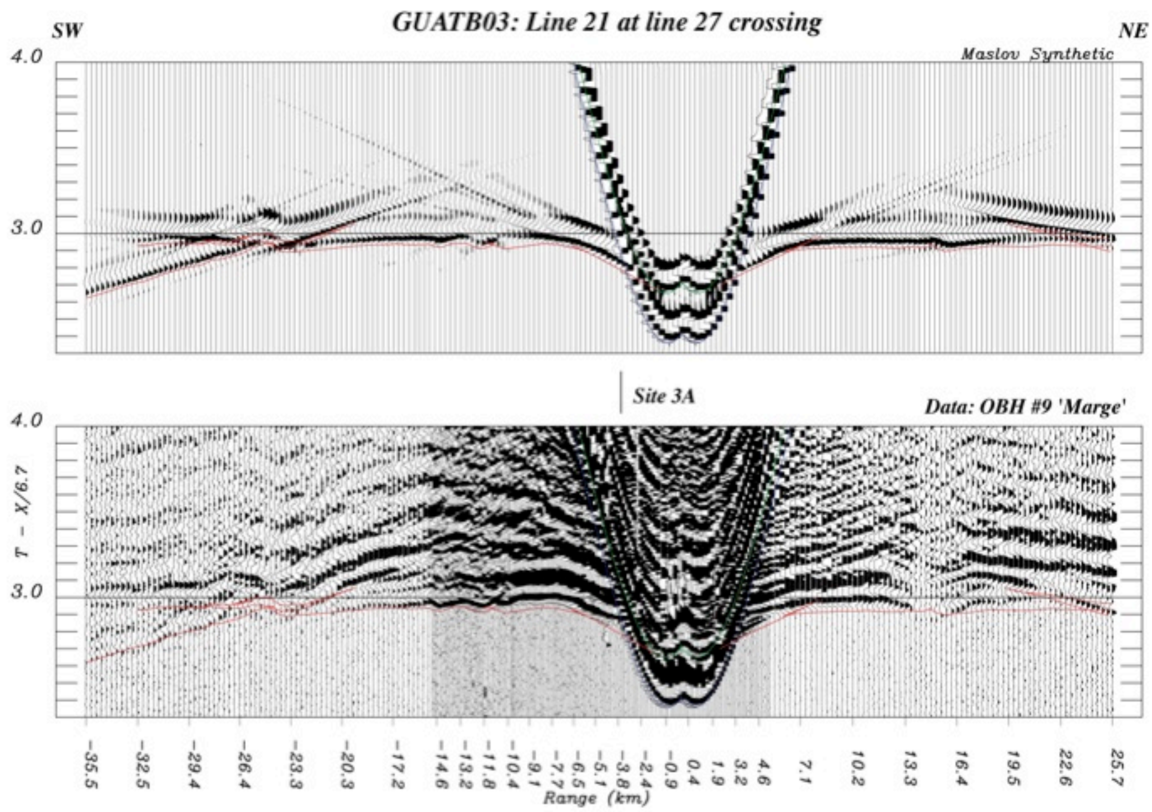
Site chosen at fairly high upper crust velocity of 4.9-5.0 km/s, Indicative of low porosity and hopefully, good drilling conditions

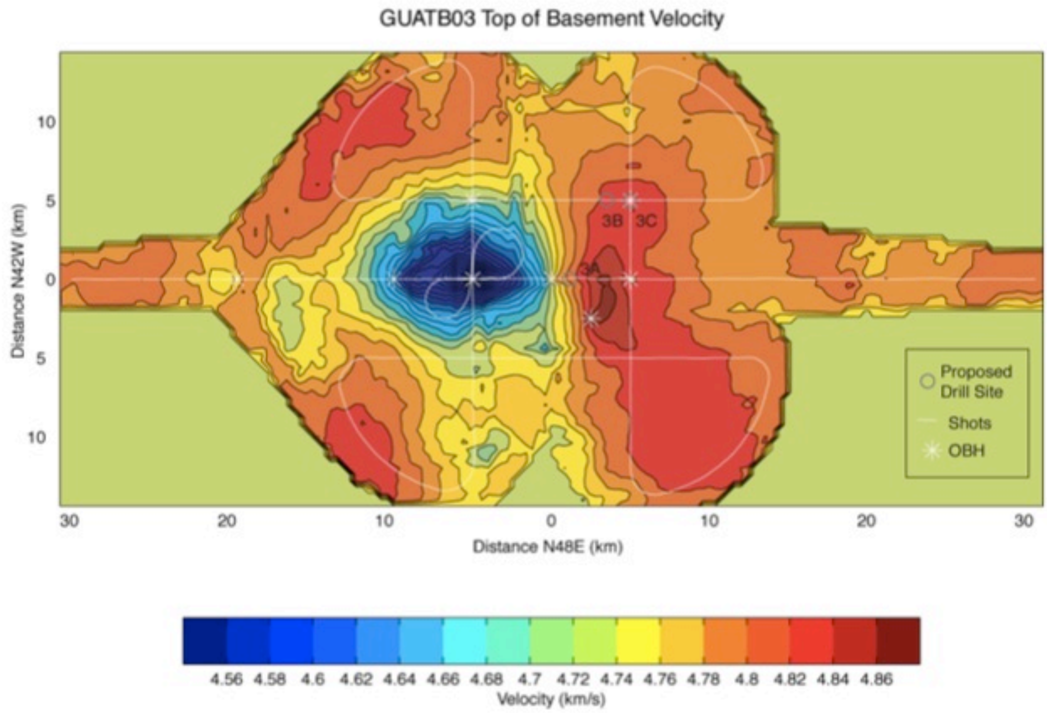




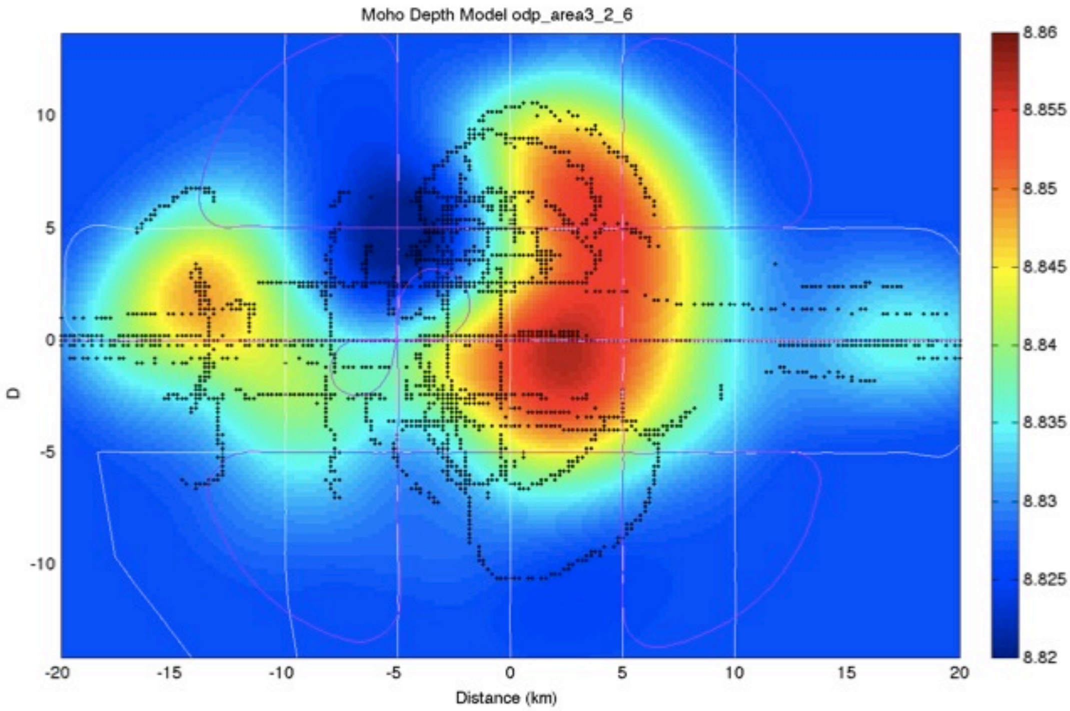


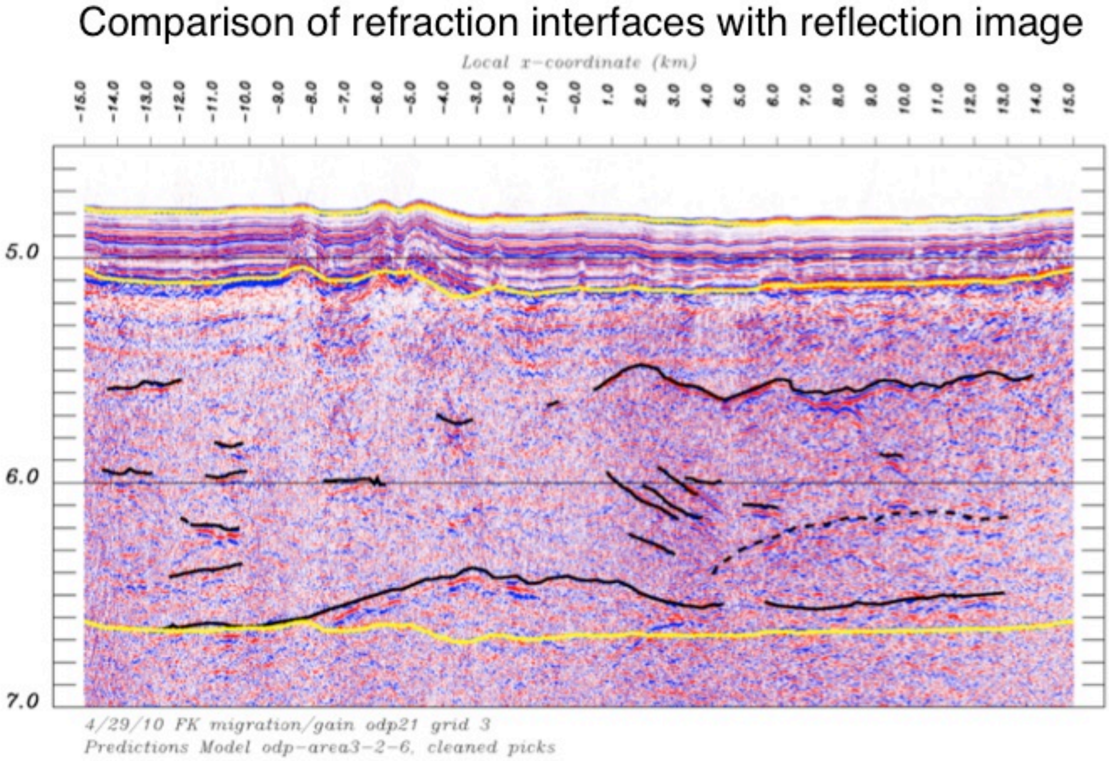

GUATB03: Line 22 Synthetic and Data at Line 25 Crossing
Maslov Synthetic
MrBurns: OBH Line 22
t-x/6.7 (s)
4.0
3.0
2.0
-13.0 -12.1 -11.2 -10.4 -9.4 -8.5 -7.5 -6.6 -5.7 -4.7 -3.8 -2.8 -1.9 -1.0 0.0 0.9 1.8 2.7 3.6 4.6 5.5 6.5 7.4 8.3 9.3 10.2 11.1 12.0
Distance (km)


GUATB03: Line 21 at line 27 crossing
SW
NE
Maslov Synthetic
Site 3A
Data: OBH #9 'Marge'
T - X/6.7
4.0
3.0
-35.5 -32.5 -29.4 -26.4 -23.3 -20.3 -17.2 -14.6 -13.2 -11.8 -10.4 -9.1 -7.7 -6.5 -5.1 -3.8 -2.4 -0.9 0.4 1.9 3.2 4.6 7.1 10.2 13.3 16.4 19.5 22.6 25.7
Range (km)

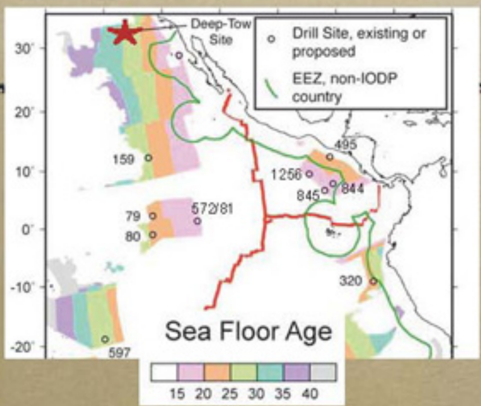


Topography (or lack thereof) on Moho



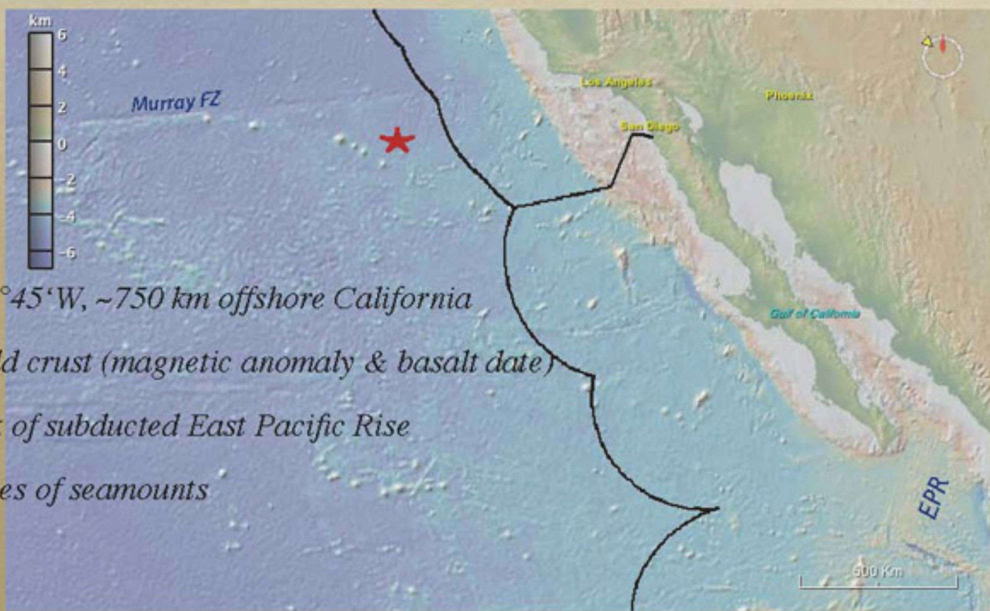

Comparison of refraction interfaces with reflection image
Local x-coordinate (km)
-15.0 -14.0 -13.0 -12.0 -11.0 -10.0 -9.0 -8.0 -7.0 -6.0 -5.0 -4.0 -3.0 -2.0 -1.0 -0.0 1.0 2.0 3.0 4.0 5.0 6.0 7.0 8.0 9.0 10.0 11.0 12.0 13.0 14.0 15.0
5.0
6.0
7.0
4/29/10 FK migration/gain odp21 grid 3
Predictions Model odp-area3-2-6, cleaned picks

"Deep Tow" Site: ~30 Myr Old Crust off Southern California



Summary by Donna Blackman
Scripps Institution of Oceanography

"Deep Tow" Location



32°25'N 125°45'W, ~750 km offshore California

31-32 Myr old crust (magnetic anomaly & basalt date)

western flank of subducted East Pacific Rise

north of series of seamounts

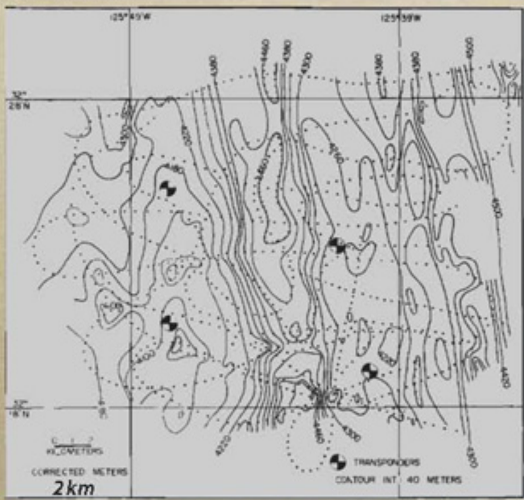
What is Known About Site?

Luyendyk, Geological Society of America Bulletin, v 81, p2237, 1970

- *Deep-Tow geophysical package*
- *sonar (sidescan & bathymetry)*
- *3.5 kHz profiler*
- *35 mm camera*
- *magnetometer*
- *airgun seismics (sediment profiling)*

Coverage

- *2 Abyssal Hills and intervening trough*
- *area ~30x20 km transected by several lines (dotted)*



shipboard bathymetry (40-m contour interval)

Local Geology of Site

EPR spreading rate during formation similar to R2K 9°N site (11 mm/yr, full rate)

Deep-tow data used to infer different origins for the 2 abyssal hills

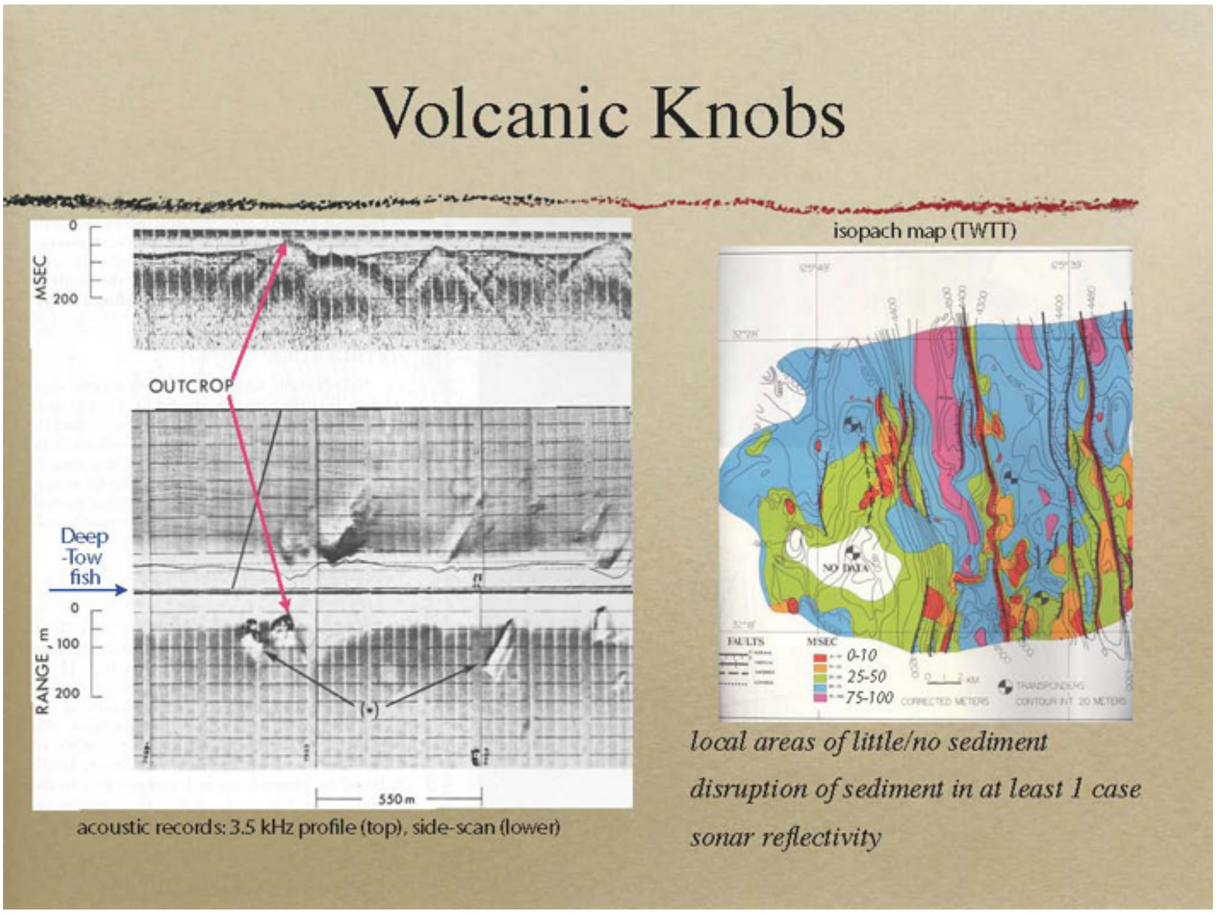
- *eastern hill- fault-controlled horst block (overlying sediment reflector offsets)*
- *western hill- elongate volcanic shield (morphology, basement reflectors)*

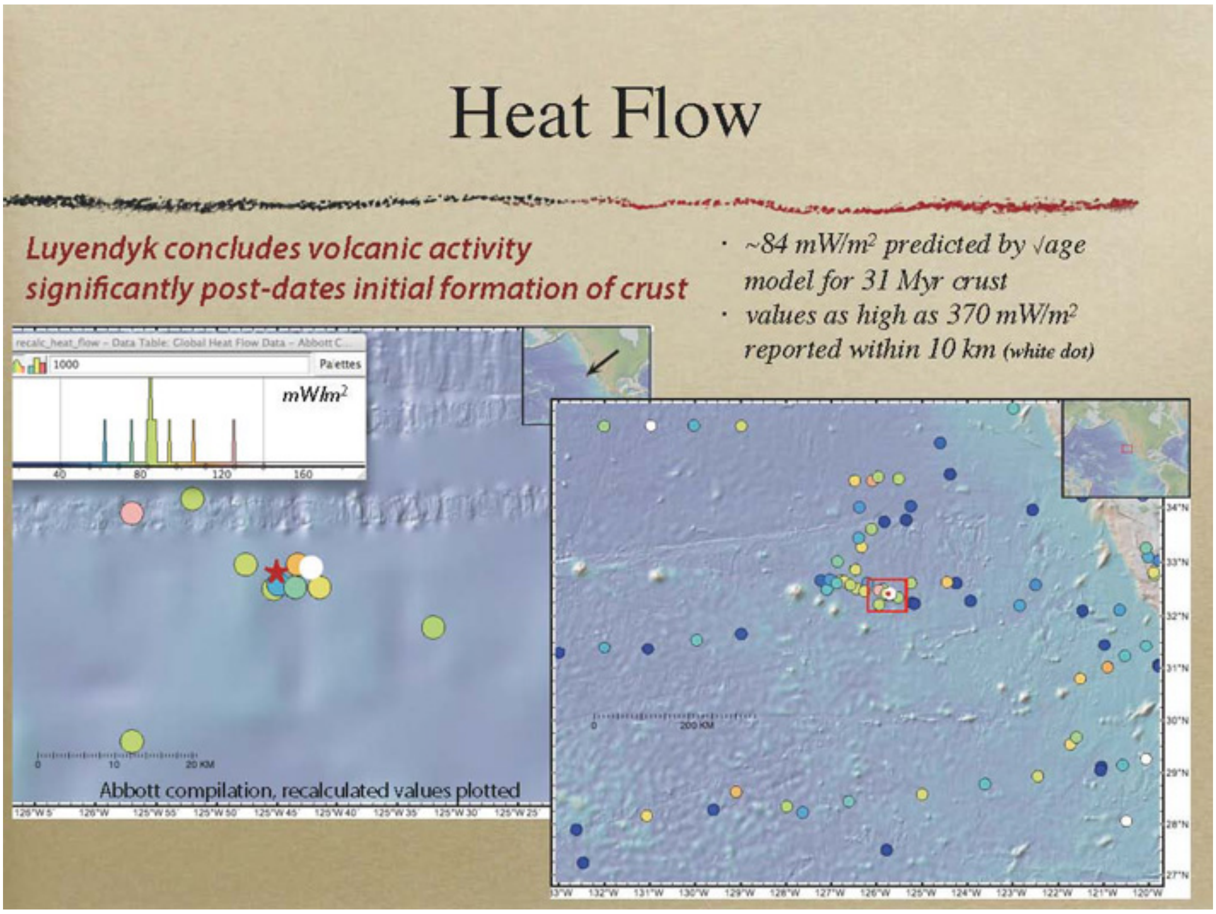
Sediment

- *40-60 m thick*
- *thin, continuous reflections- 10's cm thick volcanic ash (piston core & dredge)*
- *post-deposition offsets, basement abutments overlain by unconformity >> faulting*

Figure 6. Three-dimensional scale model of the bathymetry mapped in Figure 5. Each laminae represents 20 m. No vertical exaggeration. Bar at lower right of model is 2 km long. Model courtesy of G. Sheary, Bethlehem Steel Corporation.

model uses Deep-Tow high resolution bathymetry & illustrates different character of east/west abyssal hill


Volcanic Knobs
MSEC
OUTCROP
Deep -Tow fish
RANGE, m
550 m
acoustic records: 3.5 kHz profile (top), side-scan (lower)
isopach map (TWTT)
NO DATA
FAULTS
MSEC
0-10
25-50
75-100
local areas of little/no sediment
disruption of sediment in at least 1 case
sonar reflectivity


Heat Flow
Luyendyk concludes volcanic activity significantly post-dates initial formation of crust
~84 mW/m² predicted by √age model for 31 Myr crust
values as high as 370 mW/m² reported within 10 km (white dot)
mW/m²
Abbott compilation, recalculated values plotted
200 KM
20 KM

Inferred Structure

Luyendyk, 1970

faulting & later volcanism begin ~10 m.y. ago (sedimentation rate, angular rock on sediment)

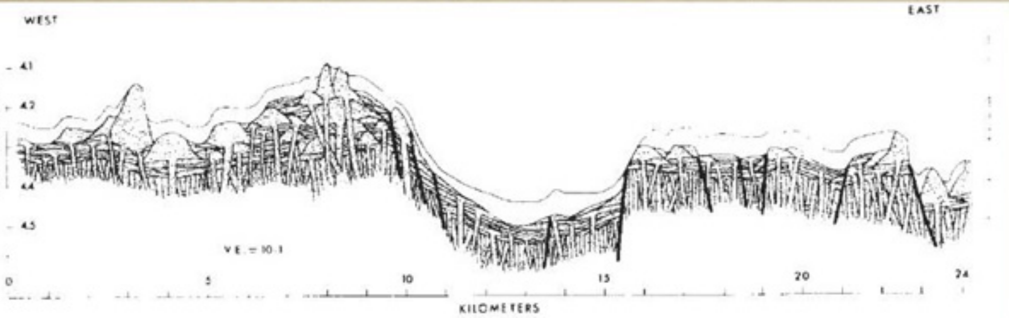
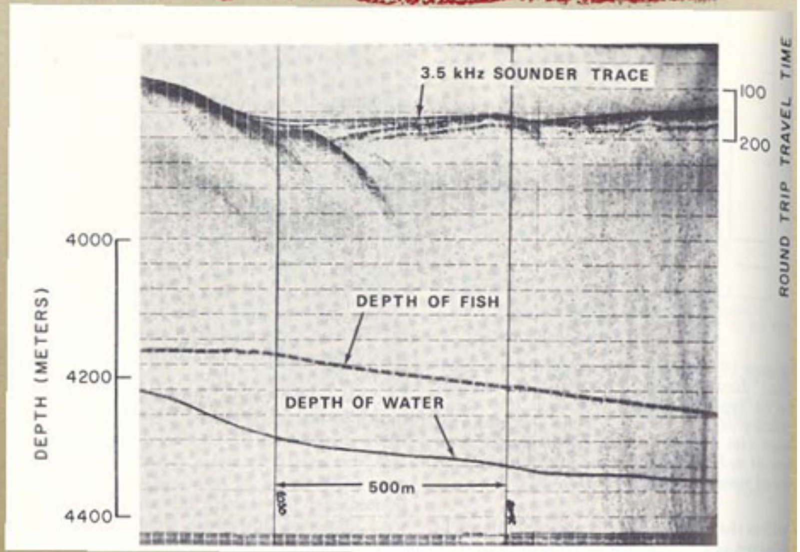


Figure 24. A model of the formation of the abyssal hills in the study area. The western hill formed primarily from volcanic activity at the crest of the East Pacific Rise, and is probably representative of other hills that have been formed at the crest of a steadily spreading rise. The eastern hill has been created, and the western hill modified, by faulting of the oceanic crust long after the crust was formed. The sediment structure is a generalized cross section across the area. The upper section of the second layer is shown diagrammatically here as a complex of vertical dikes with a thin veneer of volcanic effusives on its surface. Vertical exaggeration is times 10; the sound velocity in the sediment is assumed to be 1.5 km/sec.

Supporting Figures (Luyendyk, 1970)

Figure 20. Scattered angular rocks seen on the east slope of the volcanic hill (Fig. 11). The width of the field of view is between 8 and 9 m.



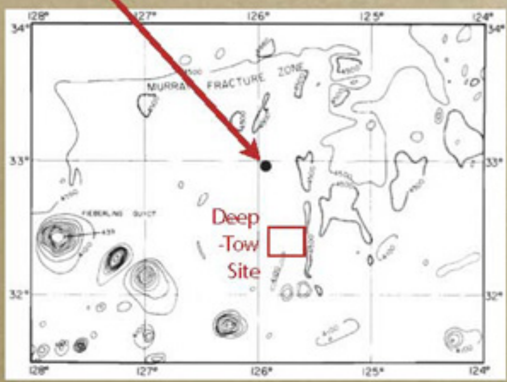
interpreted as lava fragments

sediment abuts basement of eastern hill, is overlain unconformably

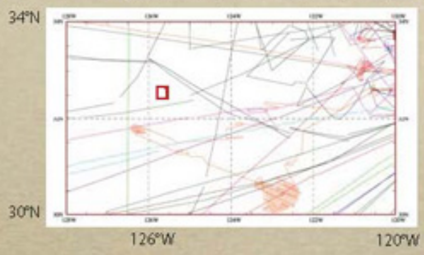
Other Studies in the Vicinity

G. Shor refraction measurement, 70 km NW

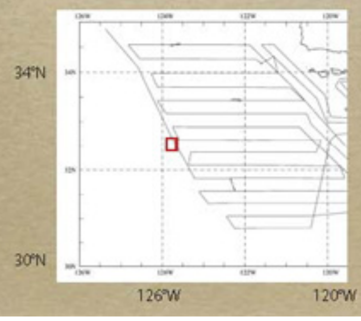
Layer	Velocity (km/s)	Thickness (km)	Depth (km)
0	1.502	4.28	–
1	2.15	0.37	4.28
2	5.68	0.82	4.65
3	6.82	4.62	5.47
4	7.91	–	10.09



Seismic Reflection (NGDC, mostly single channel)



Seismic Refraction (USGS 1984, probably sonobuoy)



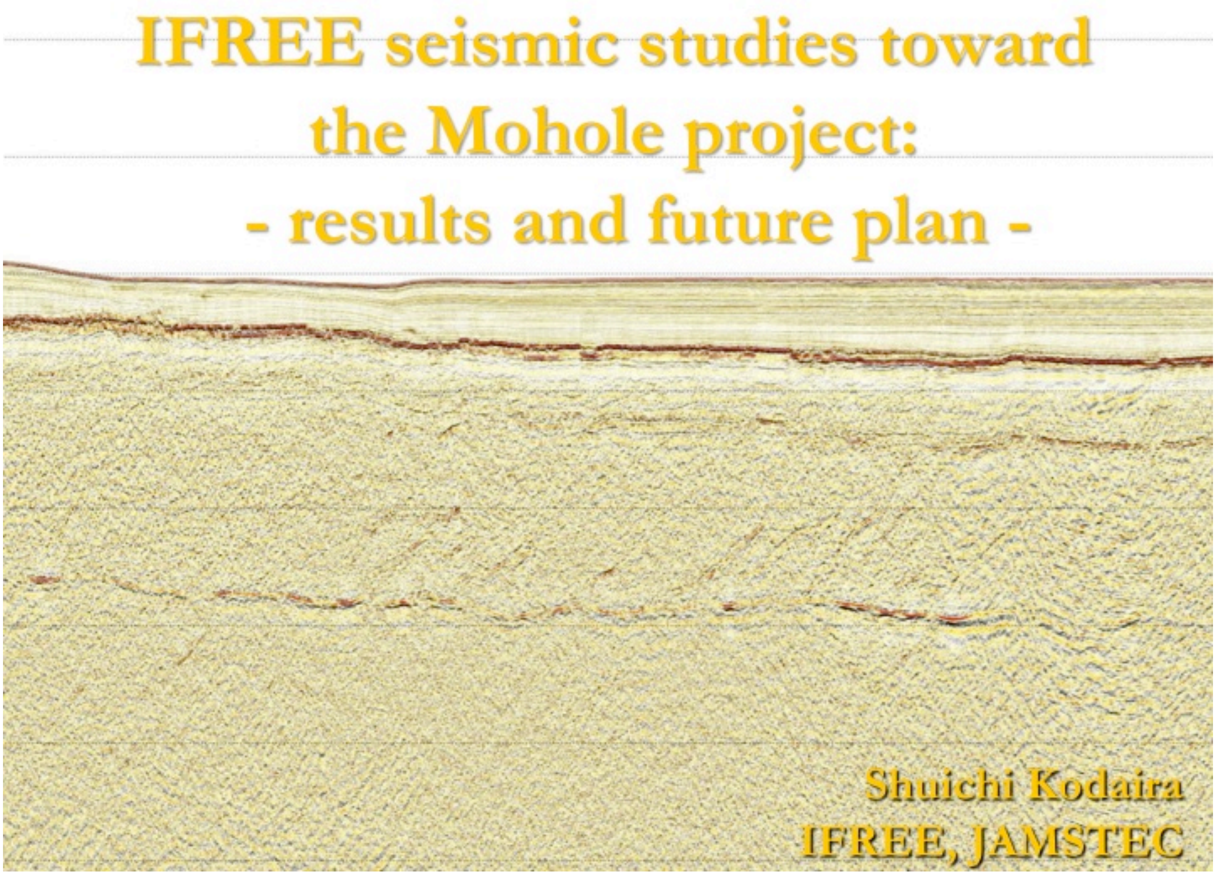
Remarks

coverage of the Deep-Tow site is not up to modern-day standards but some worthwhile information is available:

> *documentation of local bathymetry and stratigraphy is sufficient and indication of seafloor character (photos) is OK*
>
> *available heat flow and occurrence of basement knobs, inferred to be volcanic, raises serious concern*
>
> > *if Luyendyk estimate of activity, ~10 m.y. and perhaps continuing, is correct thermal structure may be hotter than typical for 30 Myr crust*

a single measure of "typical" Moho depth, determined using constant-layer modeling (not gradients) that is 70 km away

no opportunity to place results into context of ridge evolution since spreading axis subducted



Strategy and Plan

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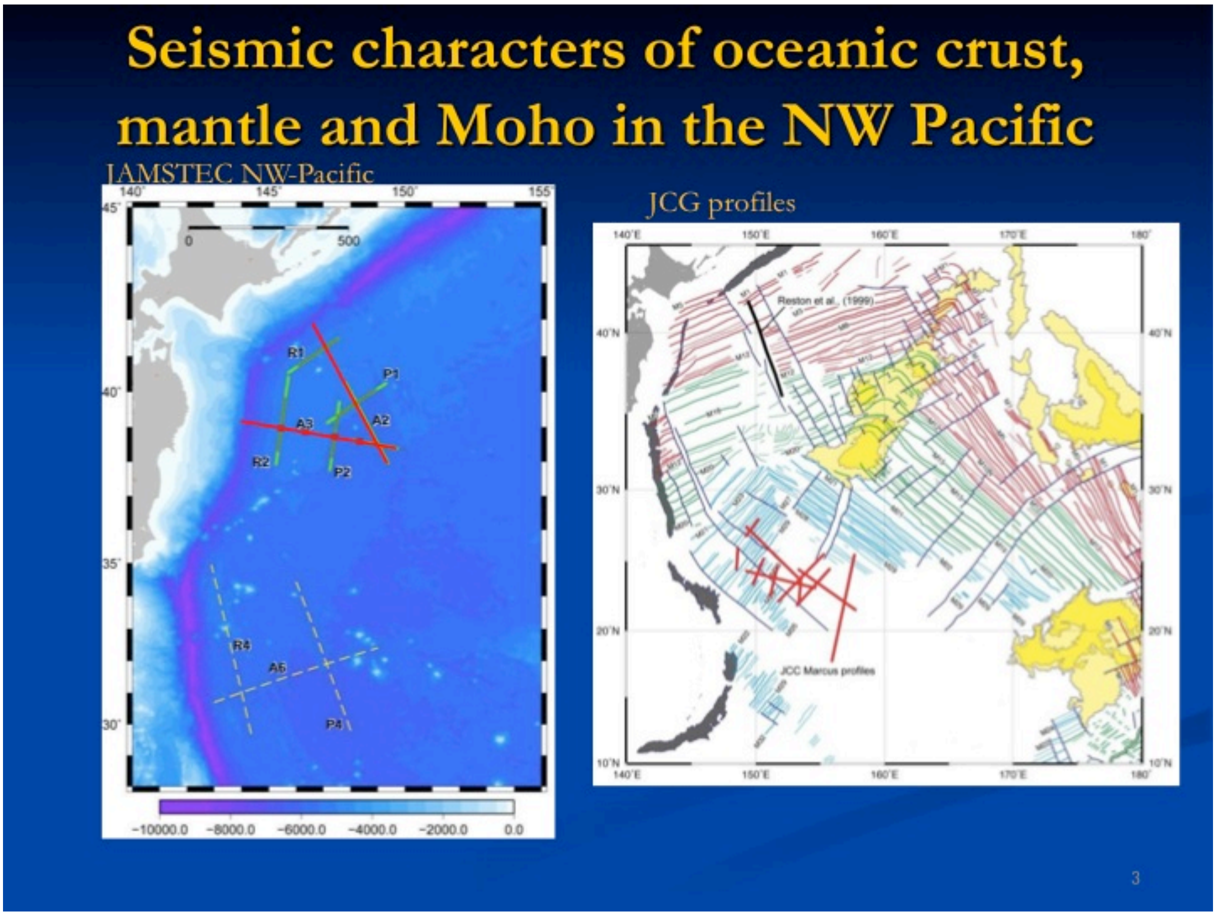
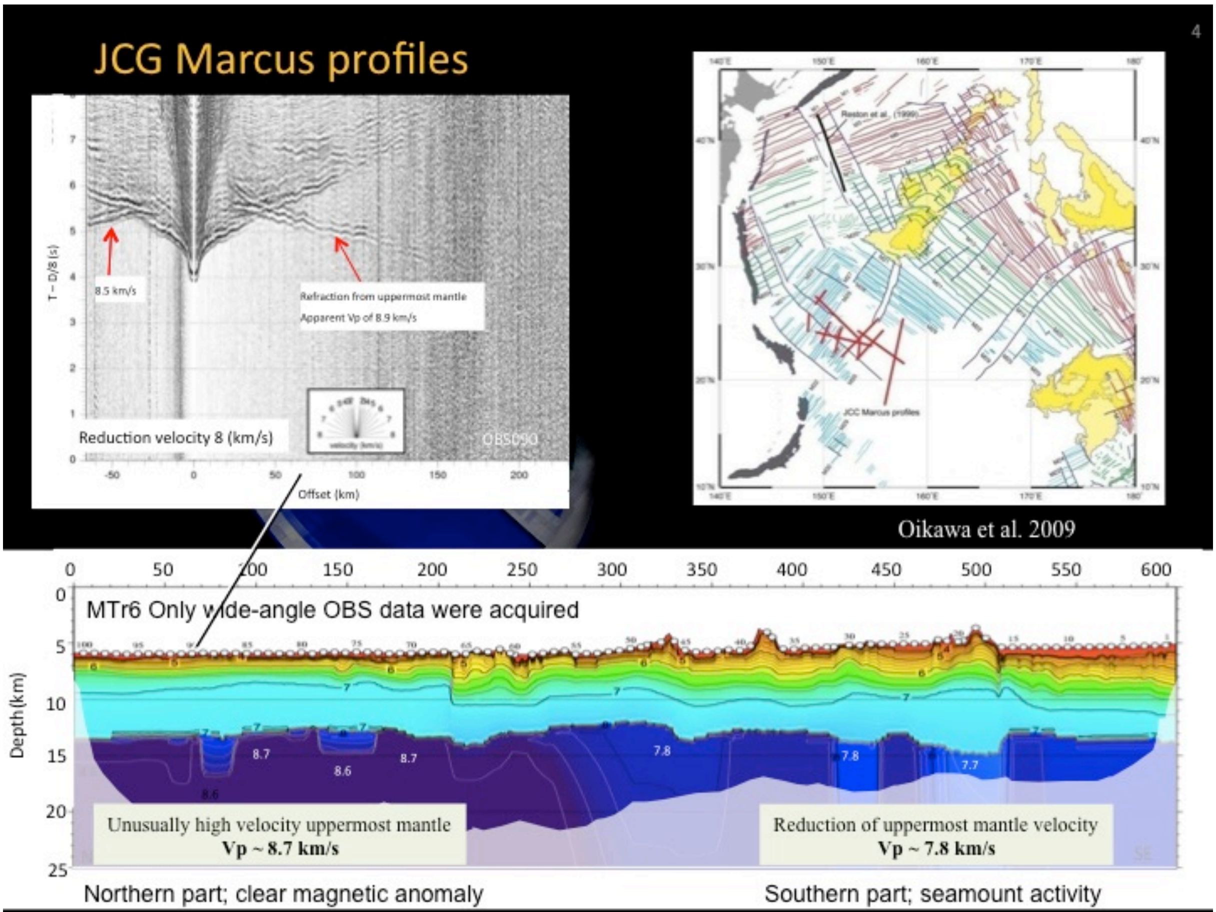
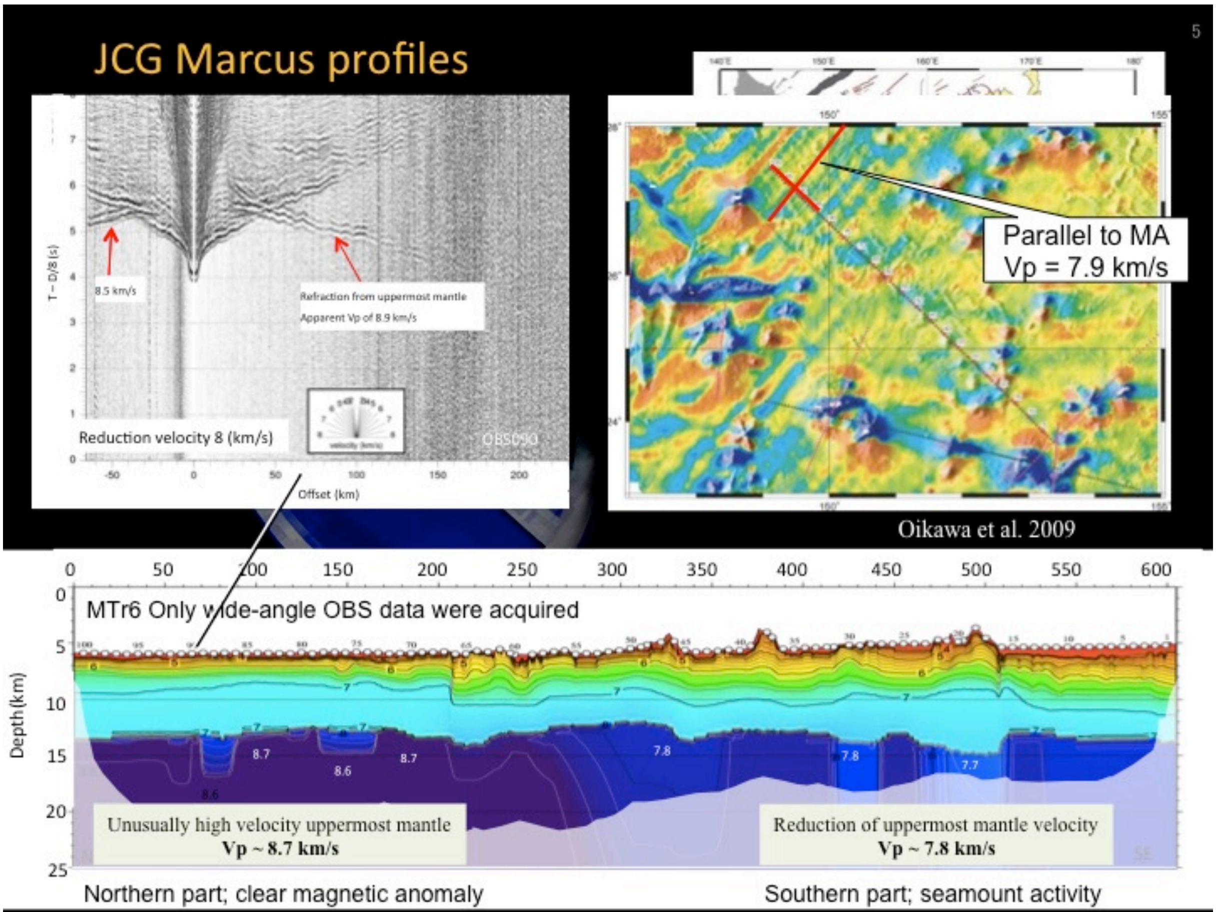
2


Seismic characters of oceanic crust, mantle and Moho in the NW Pacific
JAMSTEC NW-Pacific
R1
P1
A3
A2
R2
P2
R4
A6
P4
JCG profiles
Reston et al. (1999)
JCG Marcus profiles
3


JCG Marcus profiles
4
8.5 km/s
Refraction from uppermost mantle
Apparent Vp of 8.9 km/s
Reduction velocity 8 (km/s)
Offset (km)
T - D/8 (s)
Oikawa et al. 2009
MTr6 Only wide-angle OBS data were acquired
Depth (km)
Unusually high velocity uppermost mantle
Vp ~ 8.7 km/s
Reduction of uppermost mantle velocity
Vp ~ 7.8 km/s
Northern part; clear magnetic anomaly
Southern part; seamount activity


JCG Marcus profiles
8.5 km/s
Refraction from uppermost mantle
Apparent Vp of 8.9 km/s
Reduction velocity 8 (km/s)
Offset (km)
Parallel to MA
Vp = 7.9 km/s
Oikawa et al. 2009
MTr6 Only wide-angle OBS data were acquired
Depth (km)
Unusually high velocity uppermost mantle
Vp ~ 8.7 km/s
Reduction of uppermost mantle velocity
Vp ~ 7.8 km/s
Northern part; clear magnetic anomaly
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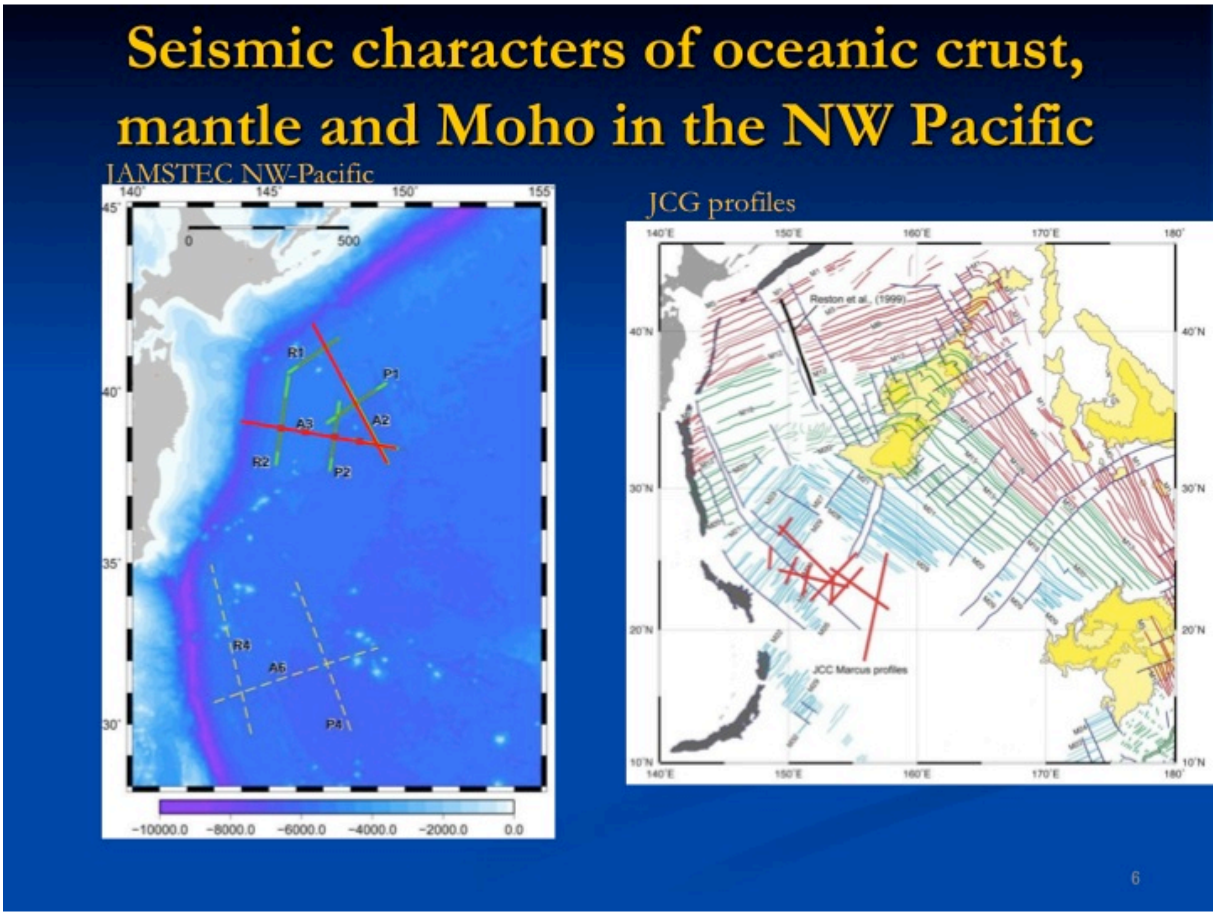
Seismic characters of oceanic crust, mantle and Moho in the NW Pacific
JAMSTEC NW-Pacific
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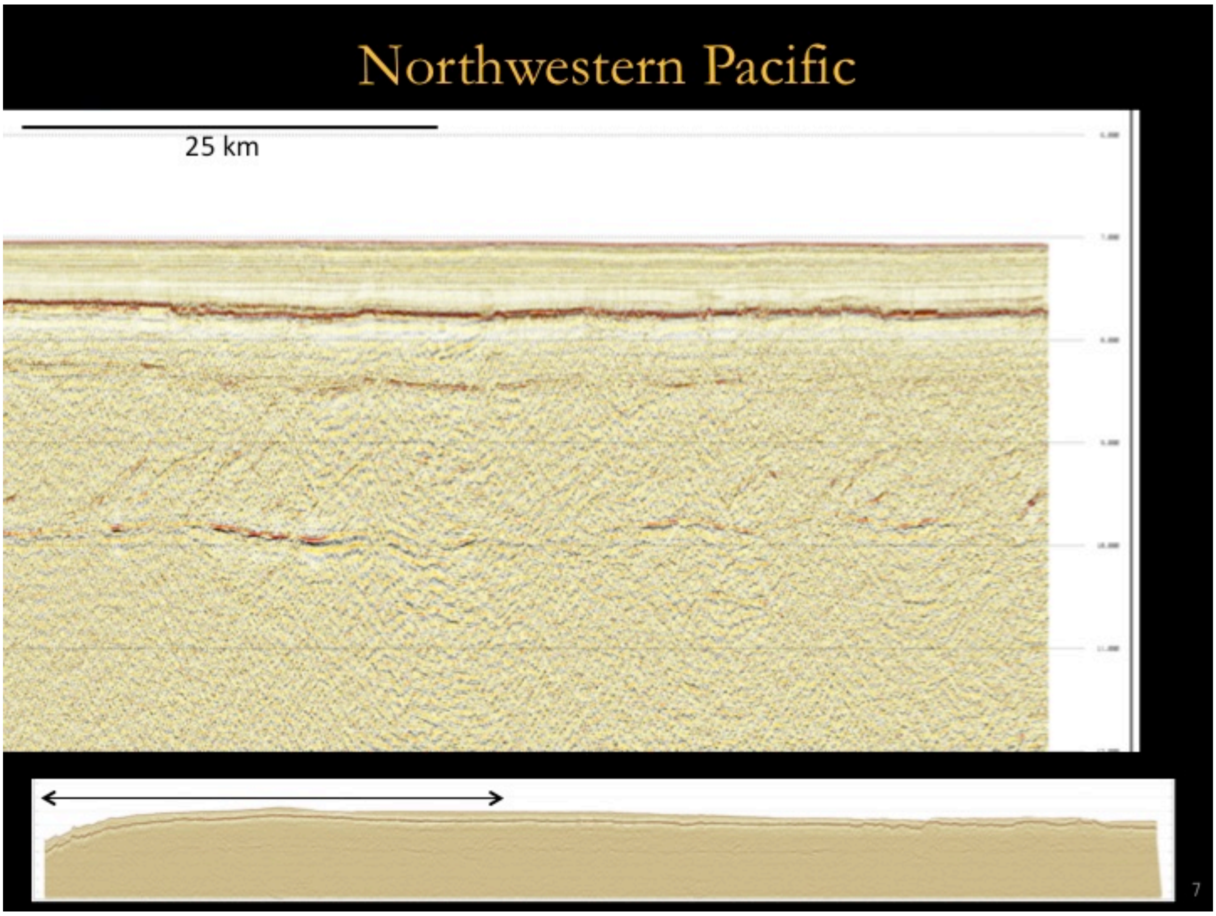
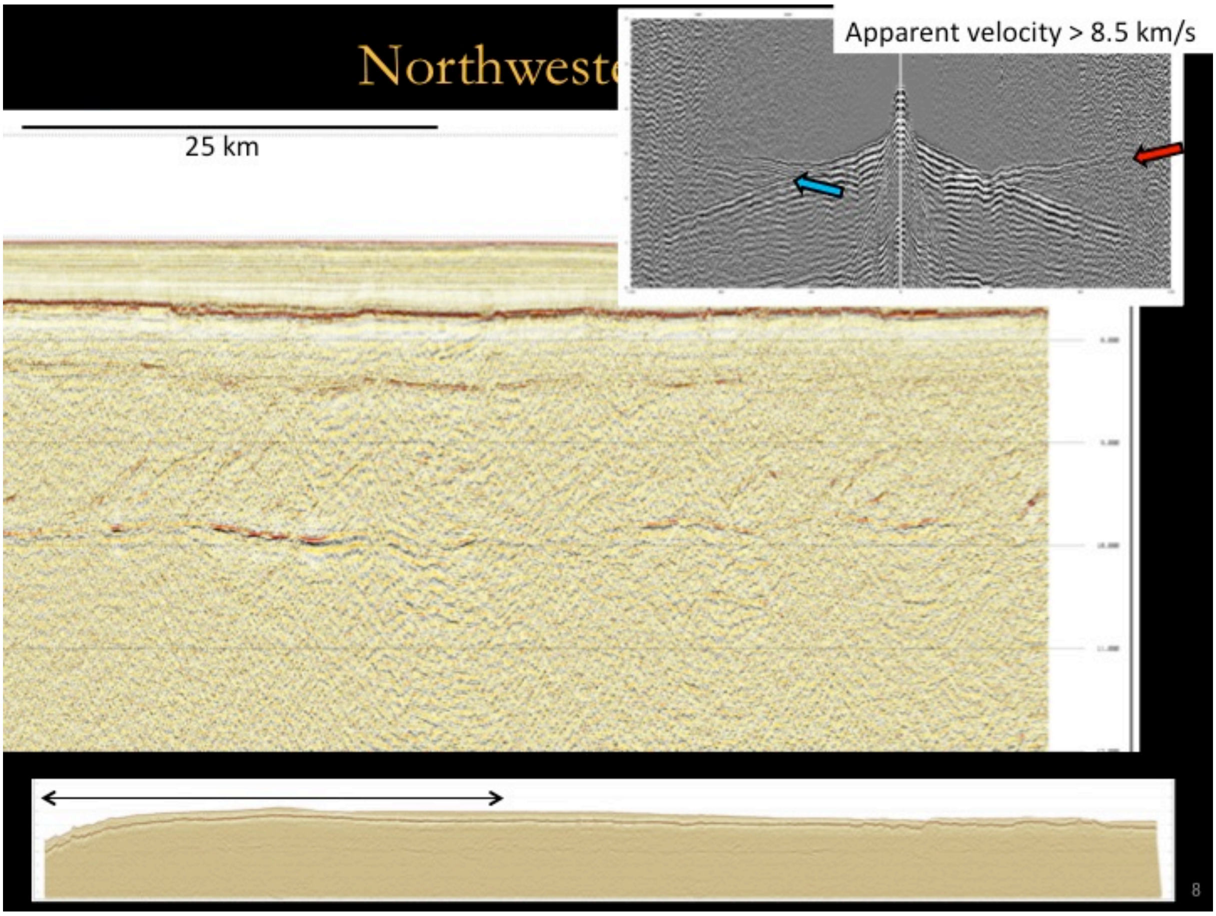
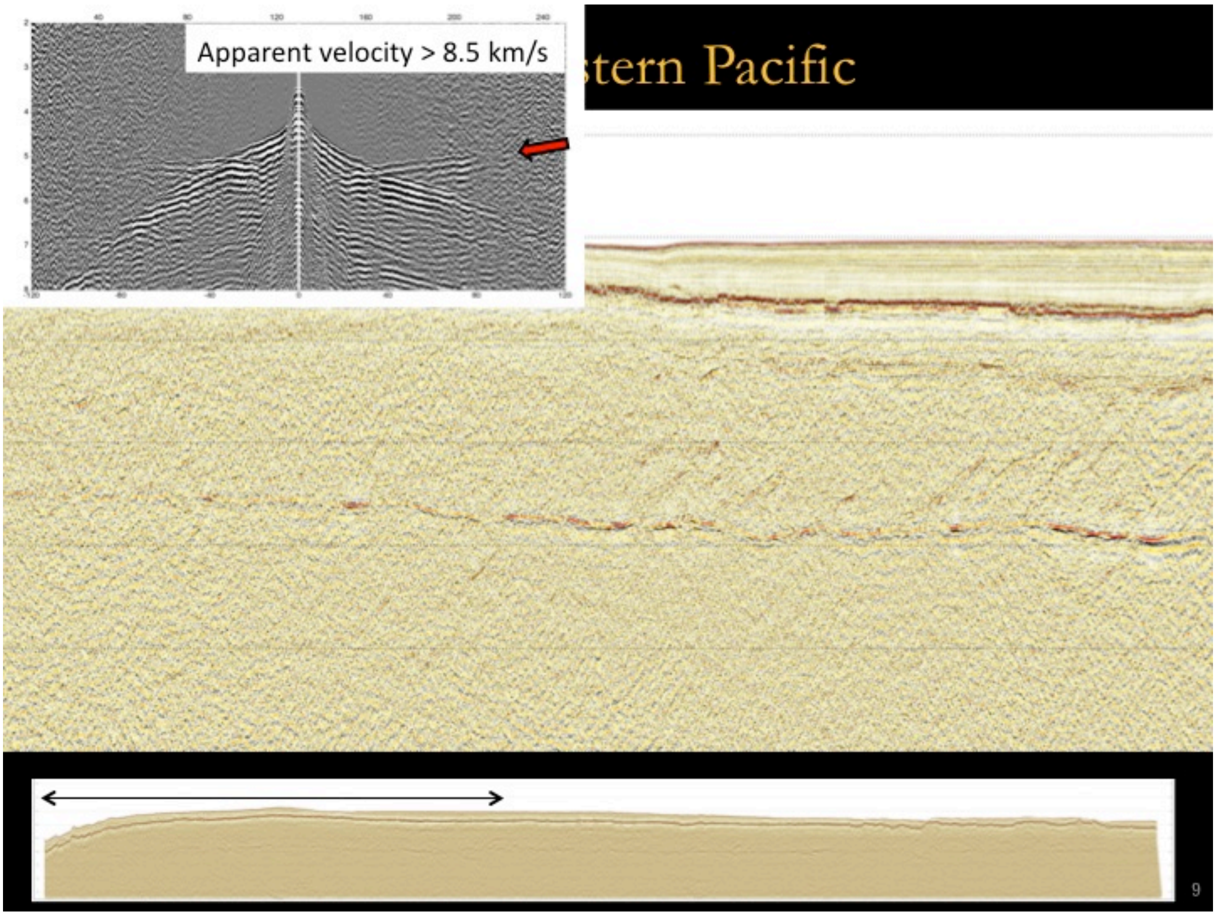
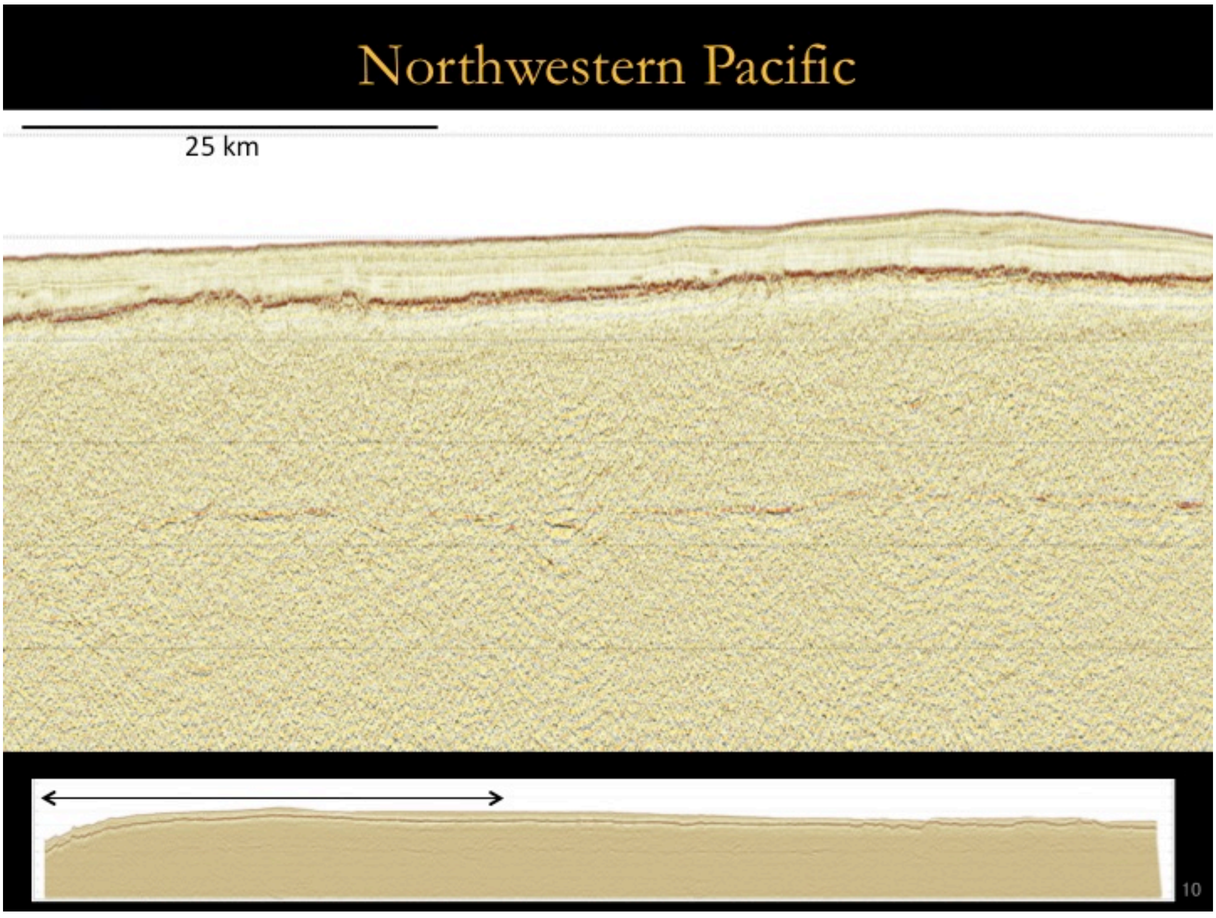
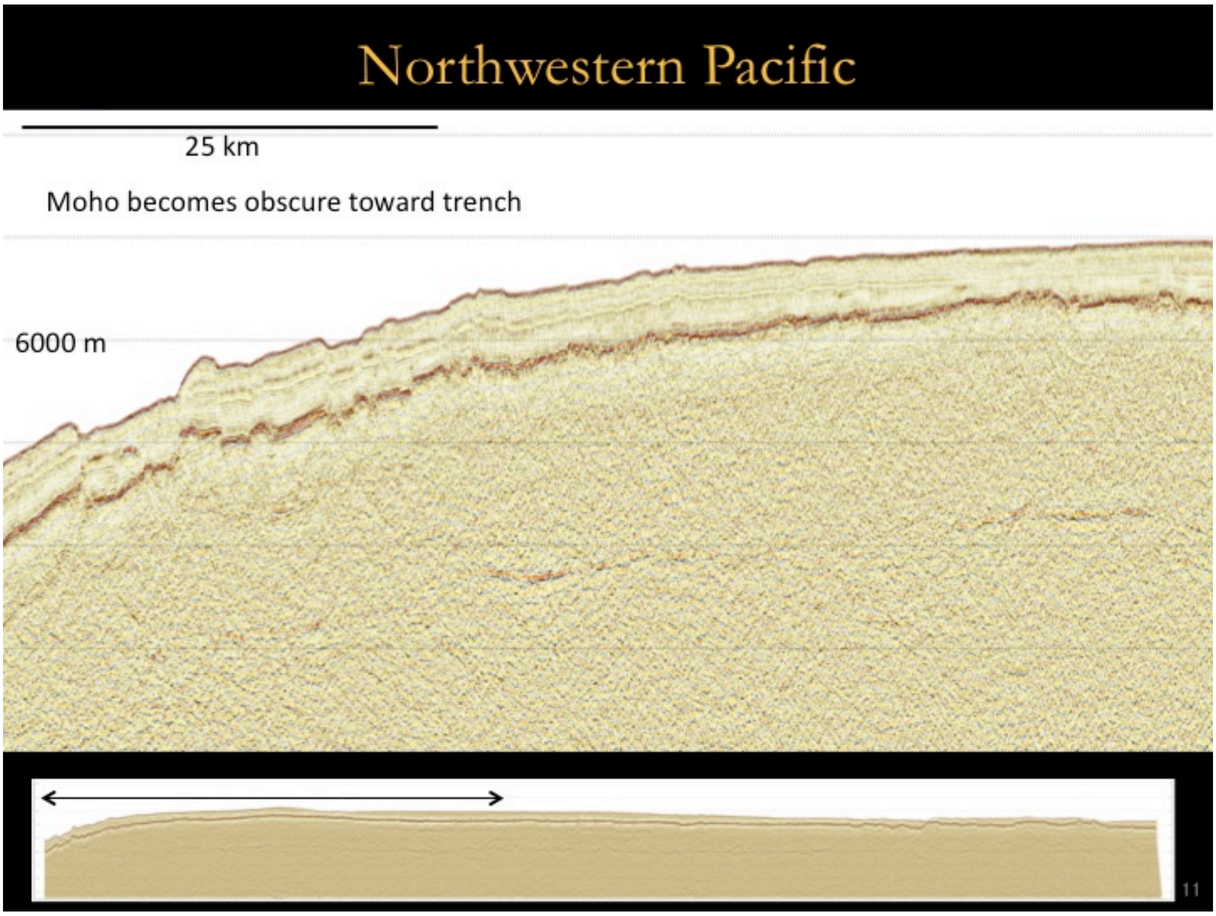
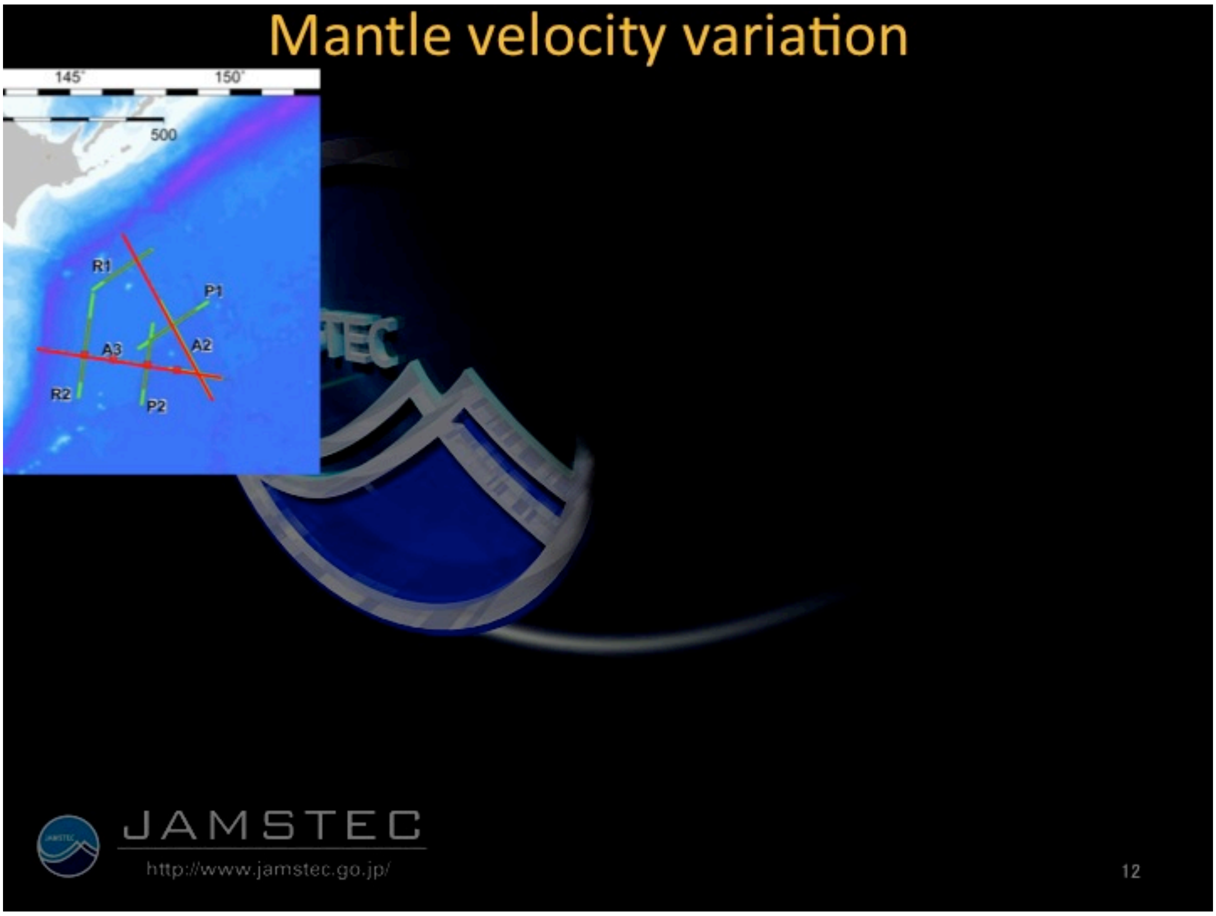

Northwestern Pacific
25 km
7

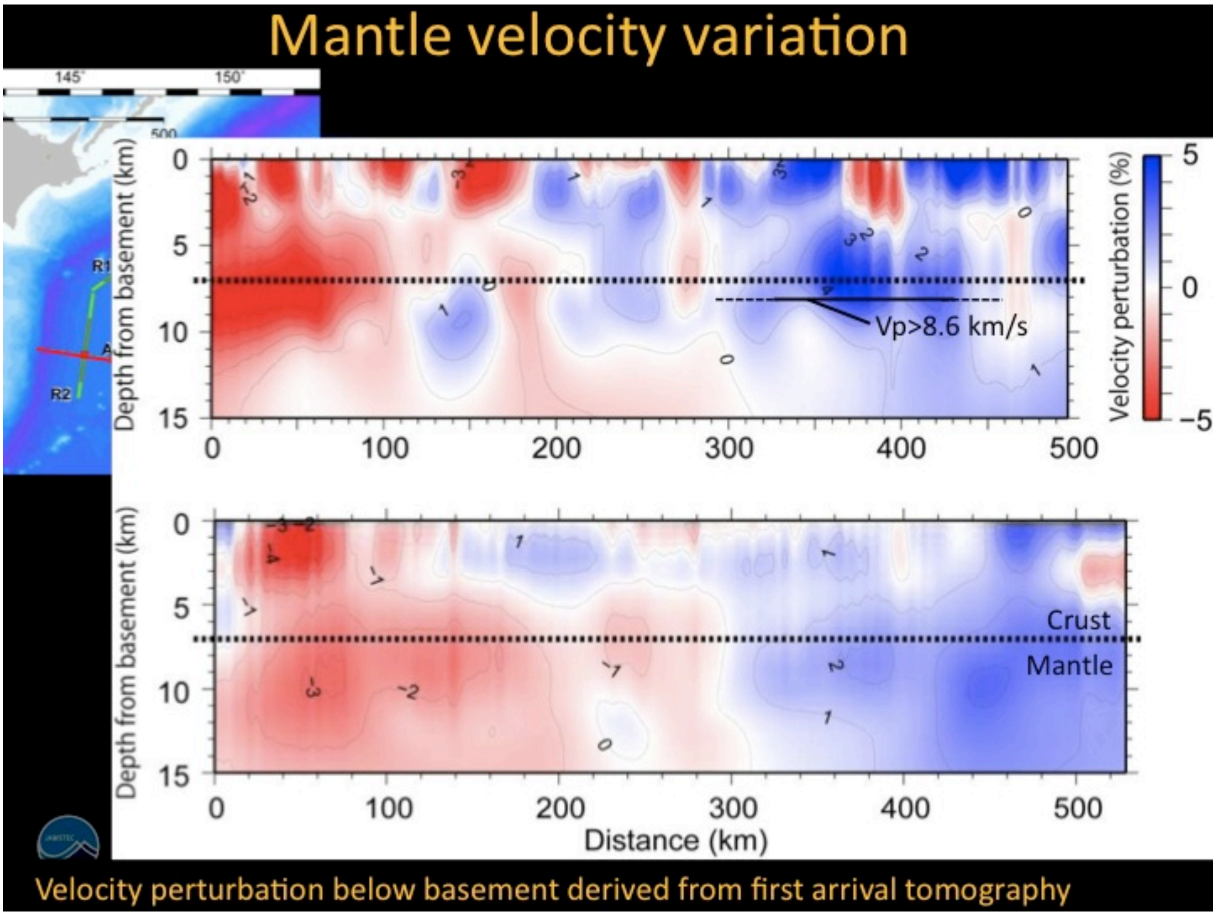

Northweste
Apparent velocity > 8.5 km/s
25 km
8

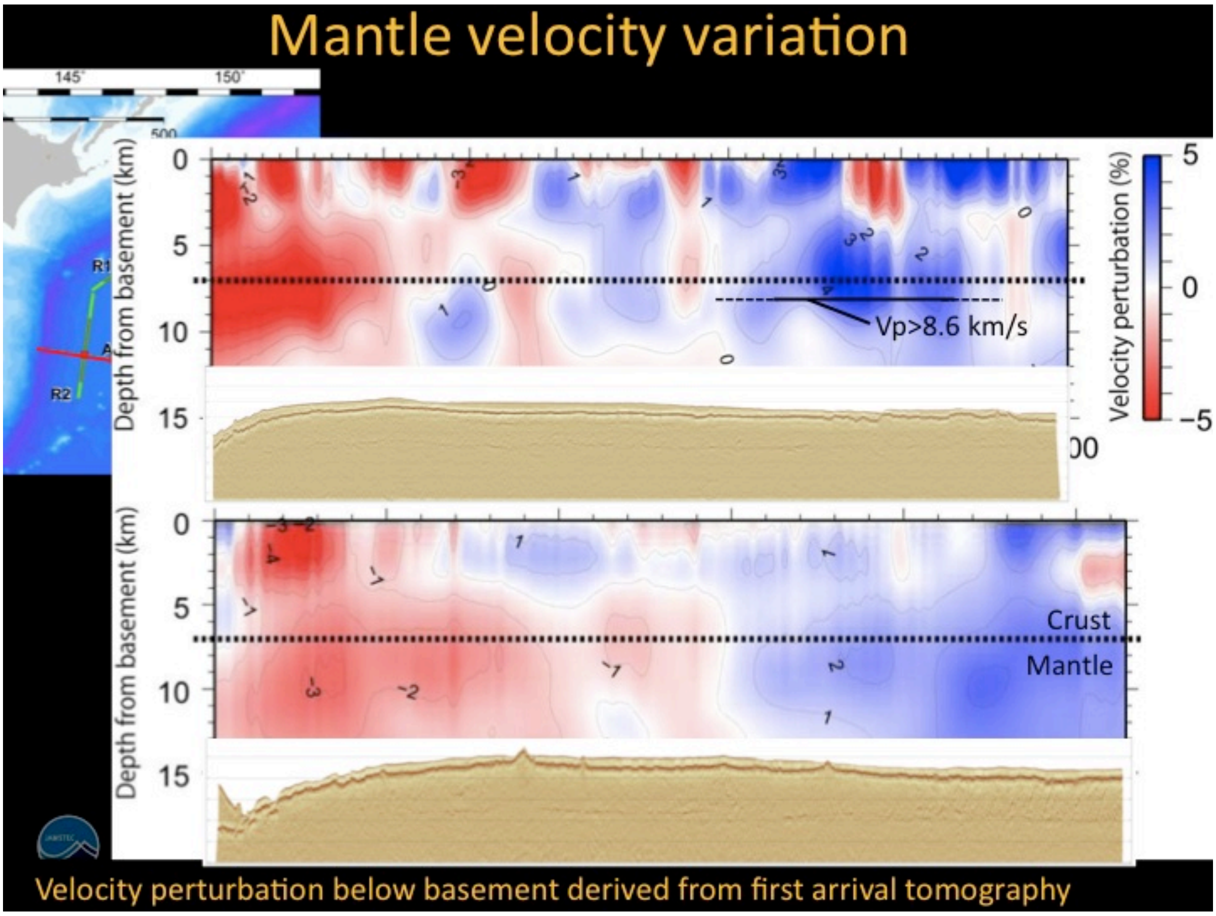

Apparent velocity > 8.5 km/s
stern Pacific
9


Northwestern Pacific
25 km
10


Northwestern Pacific
25 km
Moho becomes obscure toward trench
6000 m
11


Mantle velocity variation
145°
150°
500
R1
P1
A3
A2
R2
P2
JAMSTEC
http://www.jamstec.go.jp/
12


Mantle velocity variation
Depth from basement (km)
Velocity perturbation (%)
Vp>8.6 km/s
Crust
Mantle
Distance (km)
Velocity perturbation below basement derived from first arrival tomography


Mantle velocity variation
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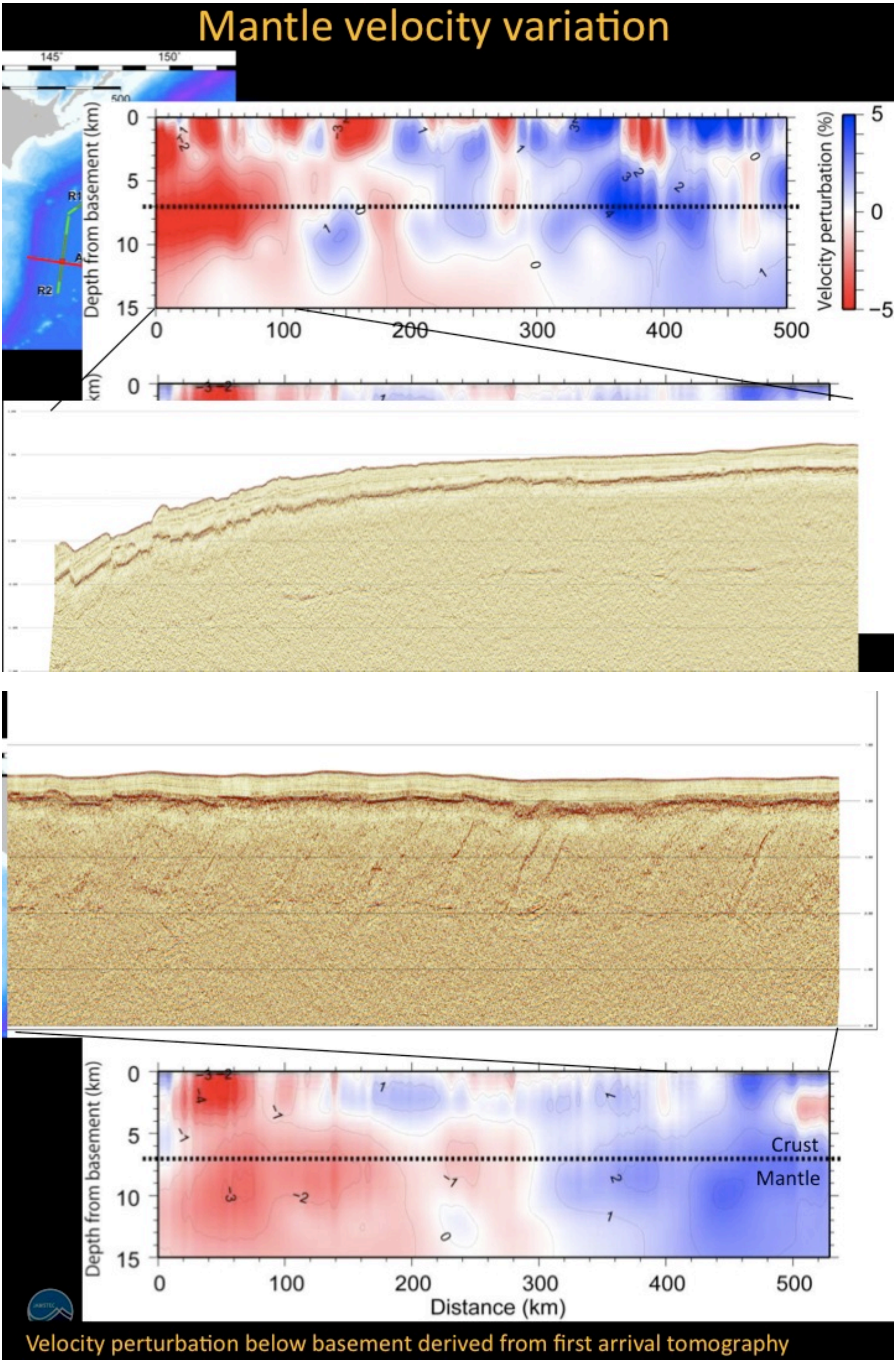
Crust
Mantle
Velocity perturbation below basement derived from first arrival tomography


Mantle velocity variation
Depth from basement (km)
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Mantle
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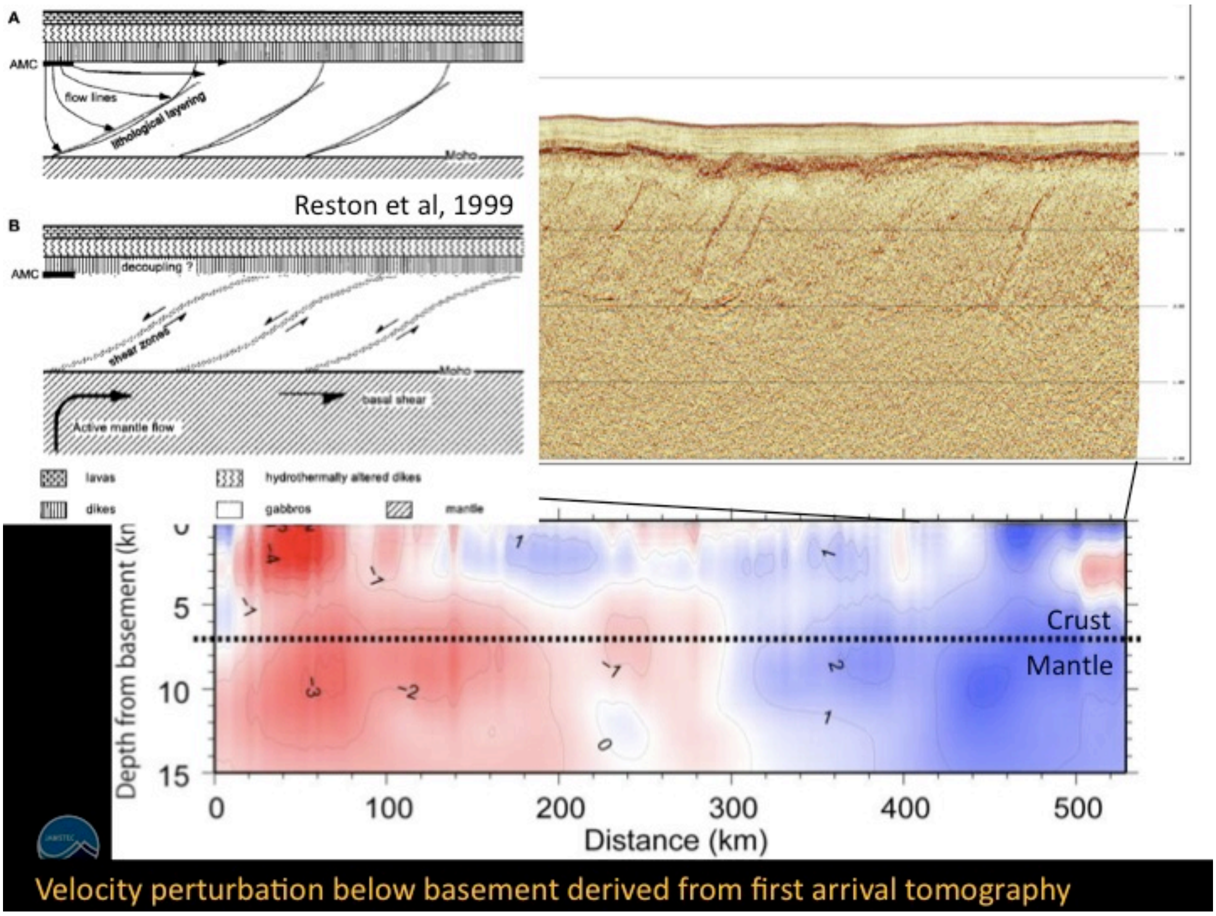
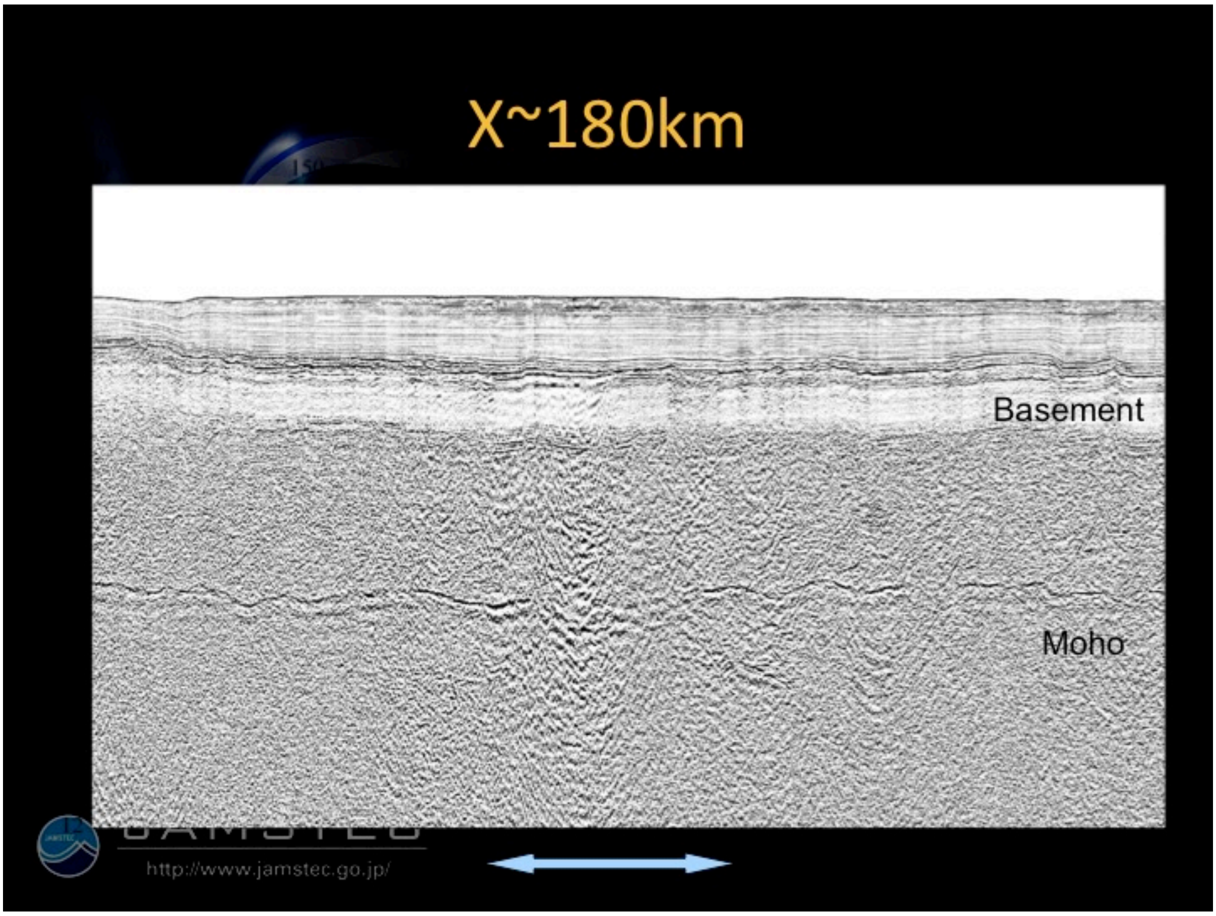
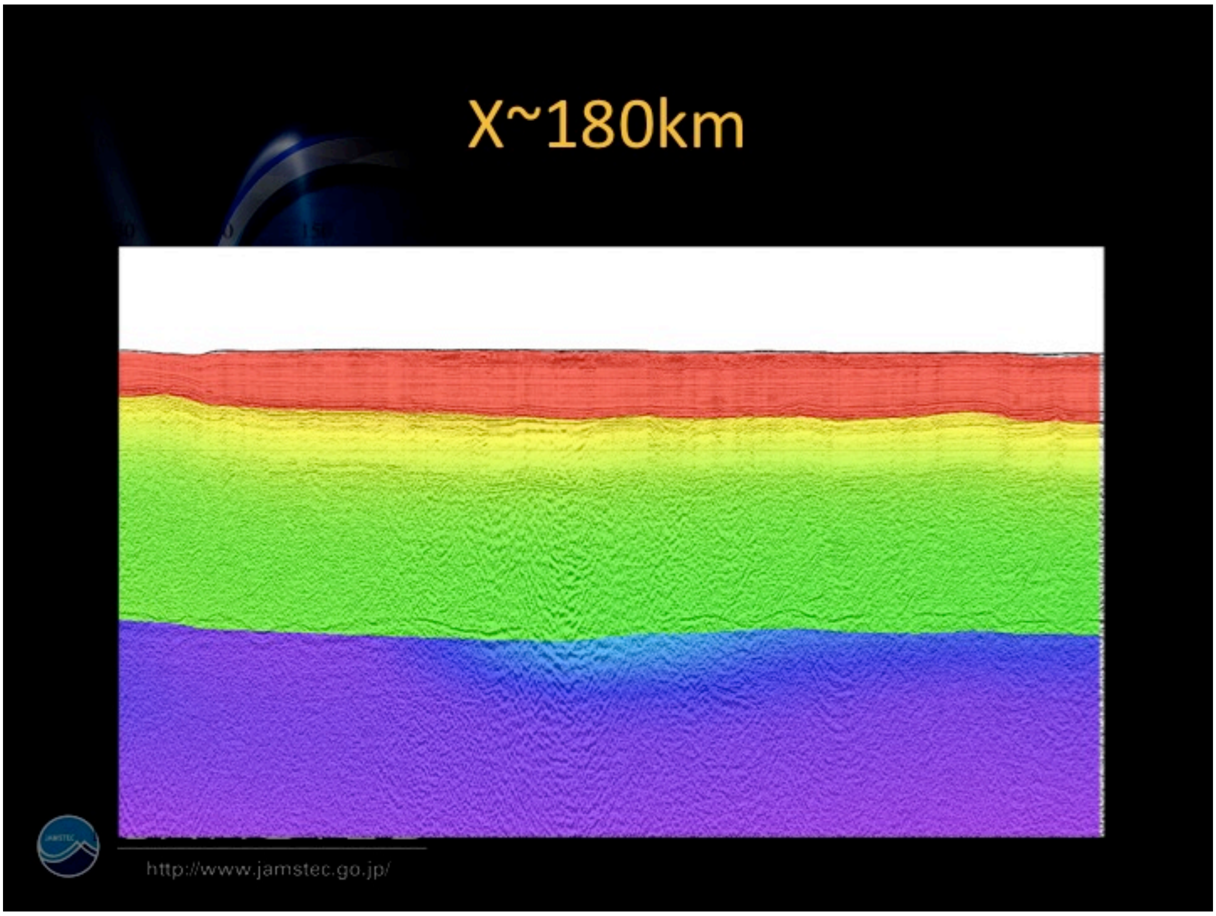
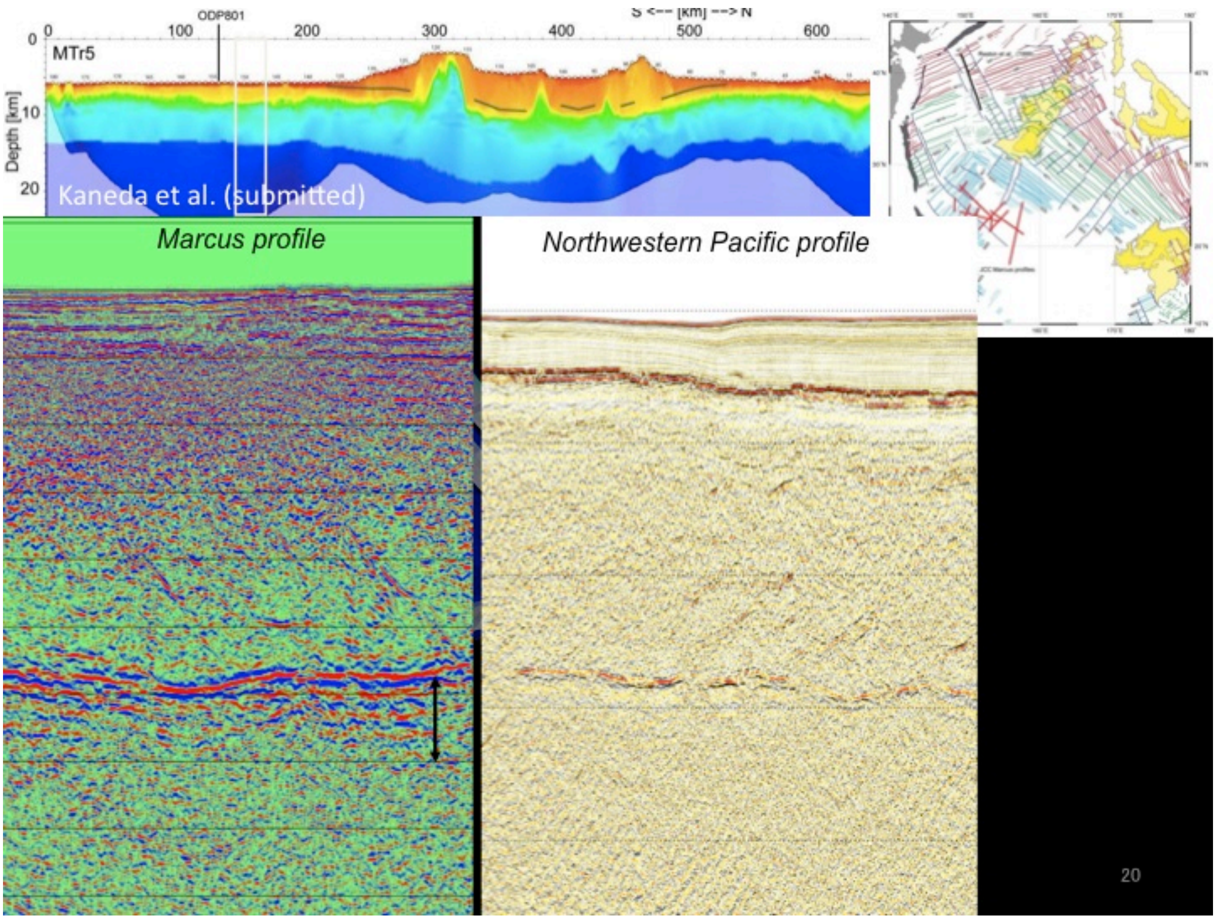
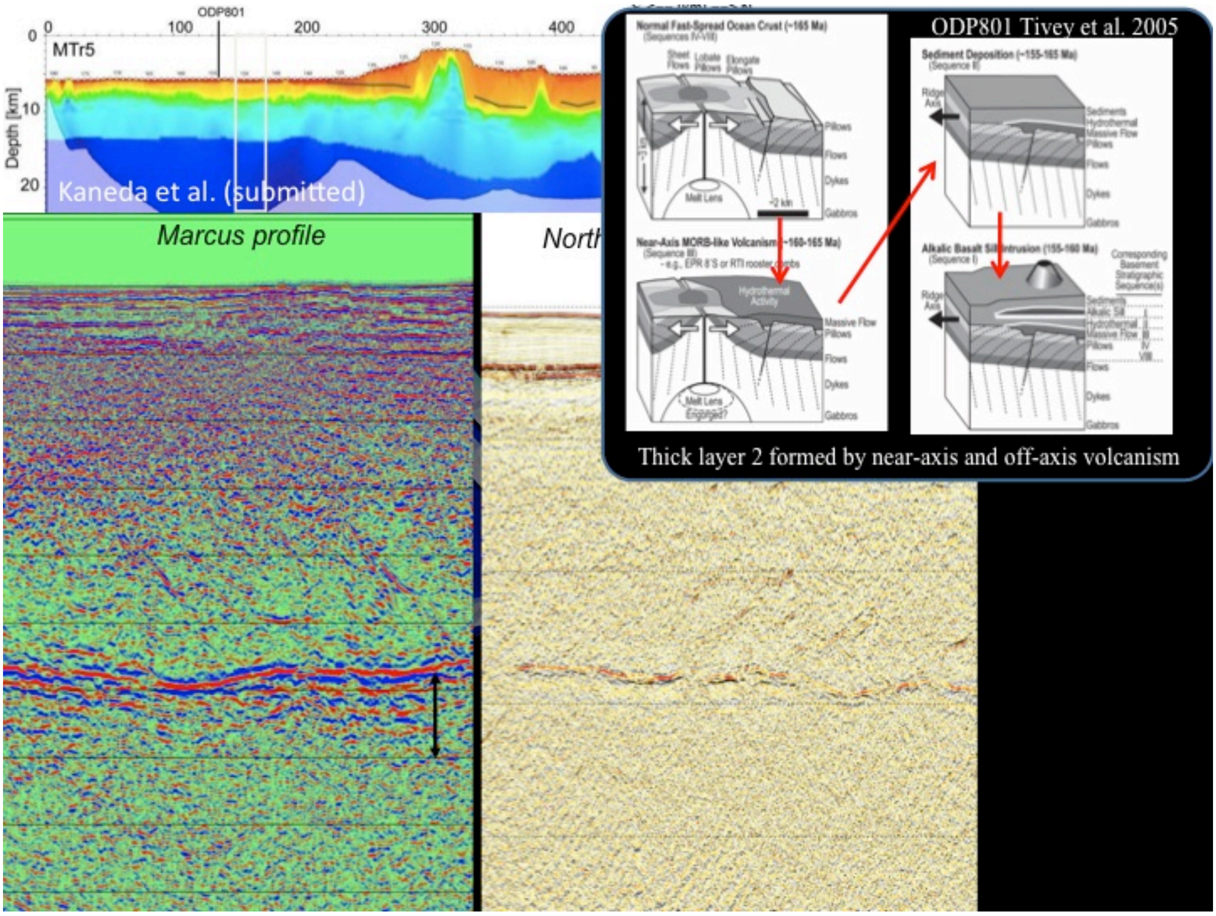
Velocity perturbation below basement derived from first arrival tomography


A
AMC
flow lines
lithological layering
Moho
Reston et al, 1999
B
AMC
decoupling ?
shear zones
Moho
basal shear
Active mantle flow
lavas
hydrothermally altered dikes
dikes
gabbros
mantle
Depth from basement (km)
Crust
Mantle
Distance (km)
Velocity perturbation below basement derived from first arrival tomography


X~180km
Basement
Moho
http://www.jamstec.go.jp/


X~180km
http://www.jamstec.go.jp/


ODP801
S <-- [km] --> N
0
100
200
300
400
500
600
MTr5
Depth [km]
10
20
Kaneda et al. (submitted)
Marcus profile
Northwestern Pacific profile
20



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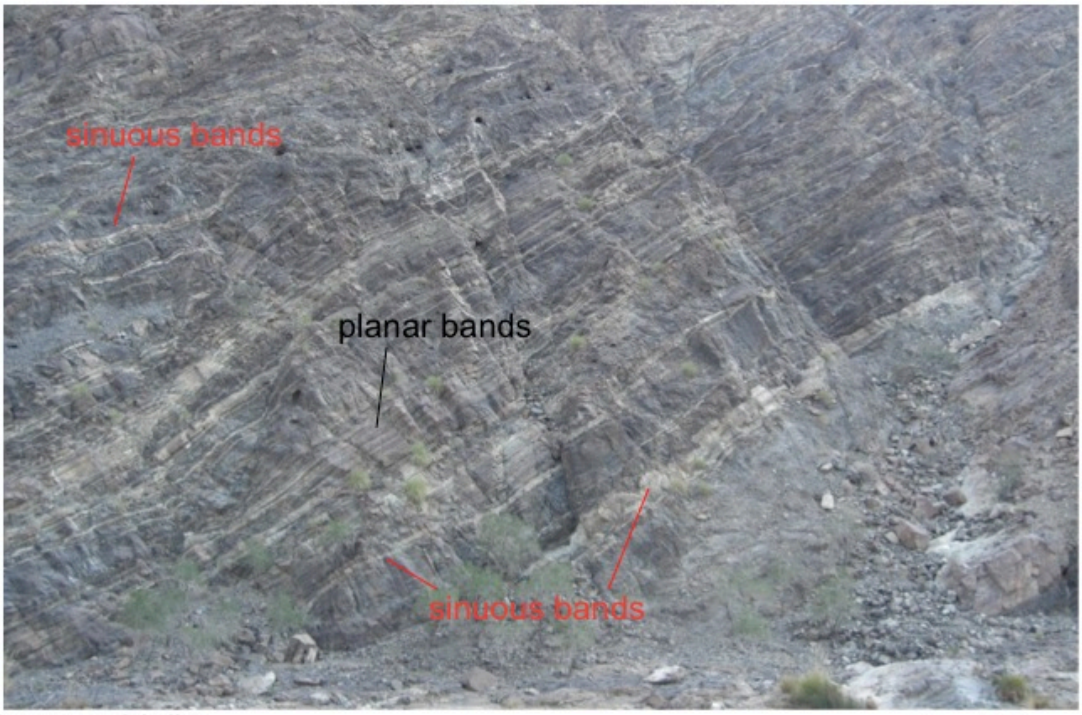
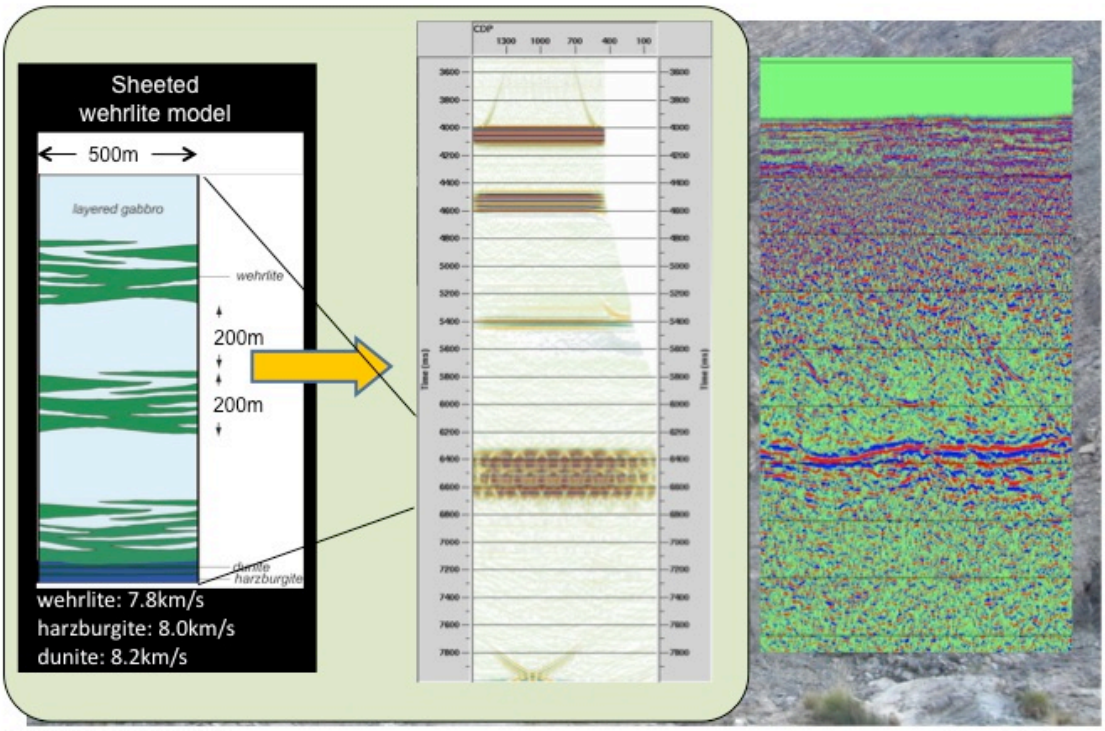
Modeling Moho reflection based on ophiolite



Oman ophiolite

Figure courtesy of Prof. S. Arai

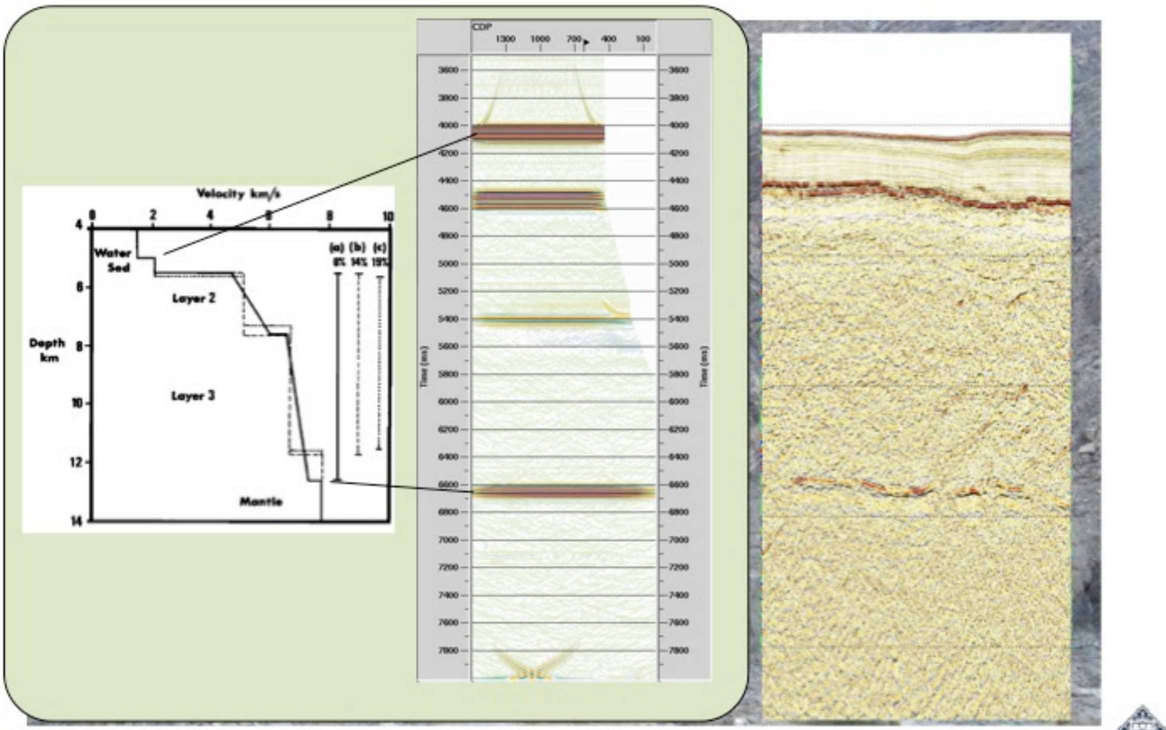
Modeling Moho reflection based on ophiolite



Oman ophiolite

Figure courtesy of Prof. S. Arai

Modeling Moho reflection based on ophiolite



Oman ophiolite

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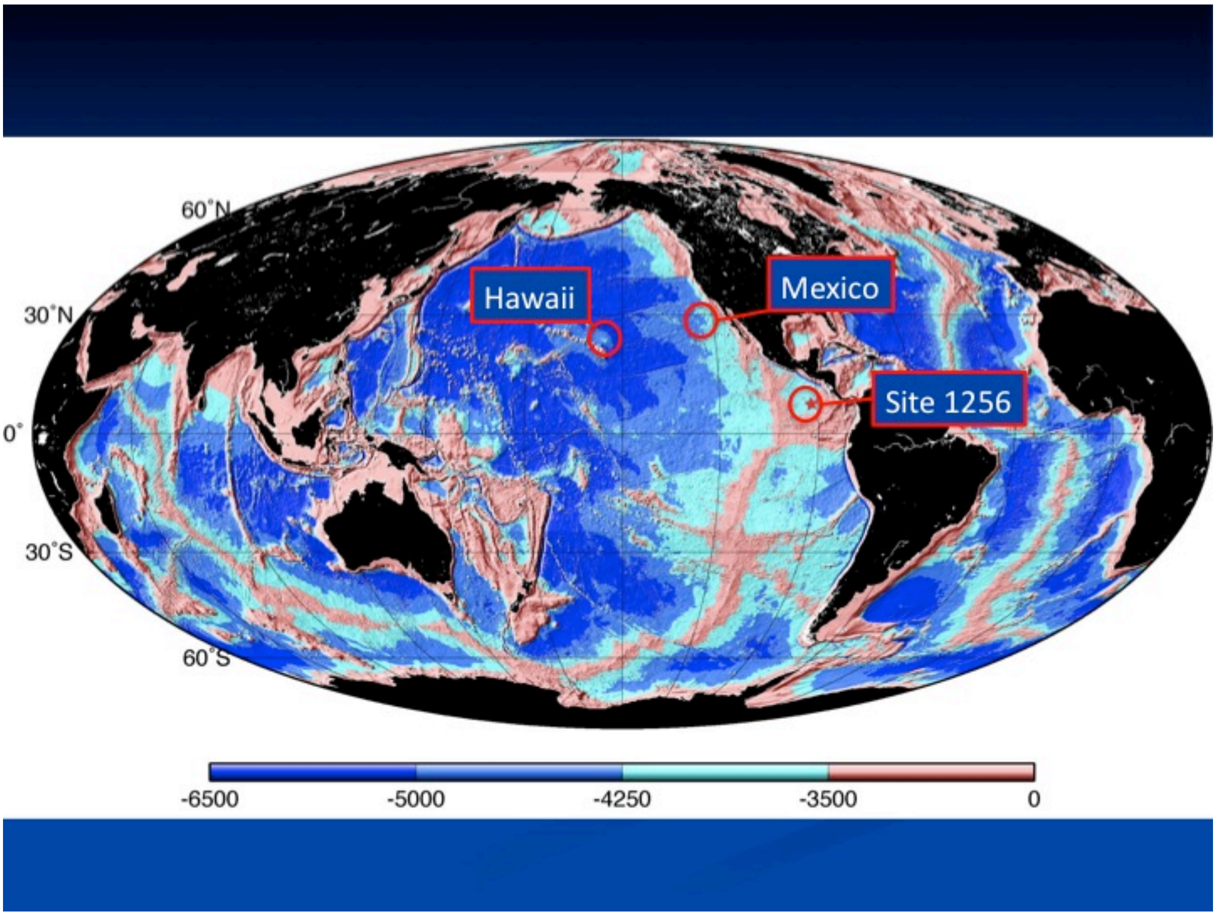
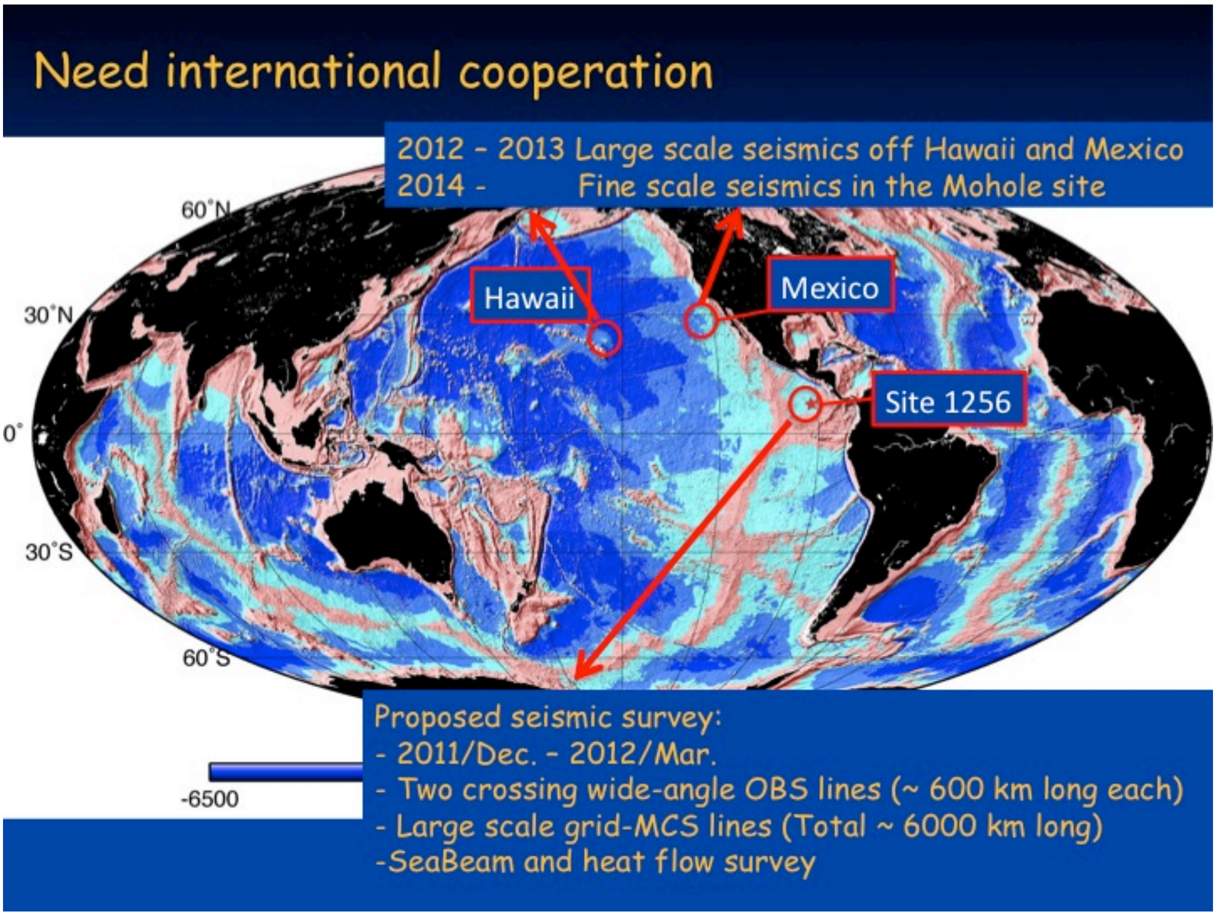
26


60°N
30°N
0°
30°S
60°S
Hawaii
Mexico
Site 1256
-6500
-5000
-4250
-3500
0


Need international cooperation
2012 – 2013 Large scale seismics off Hawaii and Mexico
2014 - Fine scale seismics in the Mohole site
60°N
30°N
0°
30°S
60°S
Hawaii
Mexico
Site 1256
-6500
Proposed seismic survey:
- 2011/Dec. – 2012/Mar.
- Two crossing wide-angle OBS lines (~ 600 km long each)
- Large scale grid-MCS lines (Total ~ 6000 km long)
-SeaBeam and heat flow survey

IODP USIO

MoHole Engineering…
Seeking solutions inside and outside of IODP

MoHole Workshop
June 3-5, 2010
Kanazawa, Japan

Greg Myers
Consortium for Ocean Leadership

IODP USIO

Outline

- The Challenge
- In the IODP toolbox
- Where do technology gaps exist
- RMR– A possible solution to borehole problems
- Summary

IODP USIO

The Challenge

- Water depth over 4km
- Hole depth over 6km - 7km
    - 10 Empire state buildings of water (4.5km)
    - 14 Empire State Buildings into the seafloor (6km)

IODP USIO

The Challenge

- Water depth over 4km
- Hole depth over 6km-7km
    - 10 Empire state buildings of water (4.5km)
    - 14 Empire State Buildings into the seafloor (6km)

IODP USIO

Drilling to MOHO is easy..all you have to do is…

- Stabilize the vessel to drill/core/log in water depths ~12,000 feet (3,600 meters) and greater
- Clean the borehole hole
- Keep the borehole vertical
- Manage pressure within the borehole
- Manage temperature within the borehole
- Manage stress within the borehole
- Collect samples, return all equipment
- Avoid unfavorable met-ocean conditions
- Find the funding and stay within time and financial constraints

IODP USIO

Site Selection Issues

- **Drilling**: Water depth, Moho depth, expected borehole temperatures, lithological variations, pressures, stresses, core size, etc
    - This will affect vessel parameters, pipe specifications, mud composition and volume, casing specs, etc
- **Logistics**: Resupply, crew rotations, permitting
    - This will affect, vessel parameters, mobilizations/ demobilizations and access
- **Weather** (Met ocean): Average sea state, storm frequency, currents, commercial fishing, whale migrations
    - This affects vessel parameters, heave compensation, drive offs, crew preparation, dynamic positioning equipment need

Critical Questions

- Can the MoHole science community deviate from status quo techniques for sampling? How about…
  - Subsea drilling systems
    - Presently, uses for shallow hole site characterization
    - Especially useful for upper 100m of young crust
    - Full depth systems under development (Seabed Rig AS)
  - Punch and go exploration
    - Drill, recovery all cuttings, wireline log, spot core or sidewall core
    - Lower cost, drill deeper
    - Latest generation logging tools needed
- What does the science community define as MoHole Success?
  - Sampling certain amount of crust, vs, upper mantle, coring, fluids, logging, etc
- How many holes must be drilled?
  - Can a multiple site program work? (1256D and Hawaii sites?)
  - Pilot hole with main hole
  - Multiple holes
  - Holes to be established for observatories?

The IODP Toolbox: Building upon Scientific Ocean Drilling technological successes

- Mission specific platforms
- Chikyu and riser drilling
- JOIDES Resolution
- Observatories
- In-situ sampling of gabbros, hydrates, microbiological communities, overpressured sediments, any many more unique materials



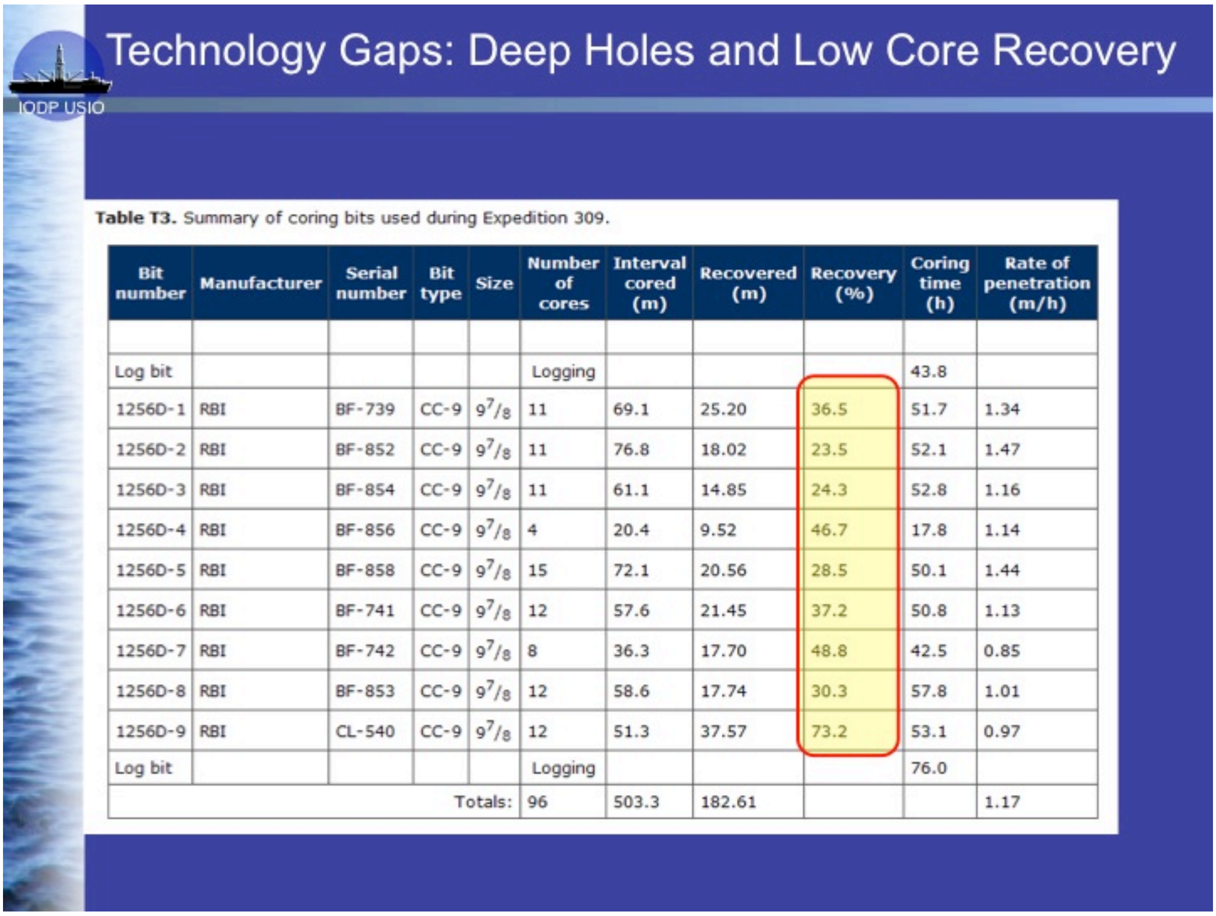


Table T3. Summary of coring bits used during Expedition 309.

Bit number	Manufacturer	Serial number	Bit type	Size	Number of cores	Interval cored (m)	Recovered (m)	Recovery (%)	Coring time (h)	Rate of penetration (m/h)
Log bit					Logging				43.8	
1256D-1	RBI	BF-739	CC-9	$9^7/_8$	11	69.1	25.20	36.5	51.7	1.34
1256D-2	RBI	BF-852	CC-9	$9^7/_8$	11	76.8	18.02	23.5	52.1	1.47
1256D-3	RBI	BF-854	CC-9	$9^7/_8$	11	61.1	14.85	24.3	52.8	1.16
1256D-4	RBI	BF-856	CC-9	$9^7/_8$	4	20.4	9.52	46.7	17.8	1.14
1256D-5	RBI	BF-858	CC-9	$9^7/_8$	15	72.1	20.56	28.5	50.1	1.44
1256D-6	RBI	BF-741	CC-9	$9^7/_8$	12	57.6	21.45	37.2	50.8	1.13
1256D-7	RBI	BF-742	CC-9	$9^7/_8$	8	36.3	17.70	48.8	42.5	0.85
1256D-8	RBI	BF-853	CC-9	$9^7/_8$	12	58.6	17.74	30.3	57.8	1.01
1256D-9	RBI	CL-540	CC-9	$9^7/_8$	12	51.3	37.57	73.2	53.1	0.97
Log bit					Logging				76.0	
				Totals:	96	503.3	182.61			1.17

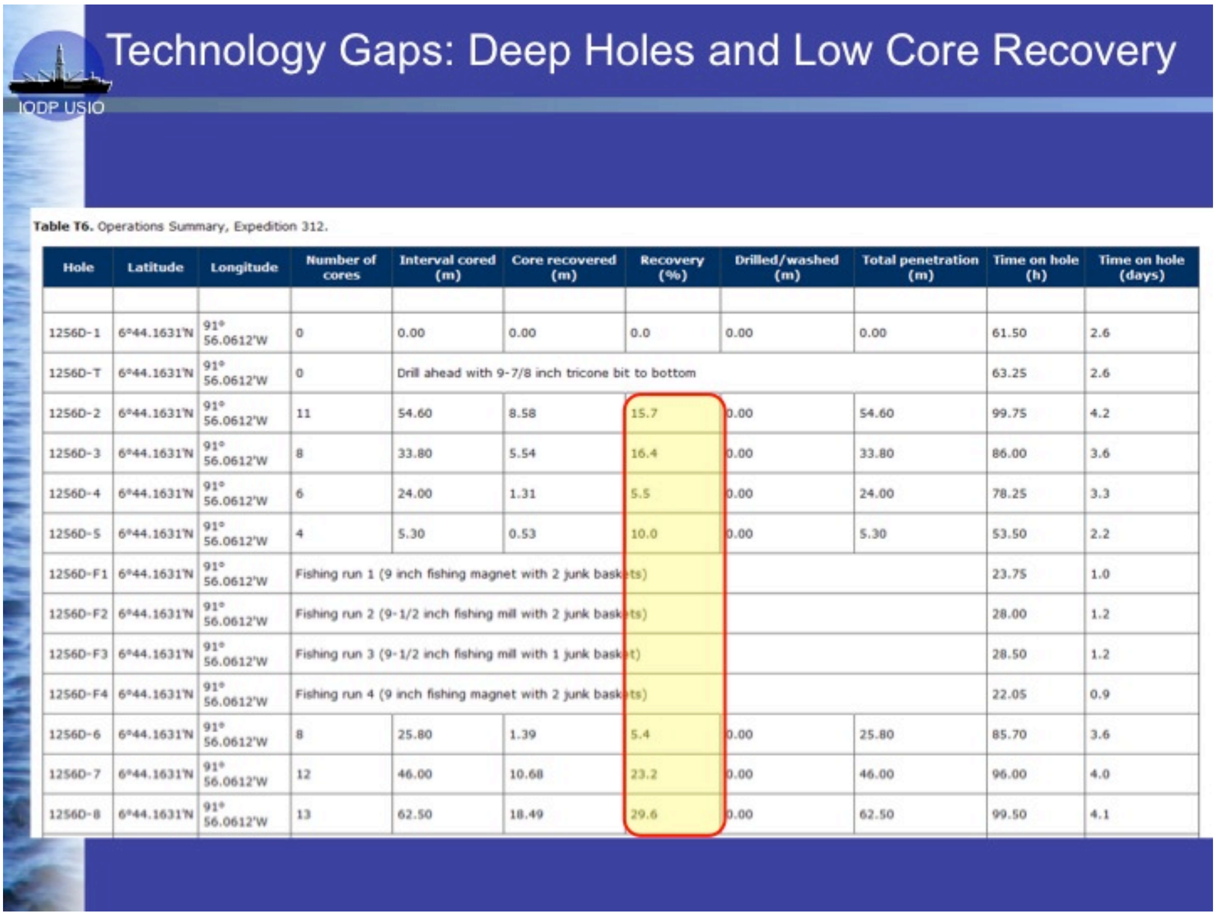


Table T6. Operations Summary, Expedition 312.

Hole	Latitude	Longitude	Number of cores	Interval cored (m)	Core recovered (m)	Recovery (%)	Drilled/washed (m)	Total penetration (m)	Time on hole (h)	Time on hole (days)
1256D-1	6°44.1631'N	91° 56.0612'W	0	0.00	0.00	0.0	0.00	0.00	61.50	2.6
1256D-T	6°44.1631'N	91° 56.0612'W	0	Drill ahead with 9-7/8 inch tricone bit to bottom					63.25	2.6
1256D-2	6°44.1631'N	91° 56.0612'W	11	54.60	8.58	15.7	0.00	54.60	99.75	4.2
1256D-3	6°44.1631'N	91° 56.0612'W	8	33.80	5.54	16.4	0.00	33.80	86.00	3.6
1256D-4	6°44.1631'N	91° 56.0612'W	6	24.00	1.31	5.5	0.00	24.00	78.25	3.3
1256D-5	6°44.1631'N	91° 56.0612'W	4	5.30	0.53	10.0	0.00	5.30	53.50	2.2
1256D-F1	6°44.1631'N	91° 56.0612'W	Fishing run 1 (9 inch fishing magnet with 2 junk baskets)						23.75	1.0
1256D-F2	6°44.1631'N	91° 56.0612'W	Fishing run 2 (9-1/2 inch fishing mill with 2 junk baskets)						28.00	1.2
1256D-F3	6°44.1631'N	91° 56.0612'W	Fishing run 3 (9-1/2 inch fishing mill with 1 junk basket)						28.50	1.2
1256D-F4	6°44.1631'N	91° 56.0612'W	Fishing run 4 (9 inch fishing magnet with 2 junk baskets)						22.05	0.9
1256D-6	6°44.1631'N	91° 56.0612'W	8	25.80	1.39	5.4	0.00	25.80	85.70	3.6
1256D-7	6°44.1631'N	91° 56.0612'W	12	46.00	10.68	23.2	0.00	46.00	96.00	4.0
1256D-8	6°44.1631'N	91° 56.0612'W	13	62.50	18.49	29.6	0.00	62.50	99.50	4.1

Technology Gaps: Deep Holes and Low Core Recovery

IODP USIO

Table T1. Hole summary, Expedition 315.

Hole	Location	Water depth (mbsl)	Number of cores	Drilled depth (m)	Interval cored (m)	Recovered (m)	Recovery (%)	Comments
C0001E	33°14.3442′N, 136°42.6924′E	2198.0	13 HPCS	118.10	118.10	112.67	95.4	Lost inner core barrel in hole
C0001F	33°14.3437′N, 136°42.7067′E	2197.0	19 HPCS, 2 ESCS	248.83	140.80	137.50	97.7	
C0001G	33°14.3237′N, 136°42.6933′E	2196.5	NA	74.50	NA	NA	NA	ROV cable tangled around drill pipe
C0001H	33°14.3233′N, 136°42.6840′E	2197.0	26 RCB	590.50	228.60	126.30	55.2	Hole caving
C0001I	33°14.2030′N, 136°42.4330′E	2198.5	NA	520.00	NA	NA	NA	Hole caving
Site C0001 totals:			32 HPCS, 2 ESCS, 26 RCB	1551.93	487.50	376.47	77.2	
C0002B	33°17.9928′N, 136°38.2029′E	1937.5	66 RCB	1057.00	582.00	208.30	35.8	
C0002C	33°18.0026′N, 136°38.1869′E	1936.6	2 HPCS	13.77	13.80	13.77	99.8	
C0002D	33°18.0075′N, 136°38.1910′E	1937.1	16 HPCS, 2 ESCS	204.00	204.00	161.90	79.4	
Site C0002 totals:			18 HPCS, 2 ESCS, 66 RCB	1274.77	799.80	383.97	48.0	

IODP USIO

Ultra-deep Drilling Statistics

Site	Water Depth (m)	Borehole Depth (m)	Total Depth (m)	Comments
Proposal 698Full-2	1,798	8,000	9,798	1 year? <250°C
KTB	0	9,101	9,101	4+ years; $338 million; 265°C
Kola SG-3	0	12,262	12,262	24 years; 190°C
Bertha Rogers 1-27	0	9,583 (31,441ft)	9,583	1974 gas well
Nankai NT3-01	~2,000	6,000	8,000	450 days allocated; ~175°C
1256D	3,635	1,507	5,142	~5 months; ~70 °C
JR			**10,290 (SODV)**	Total string length
Deepest hole	3,463	**2,111**	5,574	190°C, Site 504B
Deepest water	**5,980**	560	6,540	
Chikyu (riser)	2,500 (max)	7,000 (max)	**9,500**	<250°C borehole
Deepest hole	500	**3,700**	4,200	Off Australia, non-IODP
Deepest water	**2,200**	2,700	4,900	
Chikyu (non-riser)		7,000 (max)	**10,000**	
Deepest hole	1,936	**1,401.5**	3,337.5	C2 Leg 314
Deepest water	**4,081**	494	4,575	

Table created by Bill Ussler - MBARI

Needed downhole equipment

Drilling and Coring

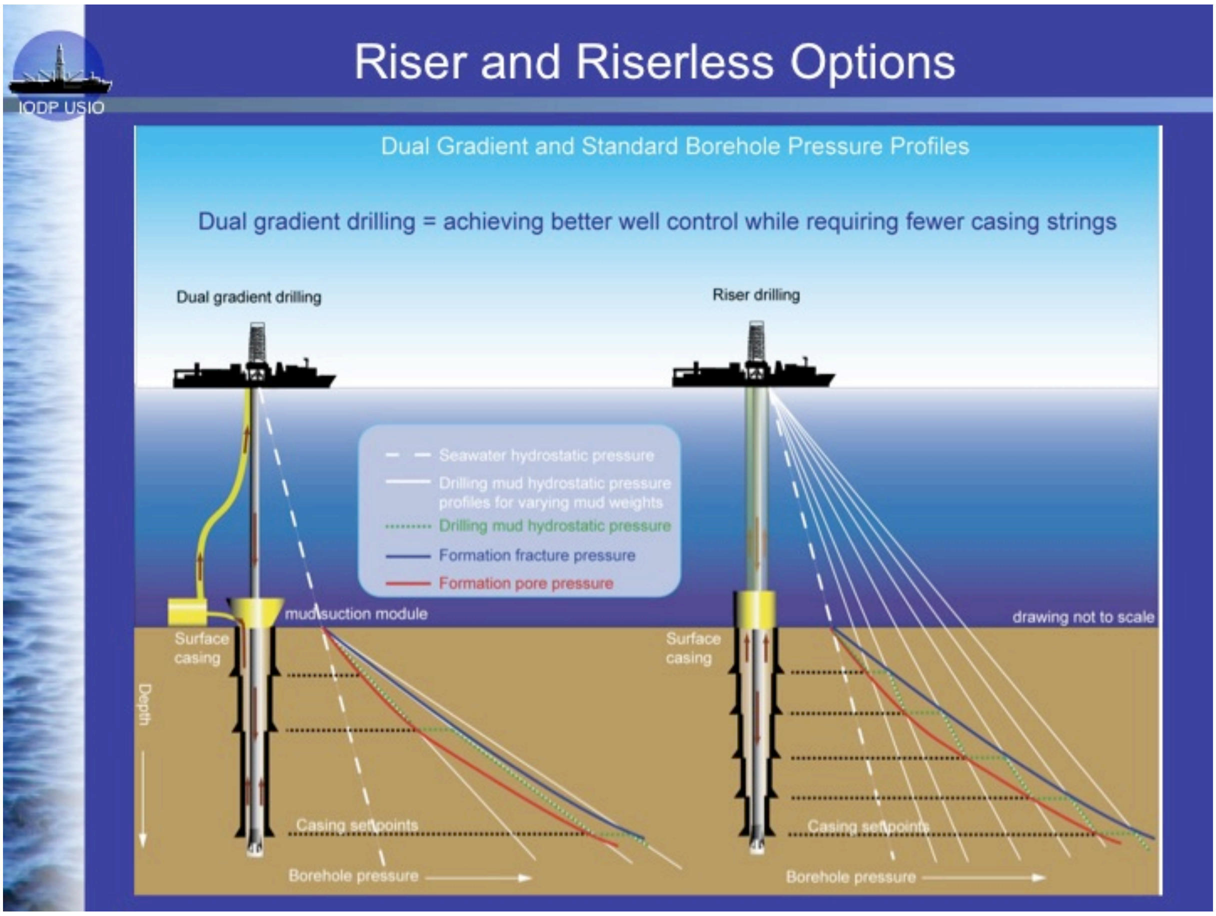
- Instrumented drill collars
- Microbio core barrels
- Transition zone corers
- High temperature mud and equipment
- Hyper-deepwater mud circulation

Logging

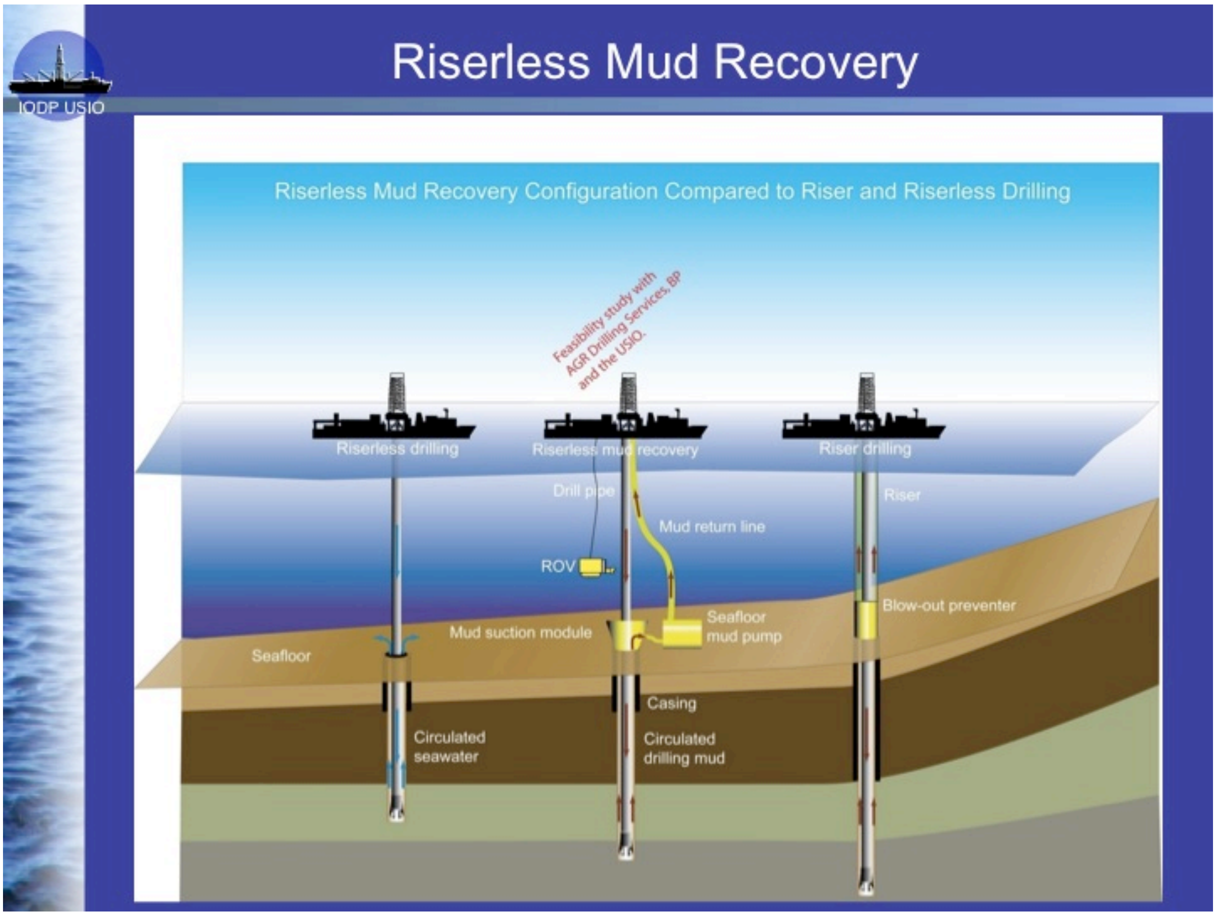
- Drill collar fluid sampling and seismic measurements
- Latest generation wireline tools deployable from all platforms
- Fluid samplers, sidewall corers, geochemistry, magnetic resonance etc

Borehole Management

- Managing the borehole means:
  - Remove cuttings
  - Provide lithostatic and pore pressure compensation
  - Develop mud cake on borehole wall to provide additional stability
  - Mitigate fluid inflows and outflows
  - Limiting excess pumping rates
- Historically, seawater with occasional mud sweeps has been utilized, thus the deepest IODP hole is 2,111m deep
- Engineered mud must be circulated continuously as part of a comprehensive plan to drill and core effectively

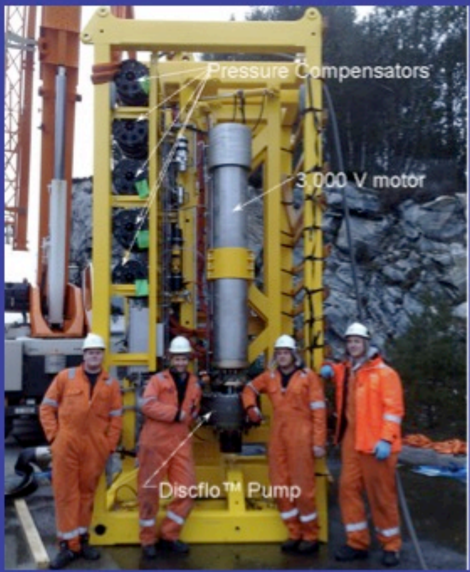


Riser and Riserless Options
IODP USIO
Dual Gradient and Standard Borehole Pressure Profiles
Dual gradient drilling = achieving better well control while requiring fewer casing strings
Dual gradient drilling
Riser drilling
Seawater hydrostatic pressure
Drilling mud hydrostatic pressure profiles for varying mud weights
Drilling mud hydrostatic pressure
Formation fracture pressure
Formation pore pressure
mud suction module
drawing not to scale
Surface casing
Depth
Casing setpoints
Borehole pressure



Riserless Mud Recovery
IODP USIO
Riserless Mud Recovery Configuration Compared to Riser and Riserless Drilling
Feasibility study with AGR Drilling Services, BP and the USIO.
Riserless drilling
Riserless mud recovery
Riser drilling
Drill pipe
Riser
Mud return line
ROV
Blow-out preventer
Seafloor mud pump
Mud suction module
Seafloor
Casing
Circulated seawater
Circulated drilling mud

Deepwater Riserless Mud Recovery Equipment



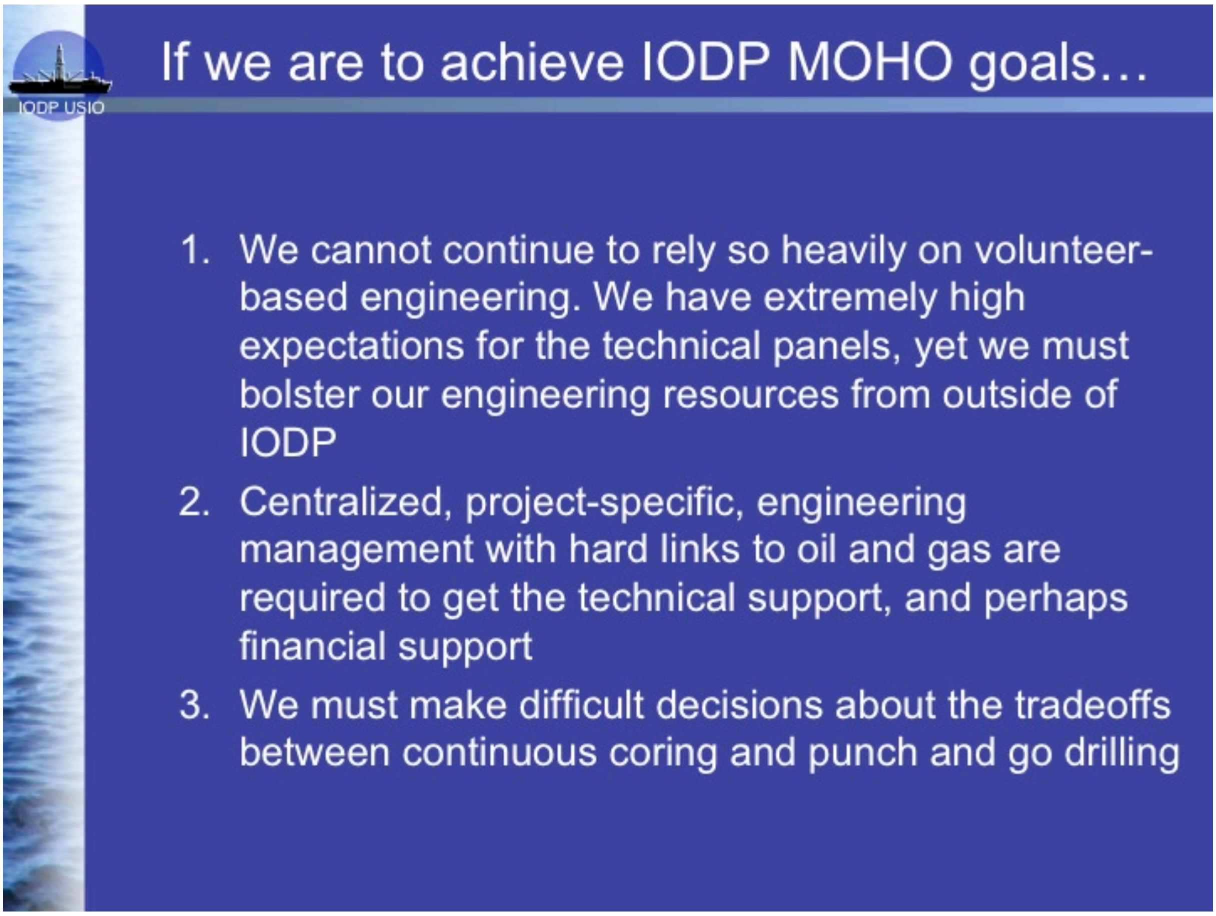
In-line pump

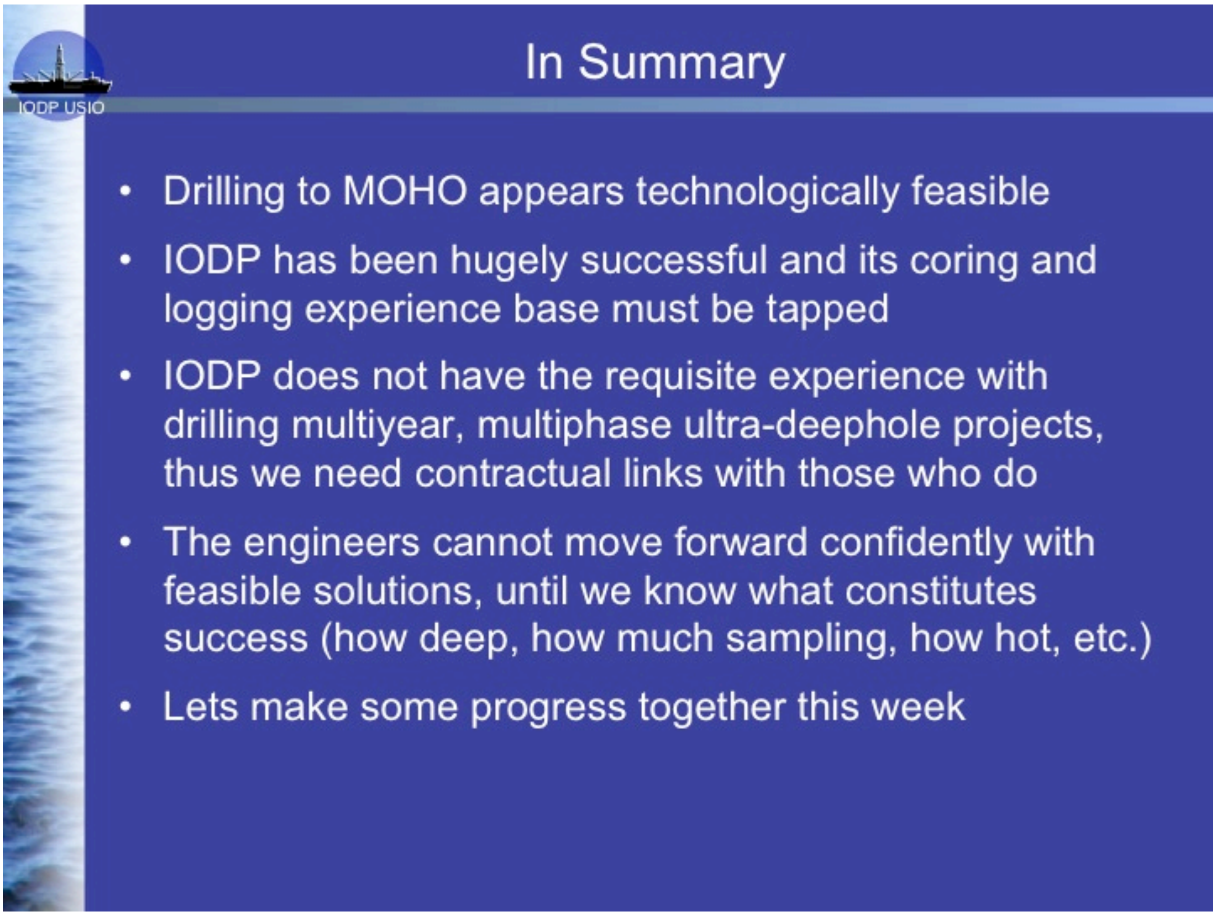
Mud suction module

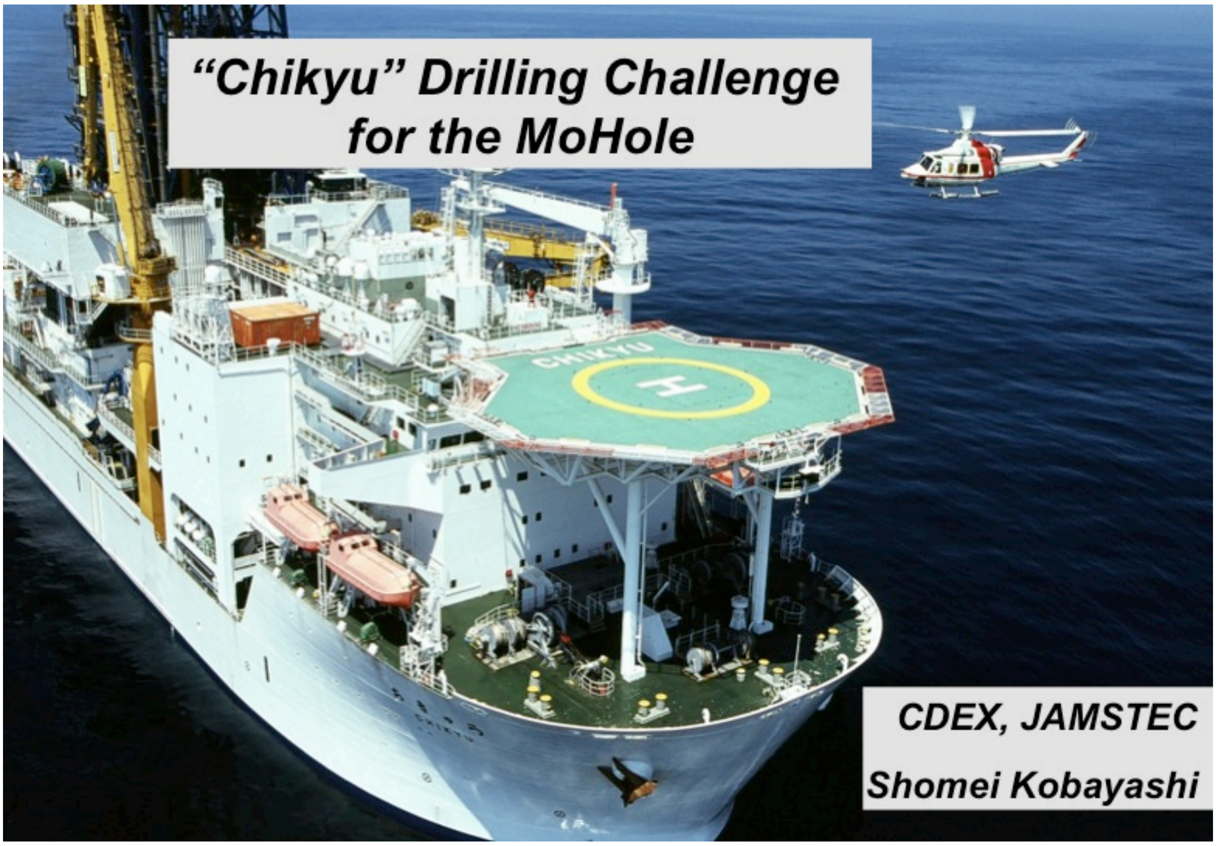
Proposal received from AGR to design and build a 5,000 meter system

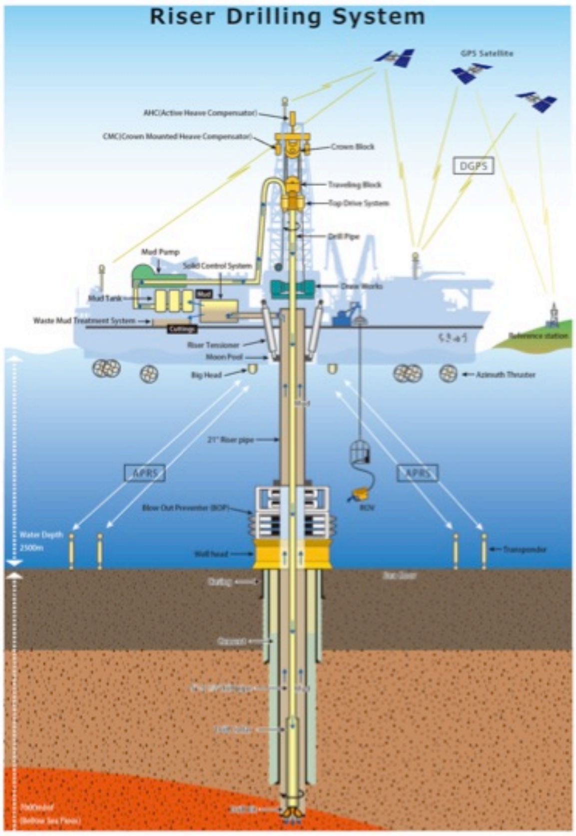
Riserless Mud Recovery Timeline

- 2009 - Feasibility project – completed by IODP-MI
  - Demonstrated RMR feasibility for IODP to 3,650 m (on paper)
  - Funded by DeepStar Industry Consortium
- 2011-2012 Field Trial from an IODP platform in <3,650 m of water
  - Must be preceded by procurement of funding and completion of engineering, vessel modifications and operations simulation
  - Funded partially by DeepStar, RPSEA, major Industry operator/s, cost sharing by AGR and IODP operators
- 2013-2014 Field trial in water depth >3,650 m
  - Must be preceded by procurement of funding and completion of engineering, vessel modifications and operations simulation
- 2015 – Ultra-deephole in hyper-deepwater capability could be ready


IODP USIO
If we are to achieve IODP MOHO goals…
1. We cannot continue to rely so heavily on volunteer-based engineering. We have extremely high expectations for the technical panels, yet we must bolster our engineering resources from outside of IODP
2. Centralized, project-specific, engineering management with hard links to oil and gas are required to get the technical support, and perhaps financial support
3. We must make difficult decisions about the tradeoffs between continuous coring and punch and go drilling


IODP USIO
In Summary
• Drilling to MOHO appears technologically feasible
• IODP has been hugely successful and its coring and logging experience base must be tapped
• IODP does not have the requisite experience with drilling multiyear, multiphase ultra-deephole projects, thus we need contractual links with those who do
• The engineers cannot move forward confidently with feasible solutions, until we know what constitutes success (how deep, how much sampling, how hot, etc.)
• Lets make some progress together this week





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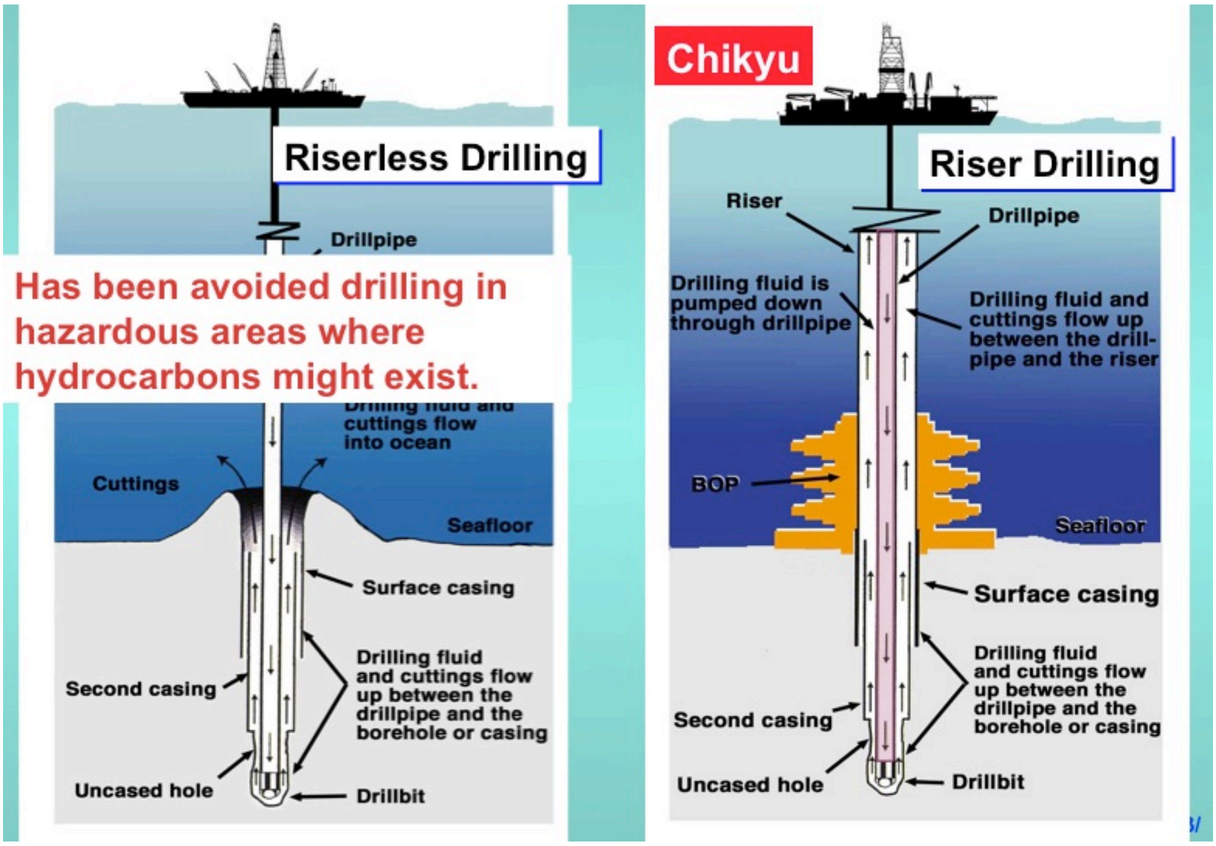

Advantages of Riser drilling

	Riser	BOP	Mud Circulation
Well Control / Formation Pressure Control	✔	✔	✔
Borehole Stability	✔		✔
Deep Penetration	✔		✔
Large & Safe Wireline Logging tools run - passage	✔		✔
Large & Safe Casing run - passage	✔		✔
Better Core Recovery	✔		✔

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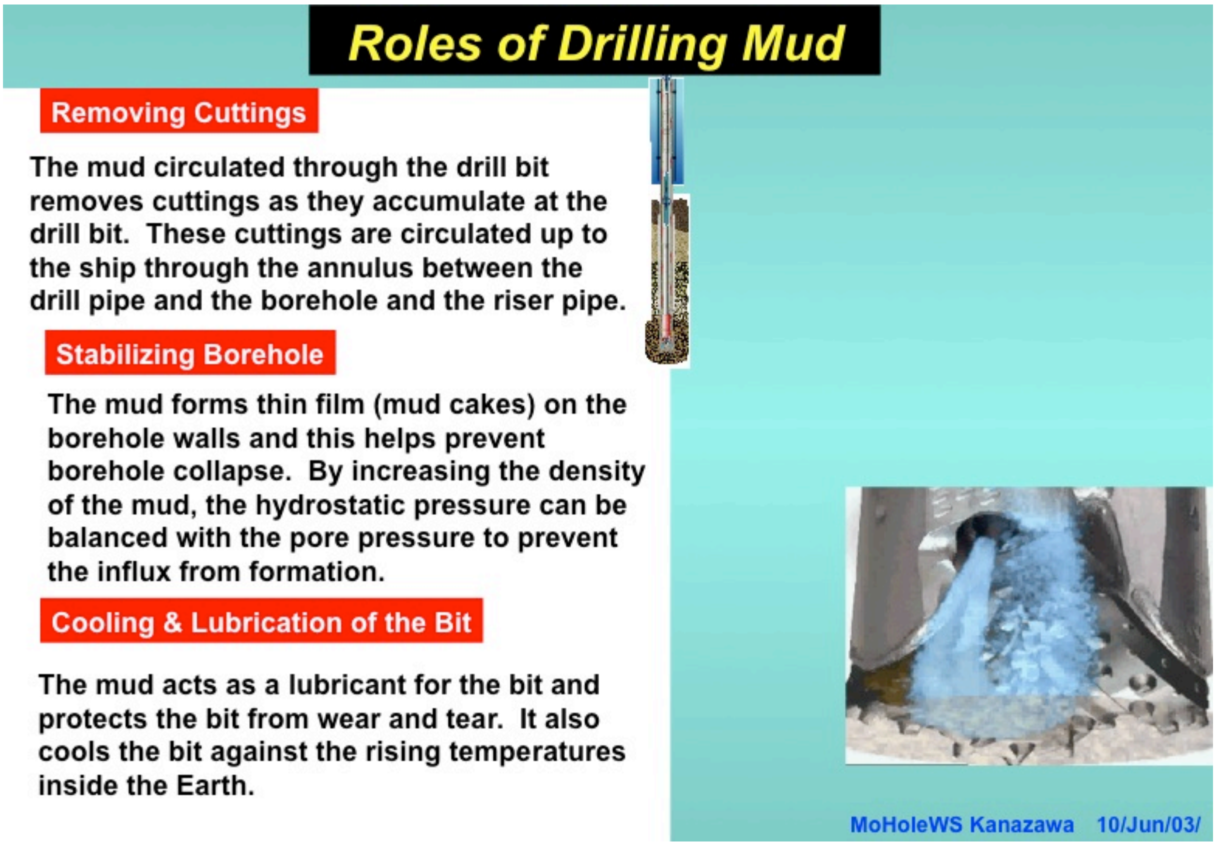
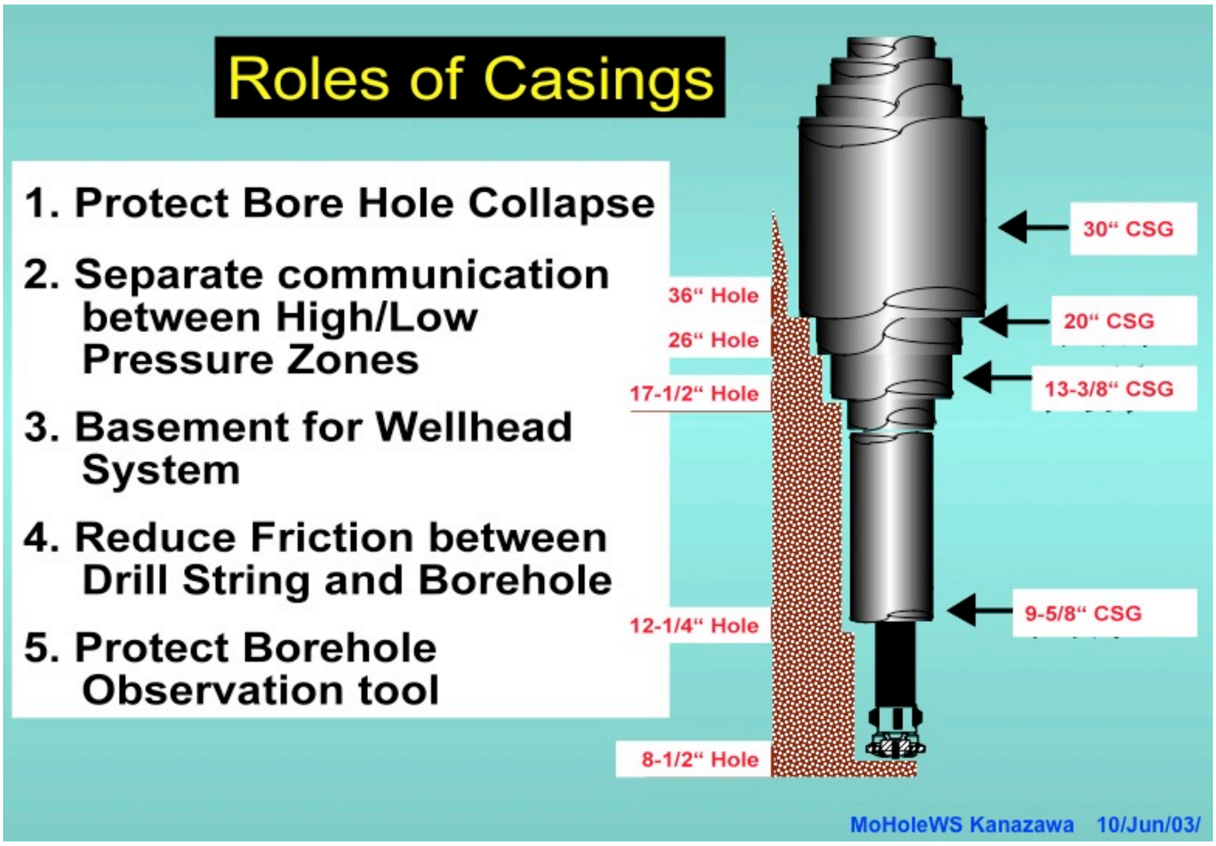
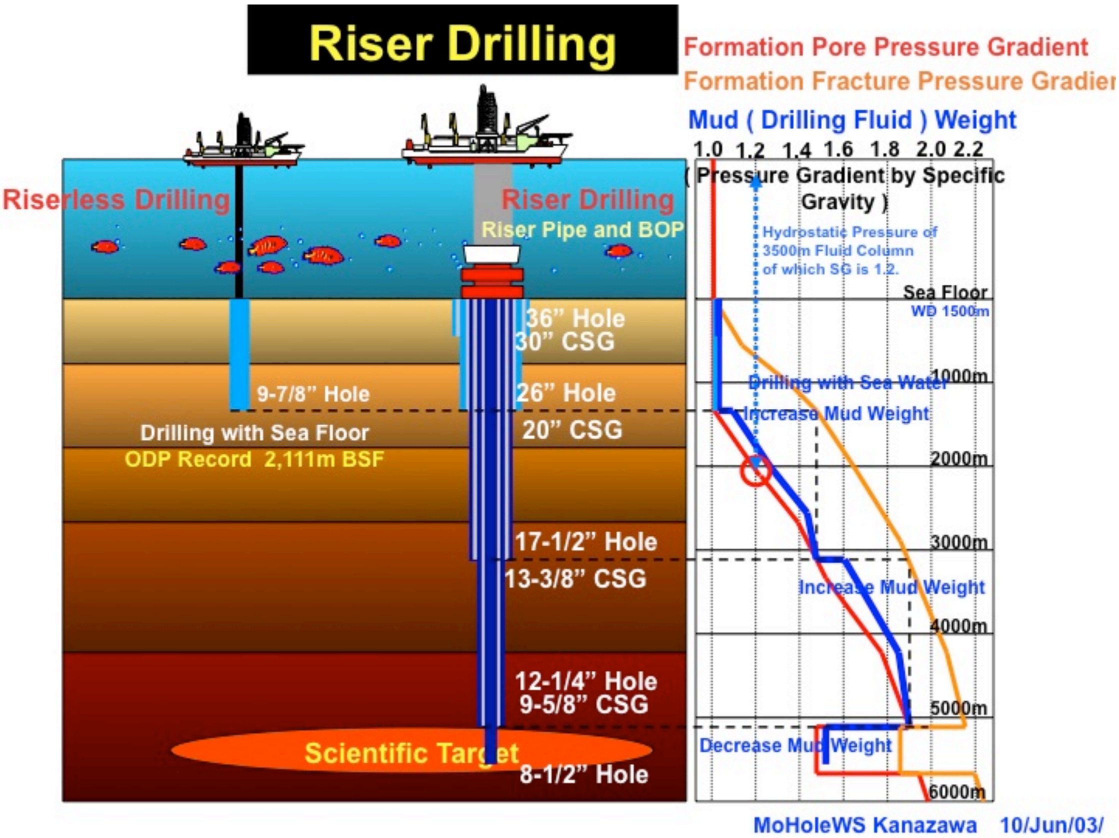

Roles of Drilling Mud
Removing Cuttings
The mud circulated through the drill bit removes cuttings as they accumulate at the drill bit. These cuttings are circulated up to the ship through the annulus between the drill pipe and the borehole and the riser pipe.
Stabilizing Borehole
The mud forms thin film (mud cakes) on the borehole walls and this helps prevent borehole collapse. By increasing the density of the mud, the hydrostatic pressure can be balanced with the pore pressure to prevent the influx from formation.
Cooling & Lubrication of the Bit
The mud acts as a lubricant for the bit and protects the bit from wear and tear. It also cools the bit against the rising temperatures inside the Earth.
MoHoleWS Kanazawa 10/Jun/03/


Roles of Casings
1. Protect Bore Hole Collapse
2. Separate communication between High/Low Pressure Zones
3. Basement for Wellhead System
4. Reduce Friction between Drill String and Borehole
5. Protect Borehole Observation tool
30" CSG
36" Hole
20" CSG
26" Hole
13-3/8" CSG
17-1/2" Hole
9-5/8" CSG
12-1/4" Hole
8-1/2" Hole
MoHoleWS Kanazawa 10/Jun/03/


Riser Drilling
Formation Pore Pressure Gradient
Formation Fracture Pressure Gradient
Mud (Drilling Fluid) Weight
1.0 1.2 1.4 1.6 1.8 2.0 2.2
(Pressure Gradient by Specific Gravity)
Hydrostatic Pressure of 3500m Fluid Column of which SG is 1.2.
Sea Floor
WD 1500m
Riserless Drilling
Riser Drilling
Riser Pipe and BOP
36" Hole
30" CSG
9-7/8" Hole
26" Hole
20" CSG
Drilling with Sea Floor
ODP Record 2,111m BSF
17-1/2" Hole
13-3/8" CSG
12-1/4" Hole
9-5/8" CSG
Scientific Target
8-1/2" Hole
Drilling with Sea Water
1000m
Increase Mud Weight
2000m
3000m
Increase Mud Weight
4000m
5000m
Decrease Mud Weight
6000m
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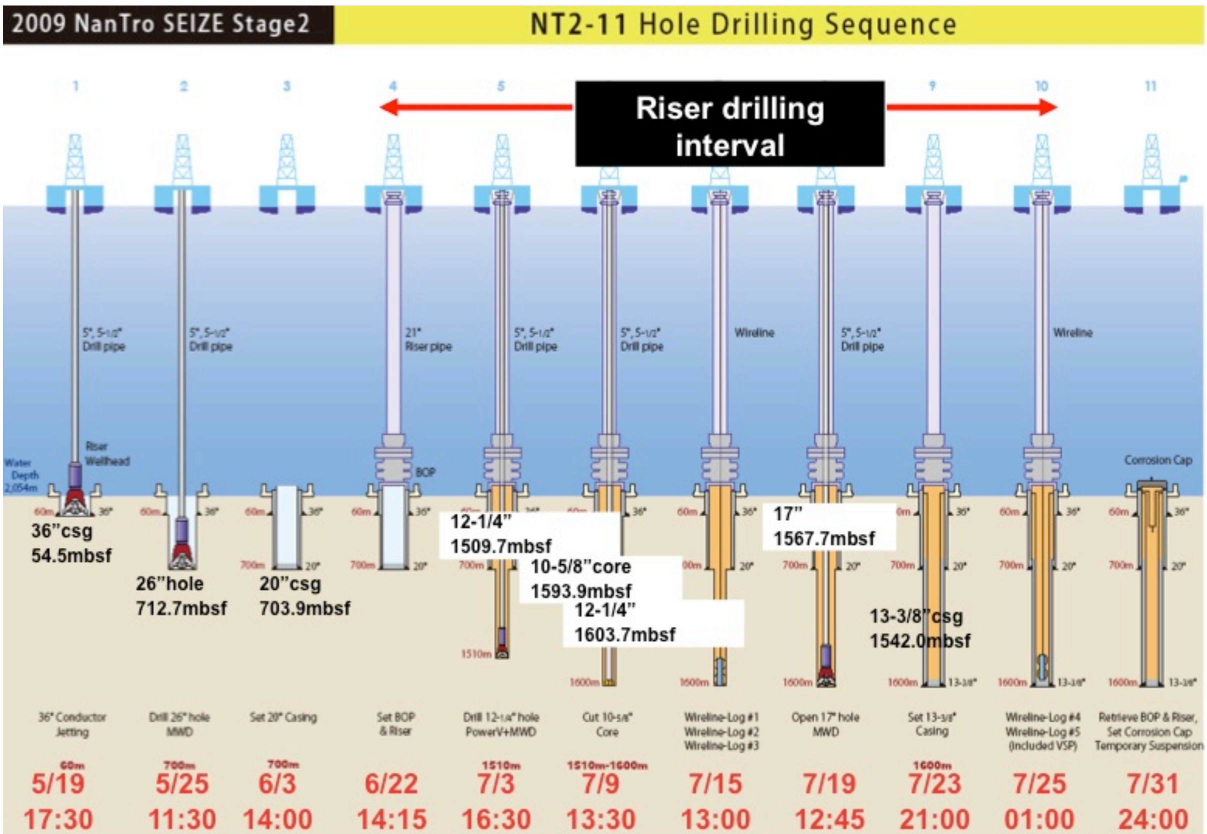
2009 NanTro SEIZE Stage2
NT2-11 Hole Drilling Sequence
Riser drilling interval
36"csg
54.5mbsf
26"hole
712.7mbsf
20"csg
703.9mbsf
12-1/4"
1509.7mbsf
10-5/8"core
1593.9mbsf
12-1/4"
1603.7mbsf
17"
1567.7mbsf
13-3/8"csg
1542.0mbsf
5/19 17:30
5/25 11:30
6/3 14:00
6/22 14:15
7/3 16:30
7/9 13:30
7/15 13:00
7/19 12:45
7/23 21:00
7/25 01:00
7/31 24:00

Limitless Wireline Logging Measurements

- Choice of combinations for hostile environments
- Dipole shear sonic, Fullbore electrical imaging, Dynamic formation testing and sampling, Magnetic resonance tools

Sonic Fullbore Imager Dynamic FormationTester & Corer Magnetic Resonance VSP

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Congratulations! Good recovery & good quality Core

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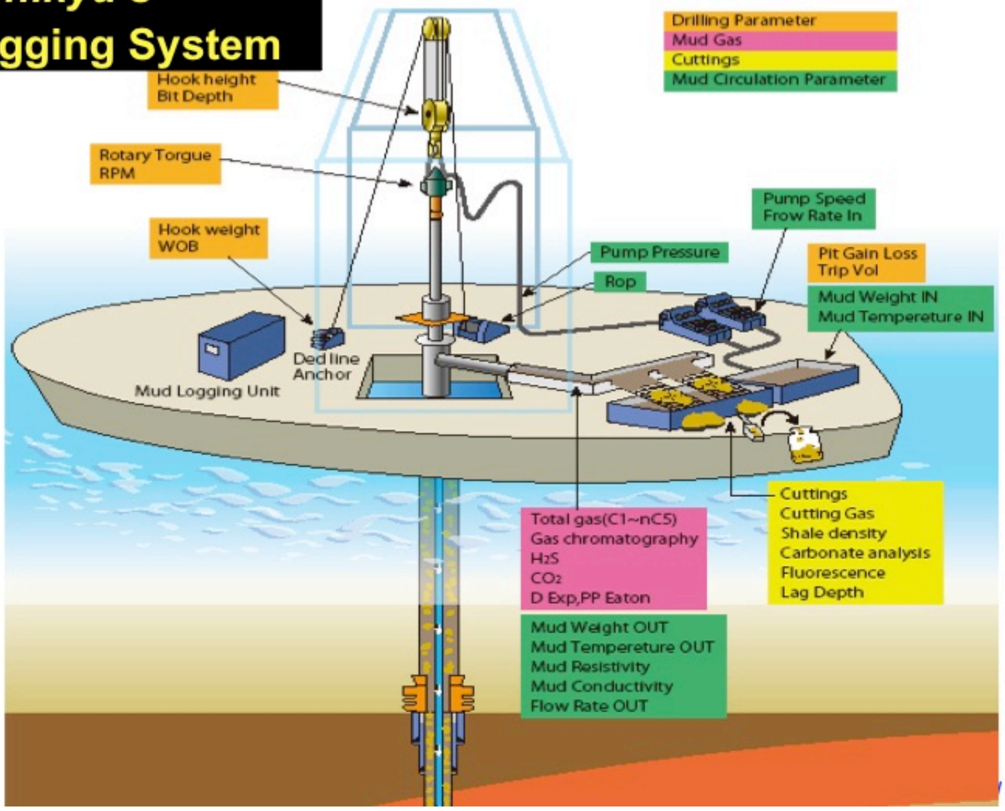
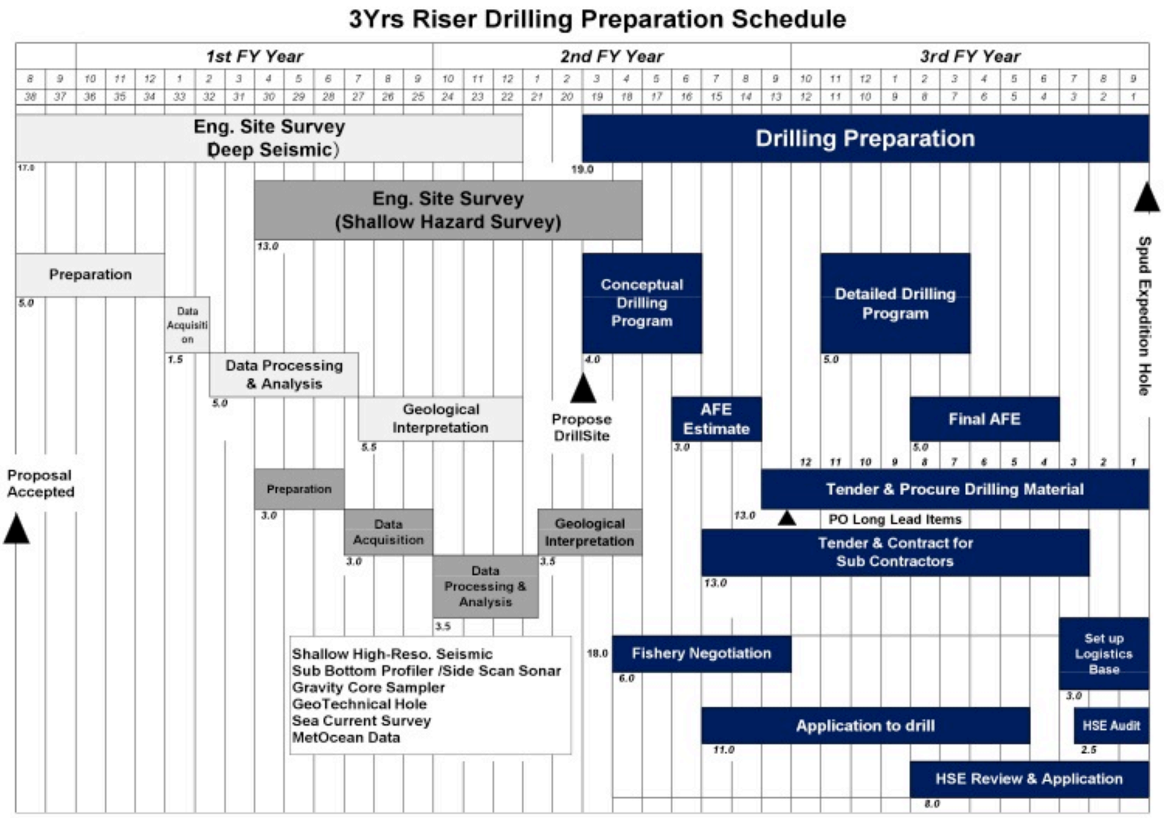
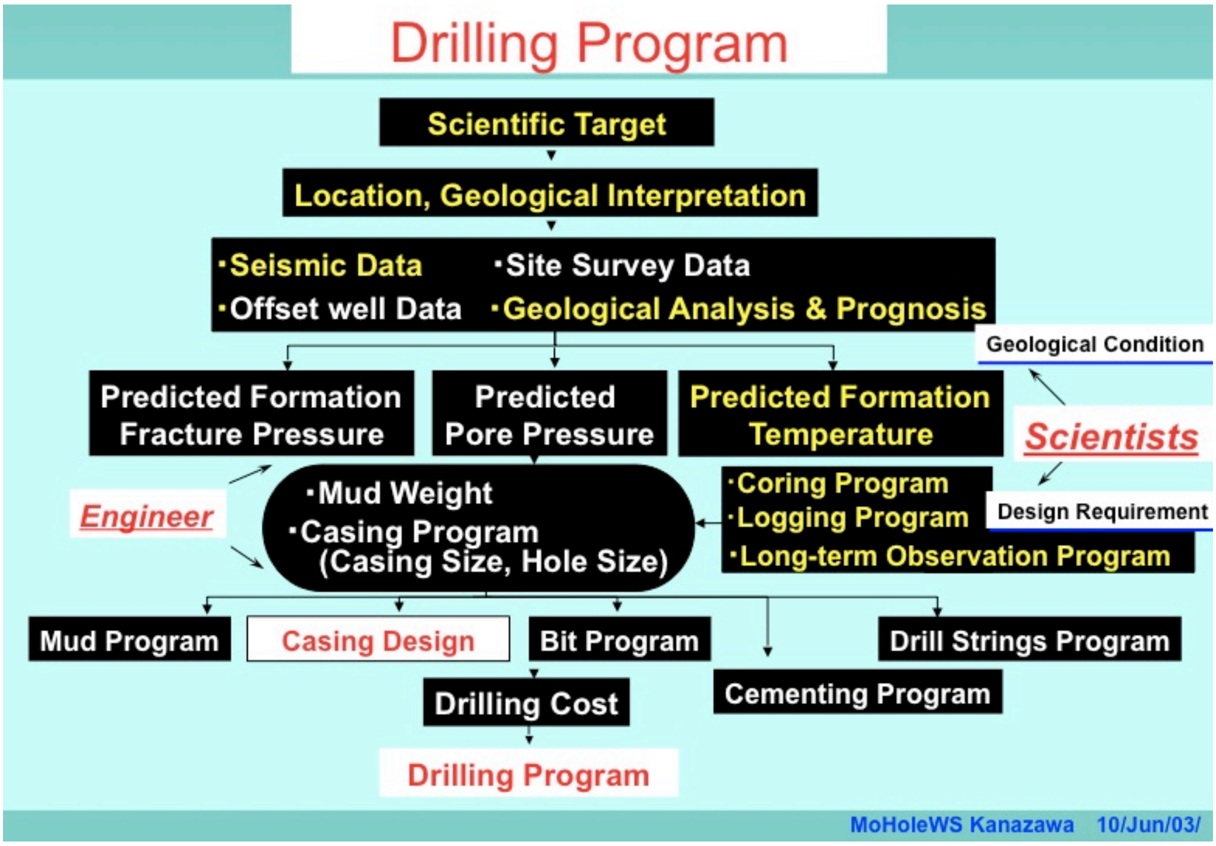
Chikyu's Mud Logging System



Mud Logging / Cuttings Examination

Analysis of the returned drill cuttings gives important and detailed real-time information on the condition of the borehole, and that of the rock being drilled through.


3Yrs Riser Drilling Preparation Schedule
1st FY Year
2nd FY Year
3rd FY Year
Eng. Site Survey
Deep Seismic)
Drilling Preparation
Eng. Site Survey
(Shallow Hazard Survey)
Preparation
Data Acquisition
Data Processing & Analysis
Geological Interpretation
Conceptual Drilling Program
Detailed Drilling Program
Propose DrillSite
AFE Estimate
Final AFE
Spud Expedition Hole
Proposal Accepted
Preparation
Data Acquisition
Data Processing & Analysis
Geological Interpretation
Tender & Procure Drilling Material
PO Long Lead Items
Tender & Contract for Sub Contractors
Shallow High-Reso. Seismic
Sub Bottom Profiler /Side Scan Sonar
Gravity Core Sampler
GeoTechnical Hole
Sea Current Survey
MetOcean Data
Fishery Negotiation
Set up Logistics Base
Application to drill
HSE Audit
HSE Review & Application


Drilling Program
Scientific Target
Location, Geological Interpretation
·Seismic Data ·Site Survey Data
·Offset well Data ·Geological Analysis & Prognosis
Geological Condition
Predicted Formation Fracture Pressure
Predicted Pore Pressure
Predicted Formation Temperature
Scientists
Engineer
·Mud Weight
·Casing Program
(Casing Size, Hole Size)
·Coring Program
·Logging Program
·Long-term Observation Program
Design Requirement
Mud Program
Casing Design
Bit Program
Drill Strings Program
Drilling Cost
Cementing Program
Drilling Program
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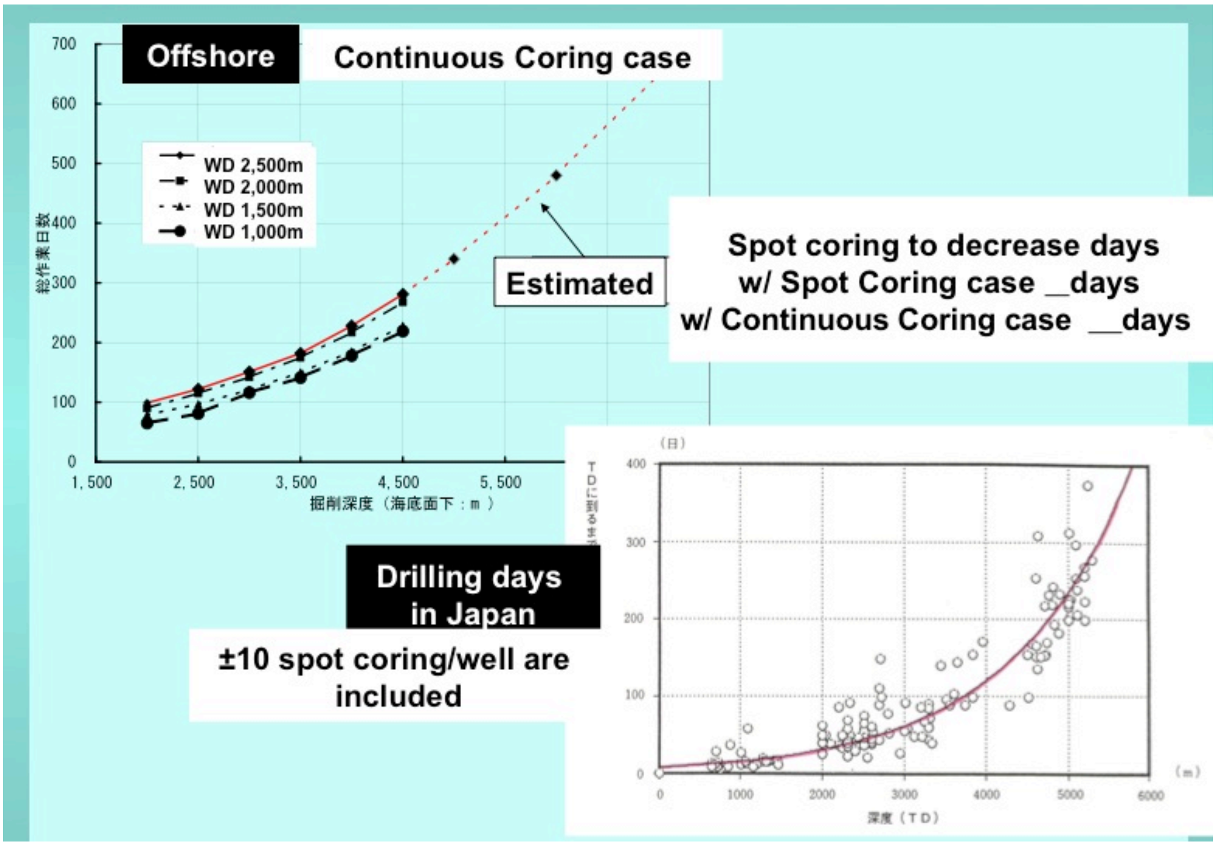
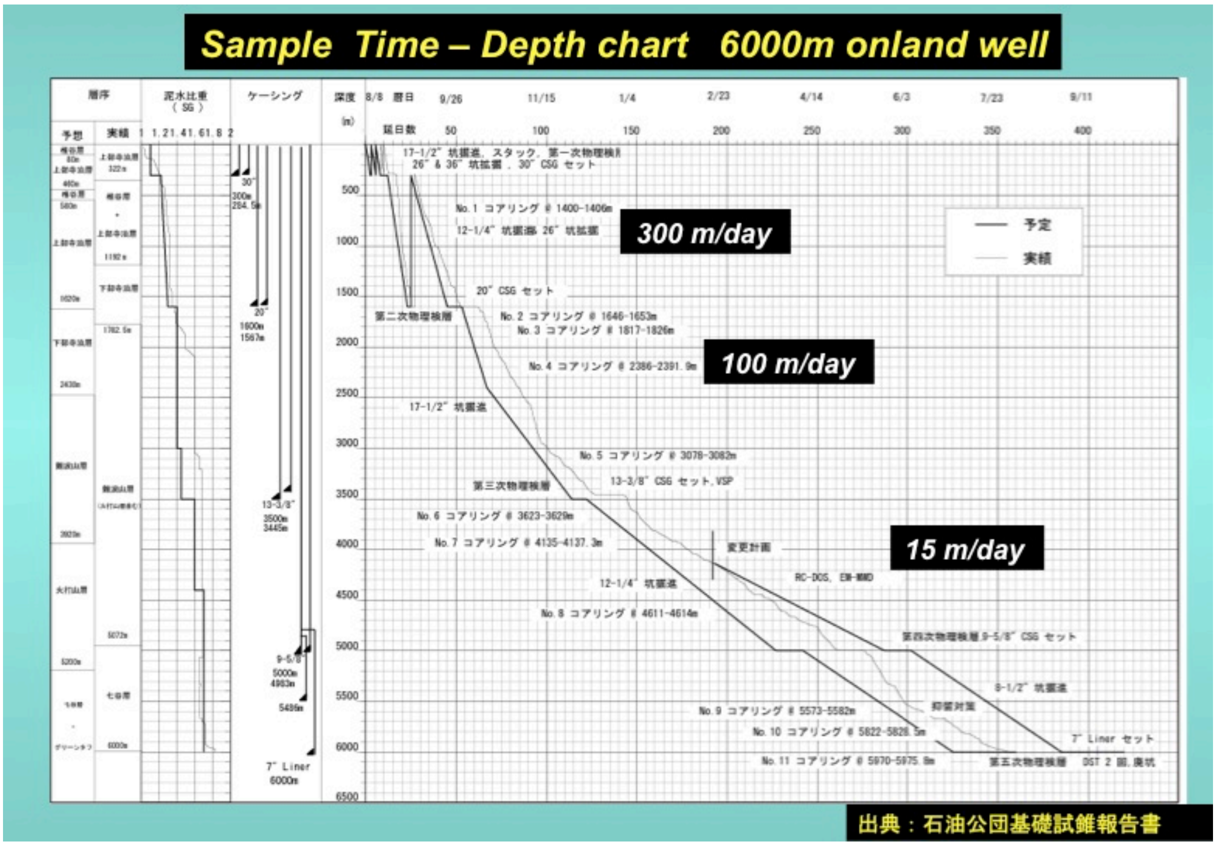
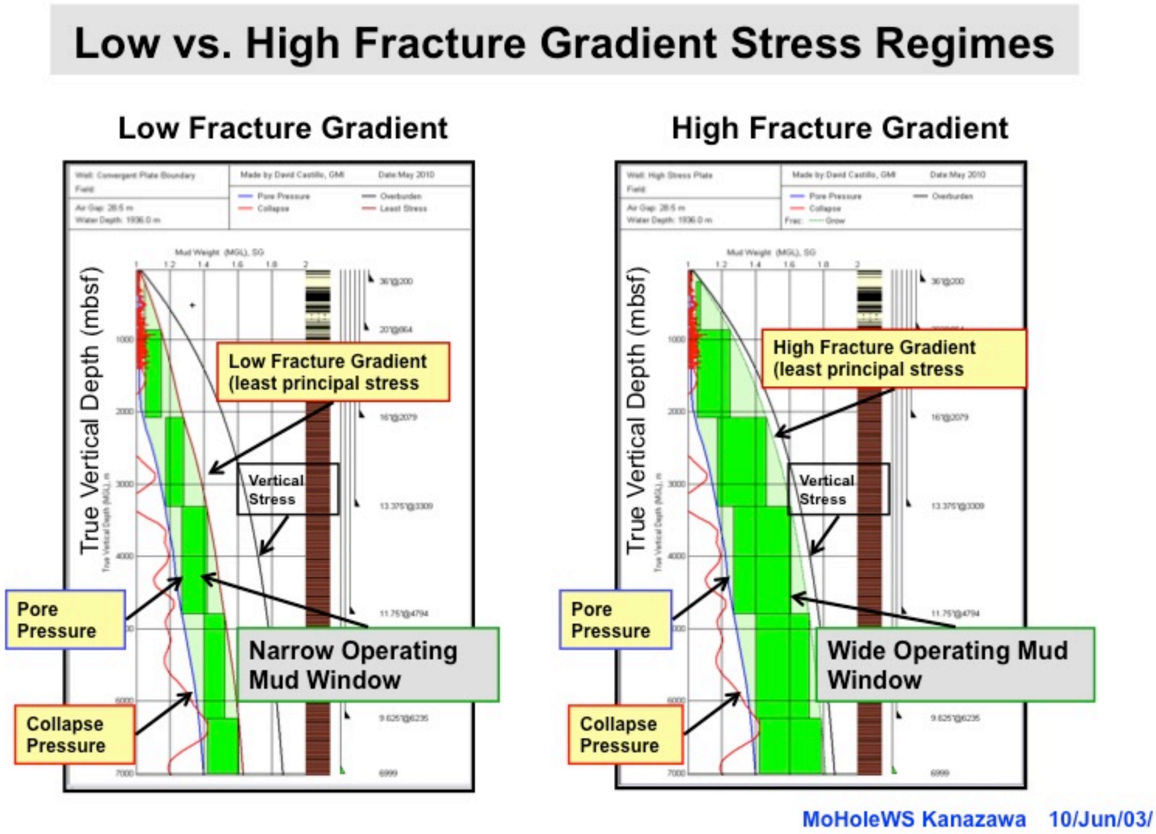

Offshore
Continuous Coring case
WD 2,500m
WD 2,000m
WD 1,500m
WD 1,000m
Estimated
総作業日数
掘削深度（海底面下：m）
Spot coring to decrease days
w/ Spot Coring case _days
w/ Continuous Coring case __days
Drilling days
in Japan
±10 spot coring/well are
included
深度（TD）


Sample Time – Depth chart 6000m onland well
層序
泥水比重（SG）
ケーシング
深度 (m)
予想
実績
No. 1 コアリング @ 1400-1406m
300 m/day
20" CSG セット
No. 2 コアリング @ 1646-1653m
No. 3 コアリング @ 1817-1826m
No. 4 コアリング @ 2386-2391.9m
100 m/day
No. 5 コアリング @ 3078-3082m
13-3/8" CSG セット, VSP
No. 6 コアリング @ 3623-3629m
No. 7 コアリング @ 4135-4137.3m
変更計画
15 m/day
No. 8 コアリング @ 4611-4614m
No. 9 コアリング @ 5573-5582m
No. 10 コアリング @ 5822-5828.5m
No. 11 コアリング @ 5970-5975.8m
7" Liner セット
7" Liner 6000m
予定
実績
出典：石油公団基礎試錐報告書


Low vs. High Fracture Gradient Stress Regimes
Low Fracture Gradient
High Fracture Gradient
True Vertical Depth (mbsf)
Low Fracture Gradient (least principal stress
High Fracture Gradient (least principal stress
Vertical Stress
Pore Pressure
Collapse Pressure
Narrow Operating Mud Window
Wide Operating Mud Window
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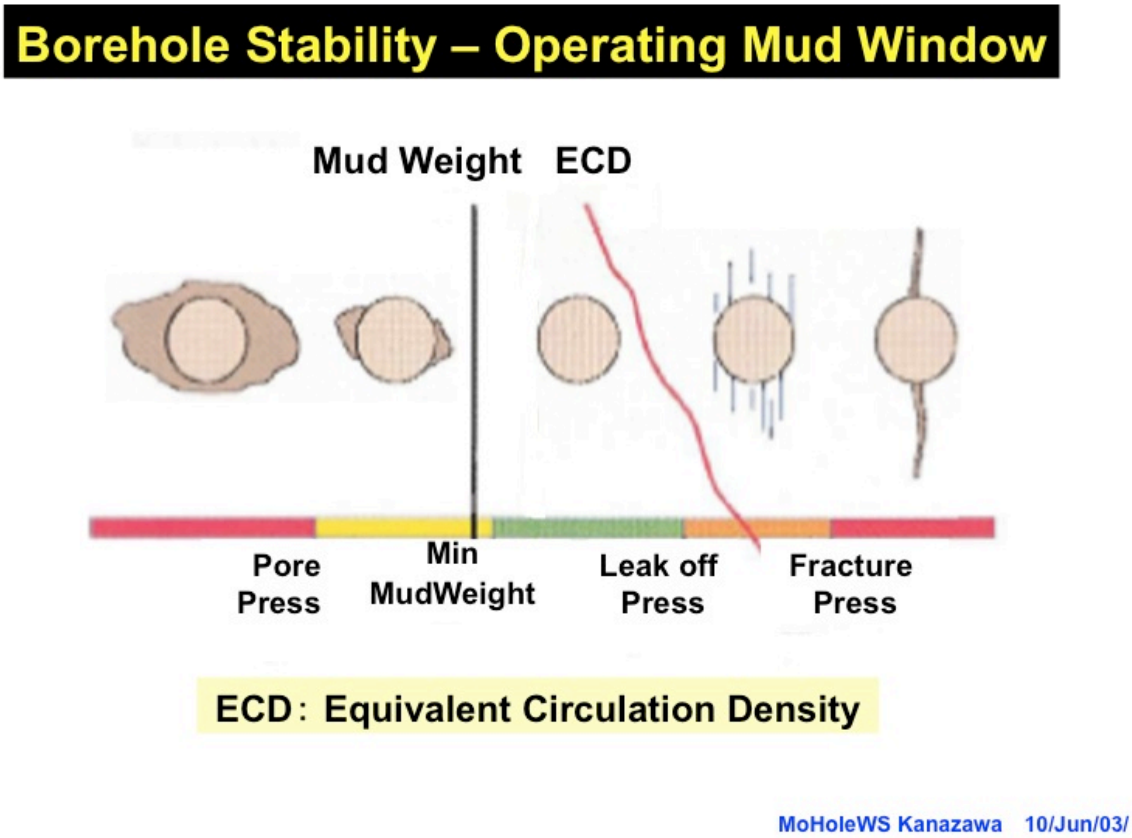
Borehole Stability – Operating Mud Window
Mud Weight ECD
Pore Press
Min MudWeight
Leak off Press
Fracture Press
ECD: Equivalent Circulation Density
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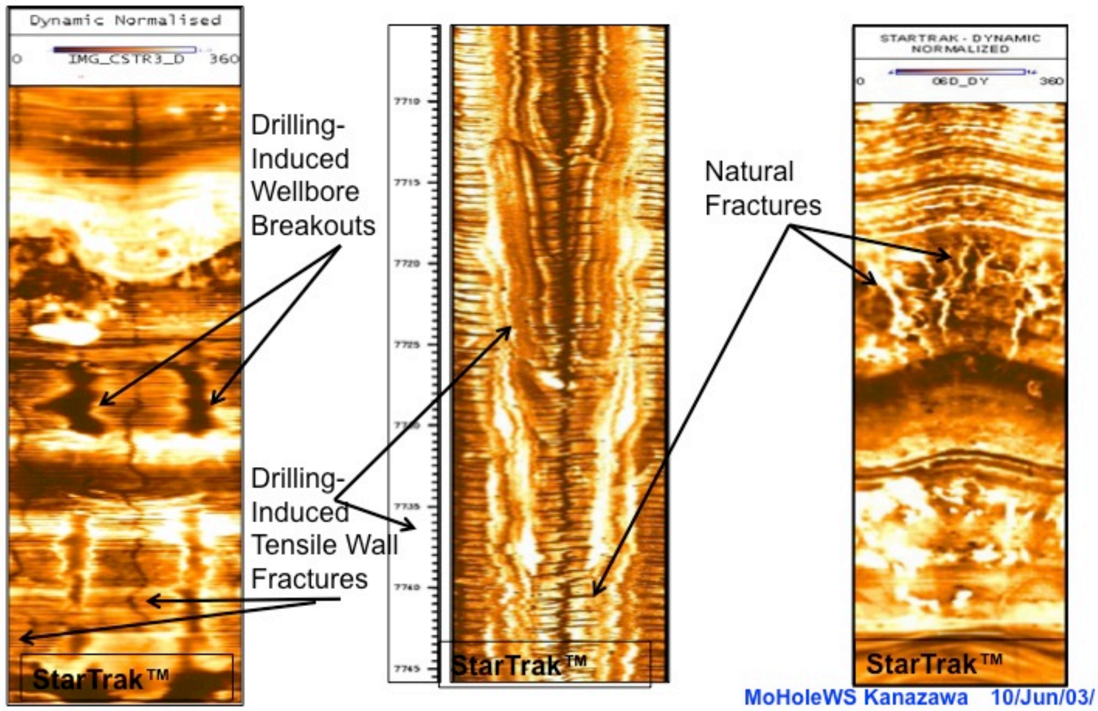
Real-Time LWD Images for Water-Based Muds



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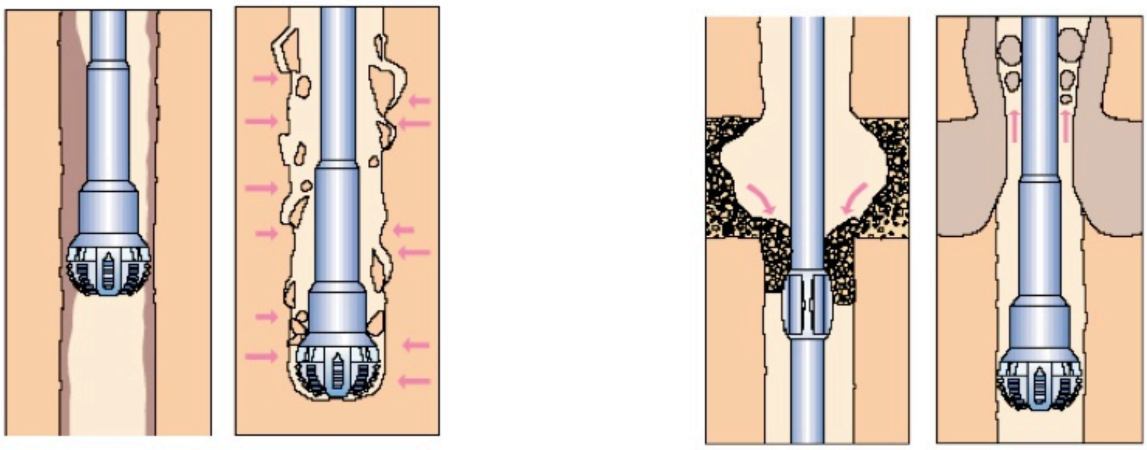
Borehole Instability – Hole trouble1



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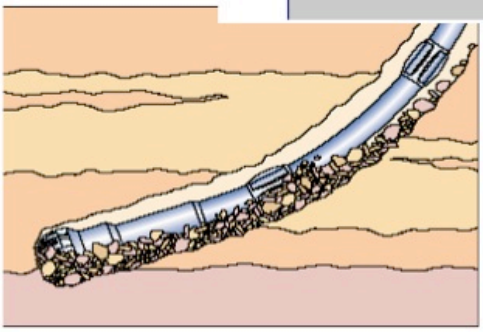
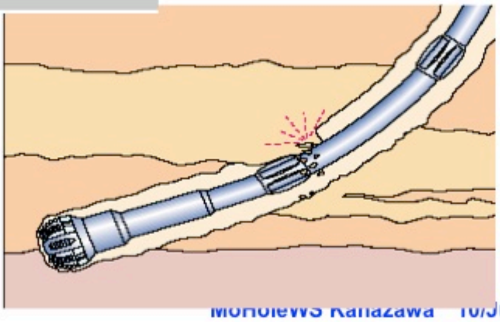
Borehole Instability – Hole trouble2

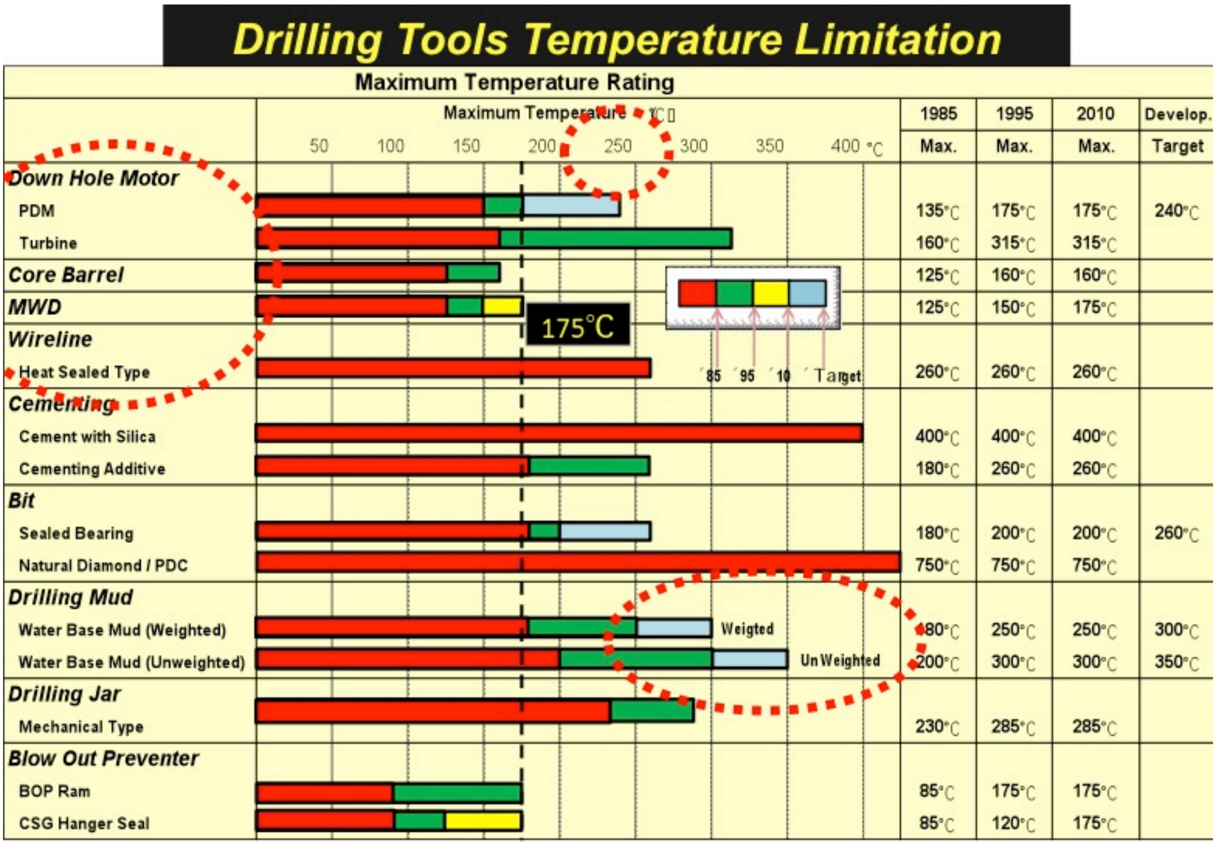
Keep hole straight to reduce the risk of failing to reach total depth



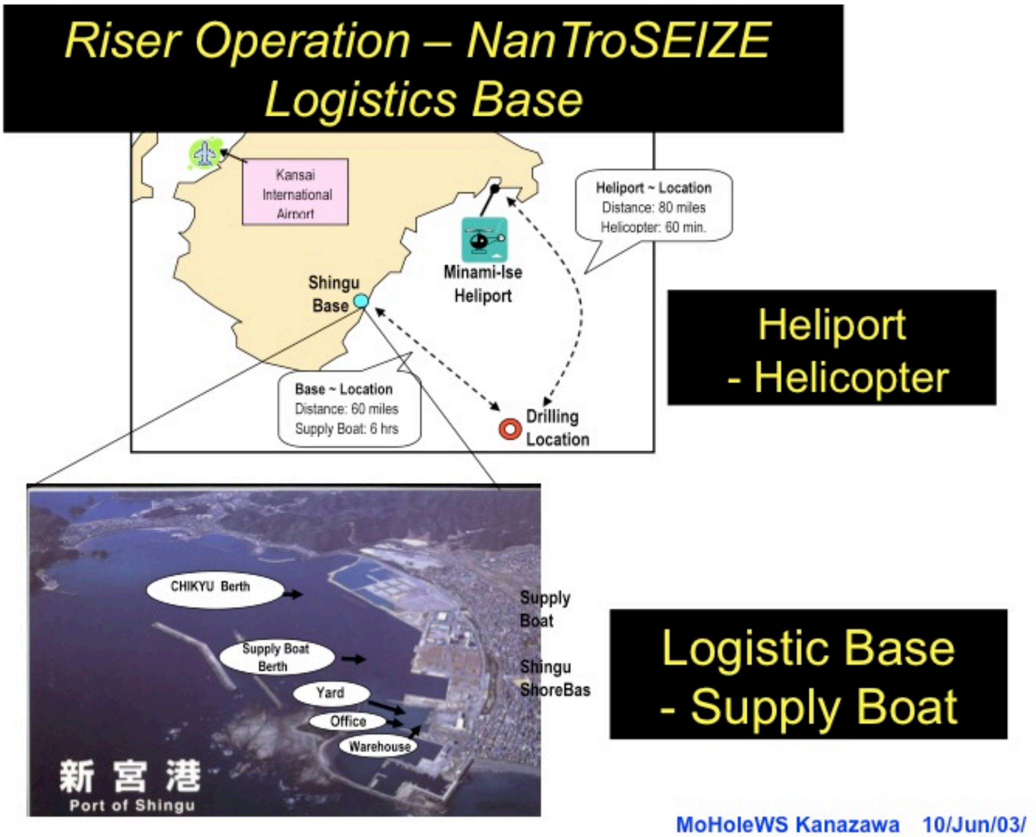


Consideration for oceanic crust *Deep Drilling*

- Drilling deep borehole into oceanic crust will require an understanding of the geomechanical processes to ensure wellbore stability and well control.
- Operating Mud windows within which to drill deep boreholes will be constrained by Pore Pressure, Fracture Pressure and Collapse Pressure.
- Mud wt windows : Efficient Hole Cleaning and proper bottom hole Pressure Management are additional operational issues needed to reduce the risk of failing to reach total depth.
- Keep hole straight to minimize the torque & drag.
- Drill a Pilot hole collecting LWD/PWD, VSP data and Leak off pressure to reduce the risk of failing to reach total depth.
- APWD: Real-Time monitoring of borehole and bottom-hole-pressures is highly recommended to ensure wellbore stability and well control.



	1985 Max.	1995 Max.	2010 Max.	Develop. Target
Down Hole Motor				
PDM	135℃	175℃	175℃	240℃
Turbine	160℃	315℃	315℃	
Core Barrel	125℃	160℃	160℃	
MWD	125℃	150℃	175℃	
Wireline				
Heat Sealed Type	260℃	260℃	260℃	
Cementing				
Cement with Silica	400℃	400℃	400℃	
Cementing Additive	180℃	260℃	260℃	
Bit				
Sealed Bearing	180℃	200℃	200℃	260℃
Natural Diamond / PDC	750℃	750℃	750℃	
Drilling Mud				
Water Base Mud (Weighted)	180℃	250℃	250℃	300℃
Water Base Mud (Unweighted)	200℃	300℃	300℃	350℃
Drilling Jar				
Mechanical Type	230℃	285℃	285℃	
Blow Out Preventer				
BOP Ram	85℃	175℃	175℃	
CSG Hanger Seal	85℃	120℃	175℃	



Crew Change by Helicopter (Shorebase - Chikyu)

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Riser site & Riser hole operation criteria

- ***BHST*** < 200 - 250℃
- ***Water depth*** < 4000m - 4500m
- ***Weather Window***: 8 months Low ***Sea current*** and Calm ***MetOcean*** conditions
- ***Seafloor Angle*** < 5 ° for the Riser Wellhesd installation
- ***Sediment*** ***thickness*** > 80m - 100m - 36" Conductor jet-in , (800m - 20" Casing)
- ***Logistics port*** < Nearby port 1000km for Supply Boat
- ***Heliport*** < Nearby port 350km for Helicopter Crew Change

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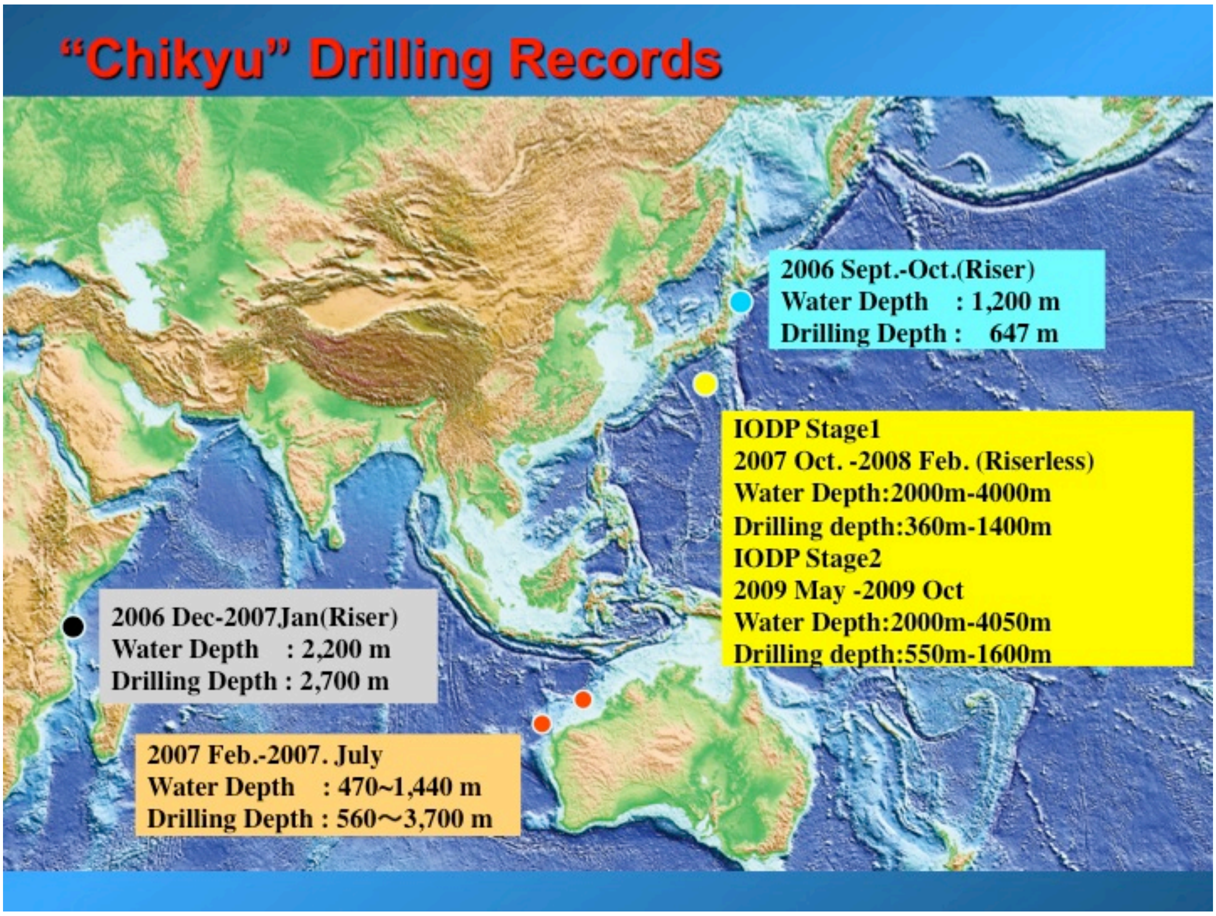
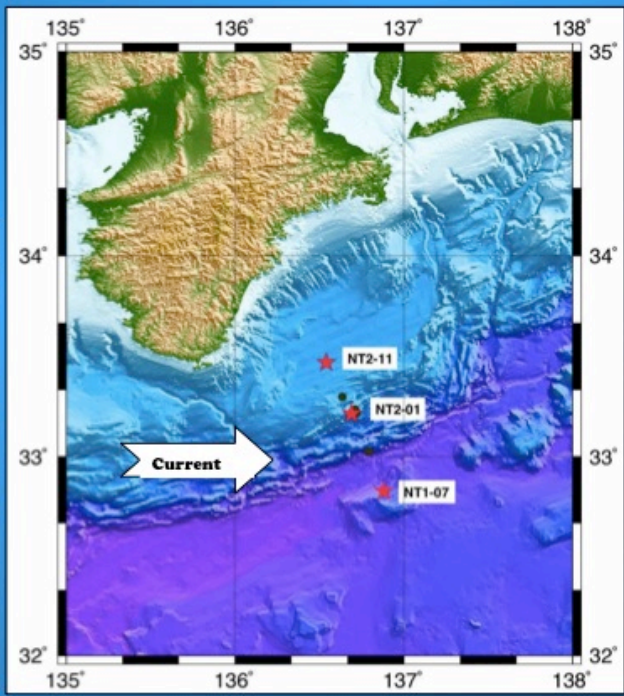
Mohole Workshop
The CHIKYU Engineering Development
Masaoki Yamao
Engineering Department
CDEX, JAMSTEC

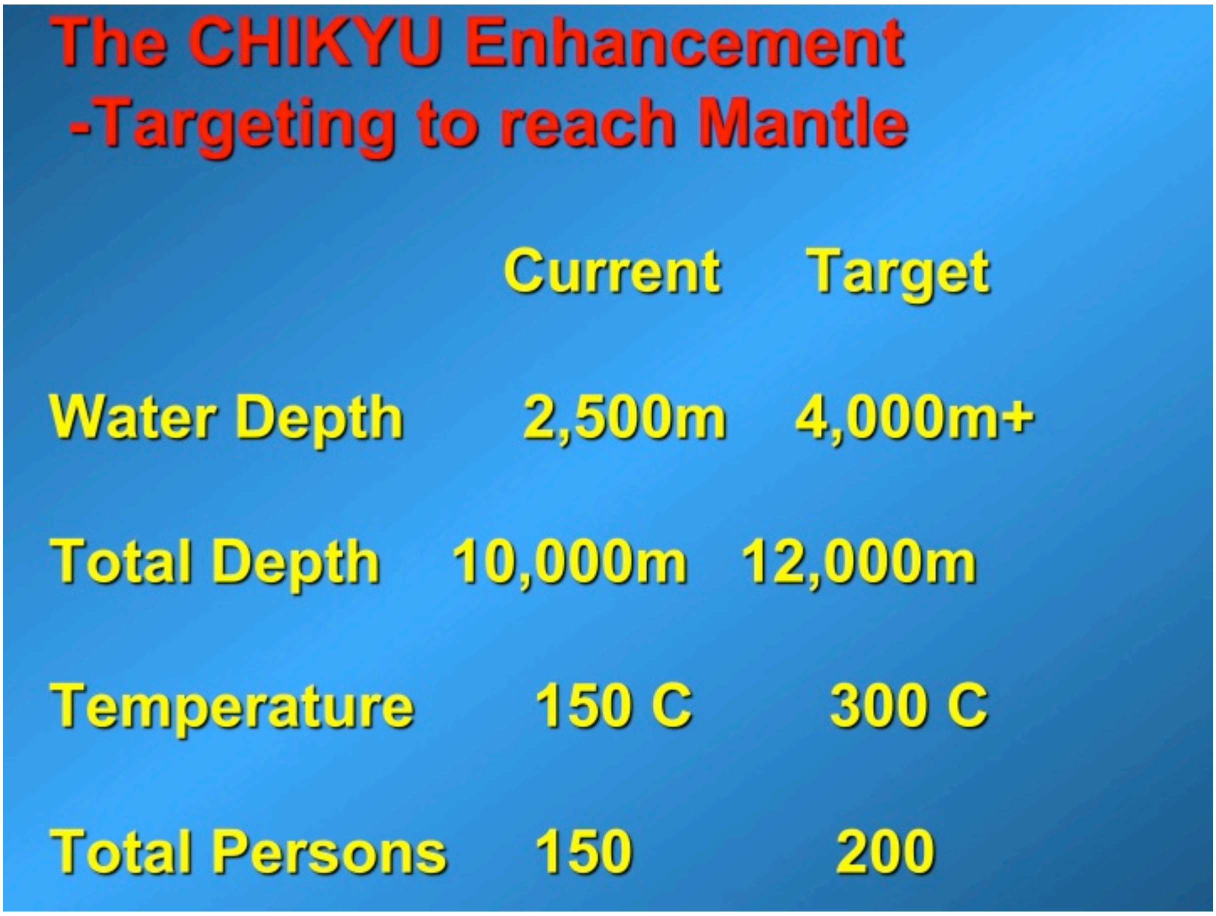

"Chikyu" Drilling Records
2006 Sept.-Oct.(Riser)
Water Depth : 1,200 m
Drilling Depth : 647 m
IODP Stage1
2007 Oct. -2008 Feb. (Riserless)
Water Depth:2000m-4000m
Drilling depth:360m-1400m
IODP Stage2
2009 May -2009 Oct
Water Depth:2000m-4050m
Drilling depth:550m-1600m
2006 Dec-2007Jan(Riser)
Water Depth : 2,200 m
Drilling Depth : 2,700 m
2007 Feb.-2007. July
Water Depth : 470~1,440 m
Drilling Depth : 560～3,700 m

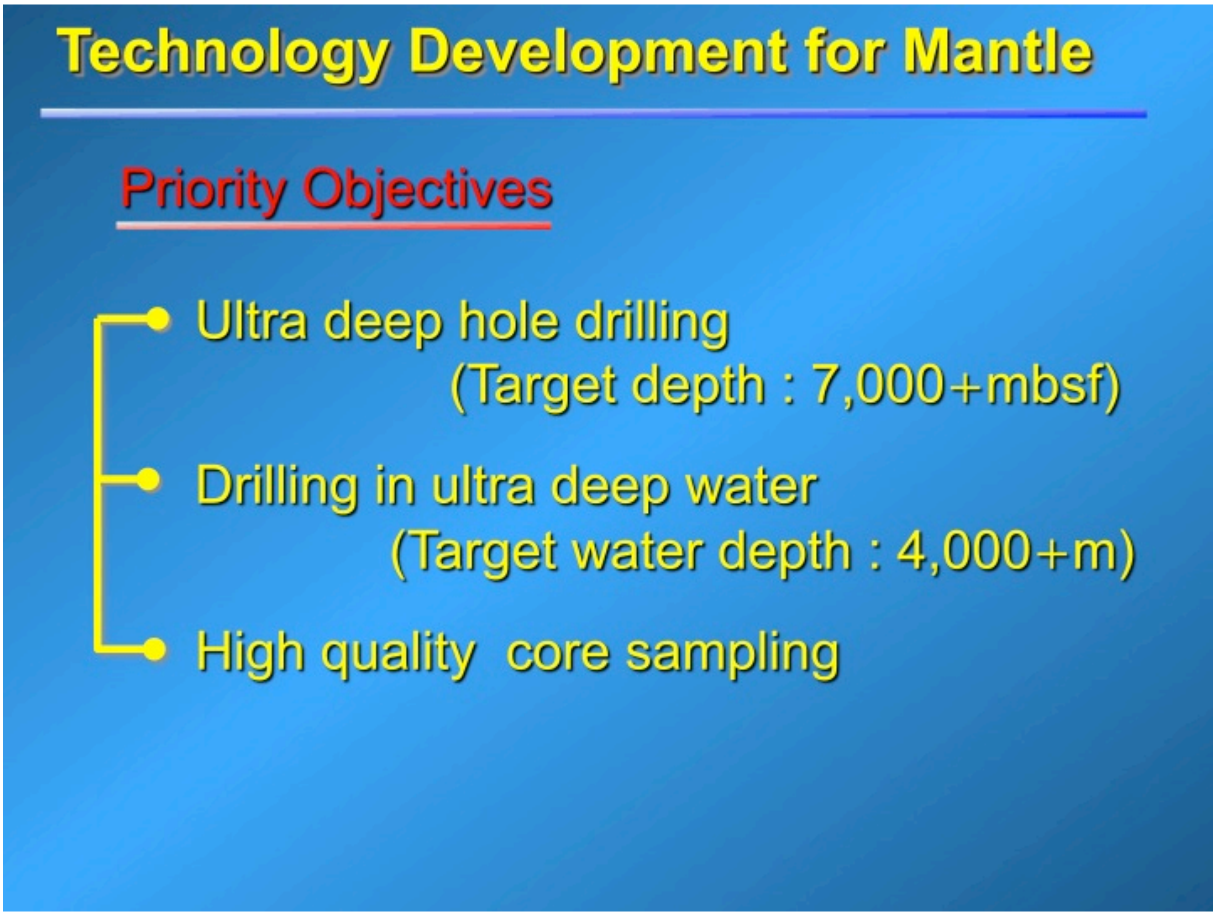
NanTroSEIZE Stage 2
(Exp. 319 & 322)

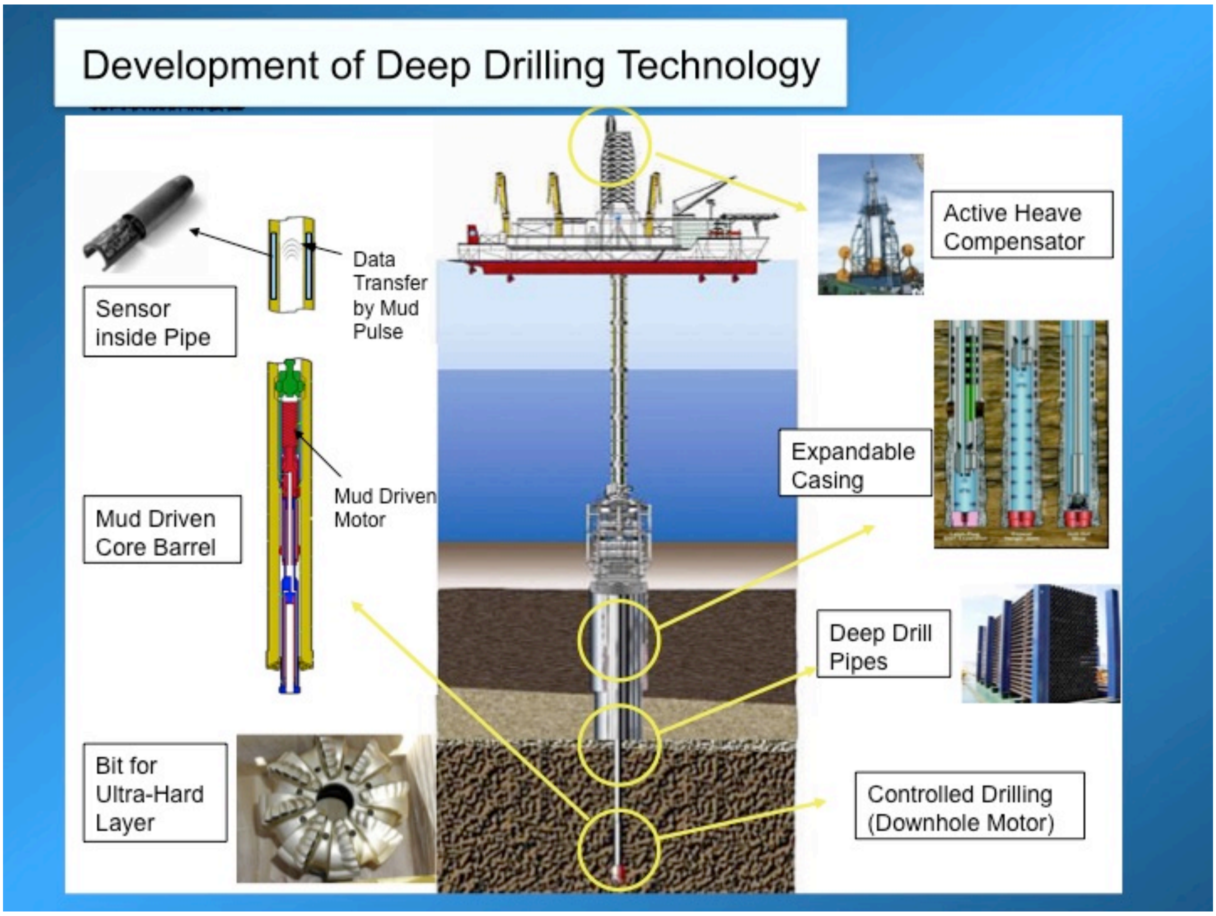
Drilling Location

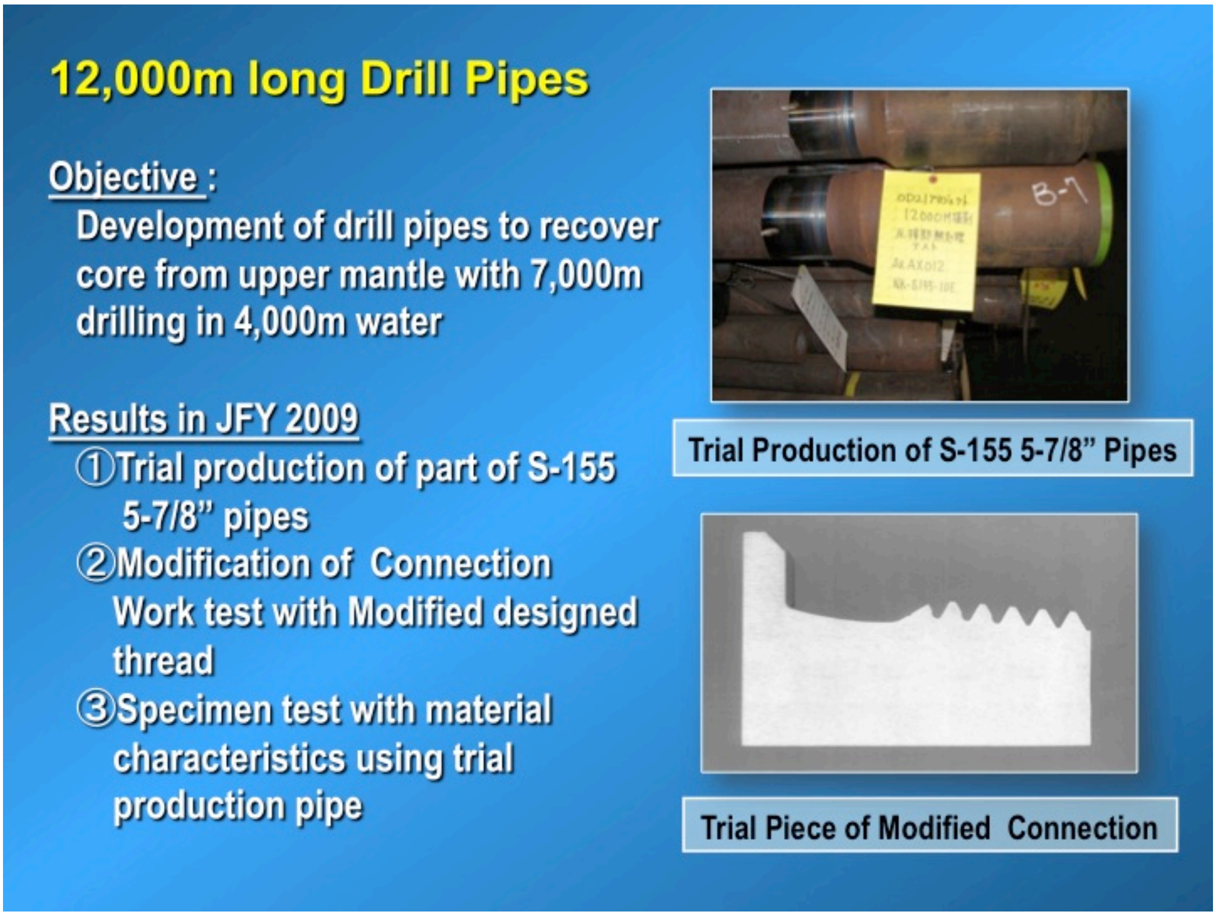


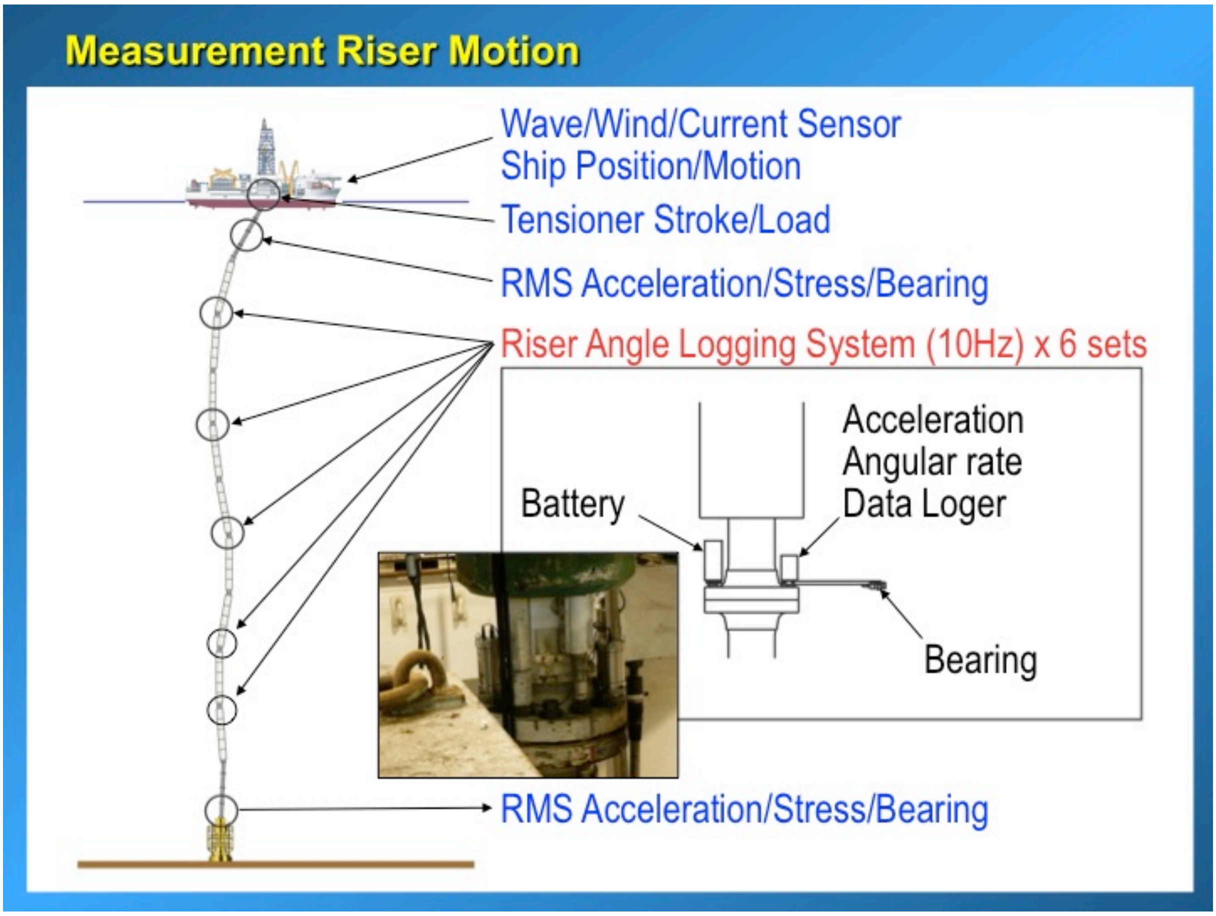
Recent Results of Technology Development

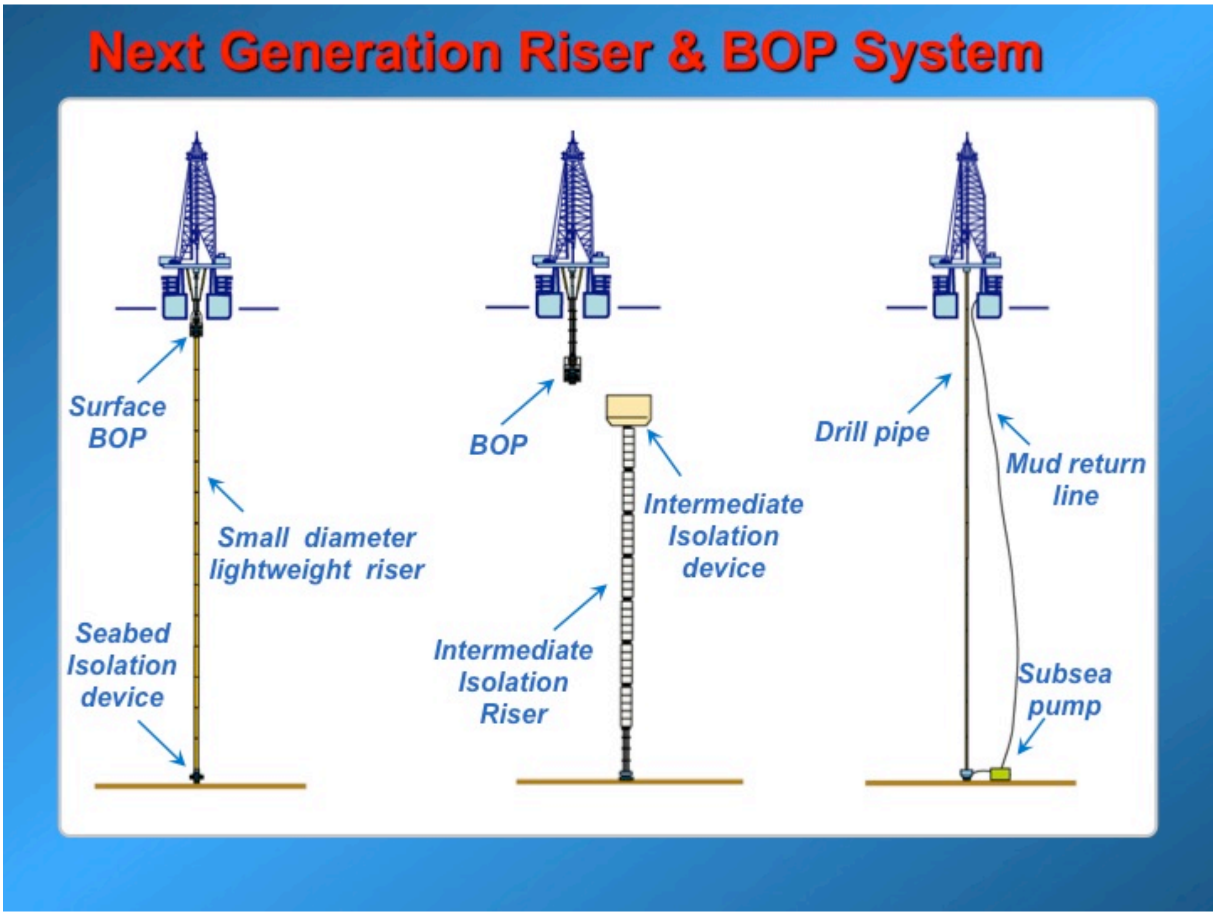

The CHIKYU Enhancement
-Targeting to reach Mantle
Current Target
Water Depth 2,500m 4,000m+
Total Depth 10,000m 12,000m
Temperature 150 C 300 C
Total Persons 150 200

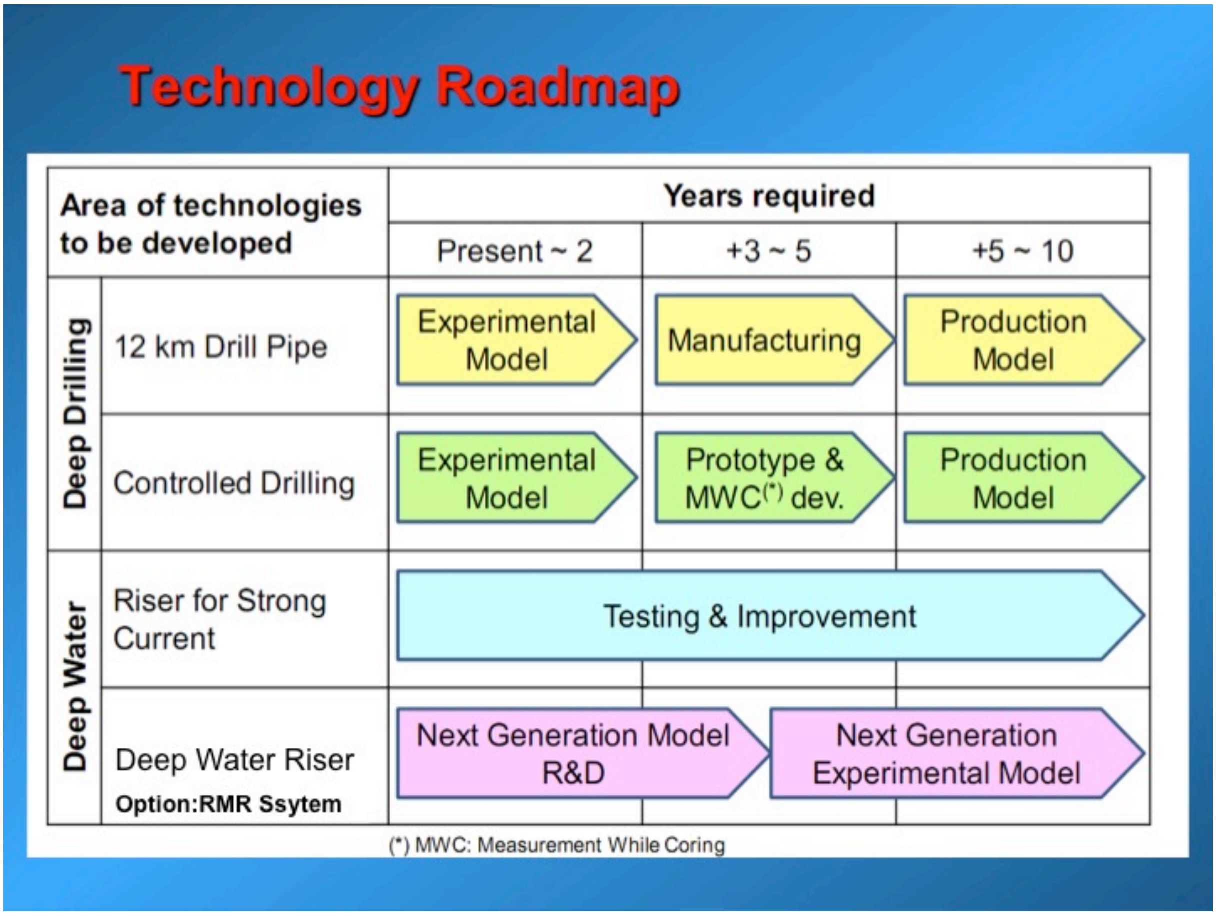

Technology Development for Mantle
Priority Objectives
Ultra deep hole drilling
(Target depth : 7,000+mbsf)
Drilling in ultra deep water
(Target water depth : 4,000+m)
High quality core sampling


Development of Deep Drilling Technology
Sensor inside Pipe
Data Transfer by Mud Pulse
Mud Driven Core Barrel
Mud Driven Motor
Bit for Ultra-Hard Layer
Active Heave Compensator
Expandable Casing
Deep Drill Pipes
Controlled Drilling (Downhole Motor)


12,000m long Drill Pipes
Objective :
Development of drill pipes to recover core from upper mantle with 7,000m drilling in 4,000m water
Results in JFY 2009
①Trial production of part of S-155 5-7/8" pipes
②Modification of Connection
Work test with Modified designed thread
③Specimen test with material characteristics using trial production pipe
Trial Production of S-155 5-7/8" Pipes
Trial Piece of Modified Connection


Measurement Riser Motion
Wave/Wind/Current Sensor
Ship Position/Motion
Tensioner Stroke/Load
RMS Acceleration/Stress/Bearing
Riser Angle Logging System (10Hz) x 6 sets
Acceleration
Angular rate
Data Loger
Battery
Bearing
RMS Acceleration/Stress/Bearing

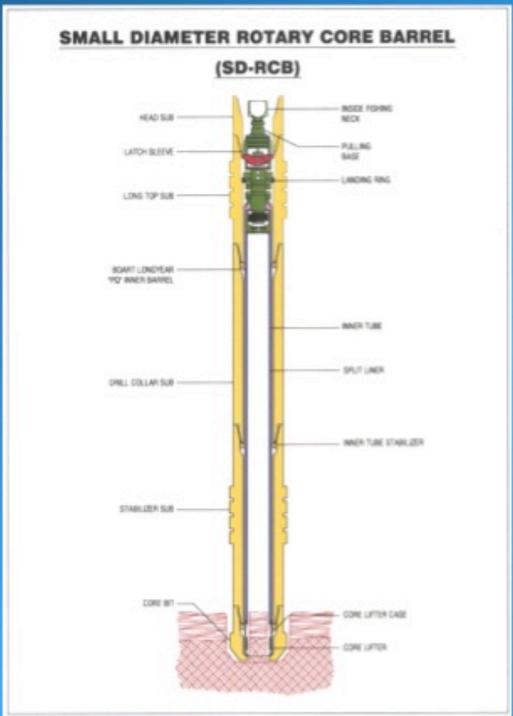

Next Generation Riser & BOP System
Surface BOP
Small diameter lightweight riser
Seabed Isolation device
BOP
Intermediate Isolation device
Intermediate Isolation Riser
Drill pipe
Mud return line
Subsea pump


Technology Roadmap
Area of technologies to be developed
Years required
Present ~ 2
+3 ~ 5
+5 ~ 10
Deep Drilling
12 km Drill Pipe
Experimental Model
Manufacturing
Production Model
Controlled Drilling
Experimental Model
Prototype & MWC(*) dev.
Production Model
Deep Water
Riser for Strong Current
Testing & Improvement
Deep Water Riser
Option:RMR Ssytem
Next Generation Model R&D
Next Generation Experimental Model
(*) MWC: Measurement While Coring


The Mohole Workshop, 3-5 June 2010 @ Kanazawa, Japan
Technical Development of Coring System in the Quest to reach the Earth's Mantle
Yuichi Shinmoto
Engineering Department
CDEX JAMSTEC
JAMSTEC
CDEX
JAMSTEC
IODP

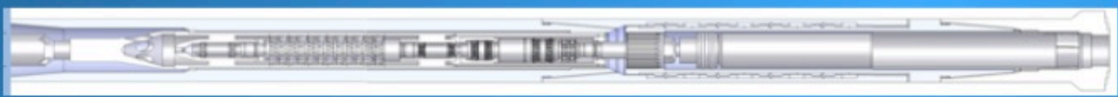

Objectives in Technical Development
• Enhancement of Core Recovery & Quality
• Improvement of Coring Efficiency
• Stabilizing & Maintaining Directional Control
• Extreme High Temperature Endurance
• Prevention of Equipment Fatigue
(Drill-pipes, Hydralift Power-Swivel (HPS), etc.)
• Borehole Stabilization with Mud Circulation

Small-Diameter Rotary Core Barrel (SD-RCB)



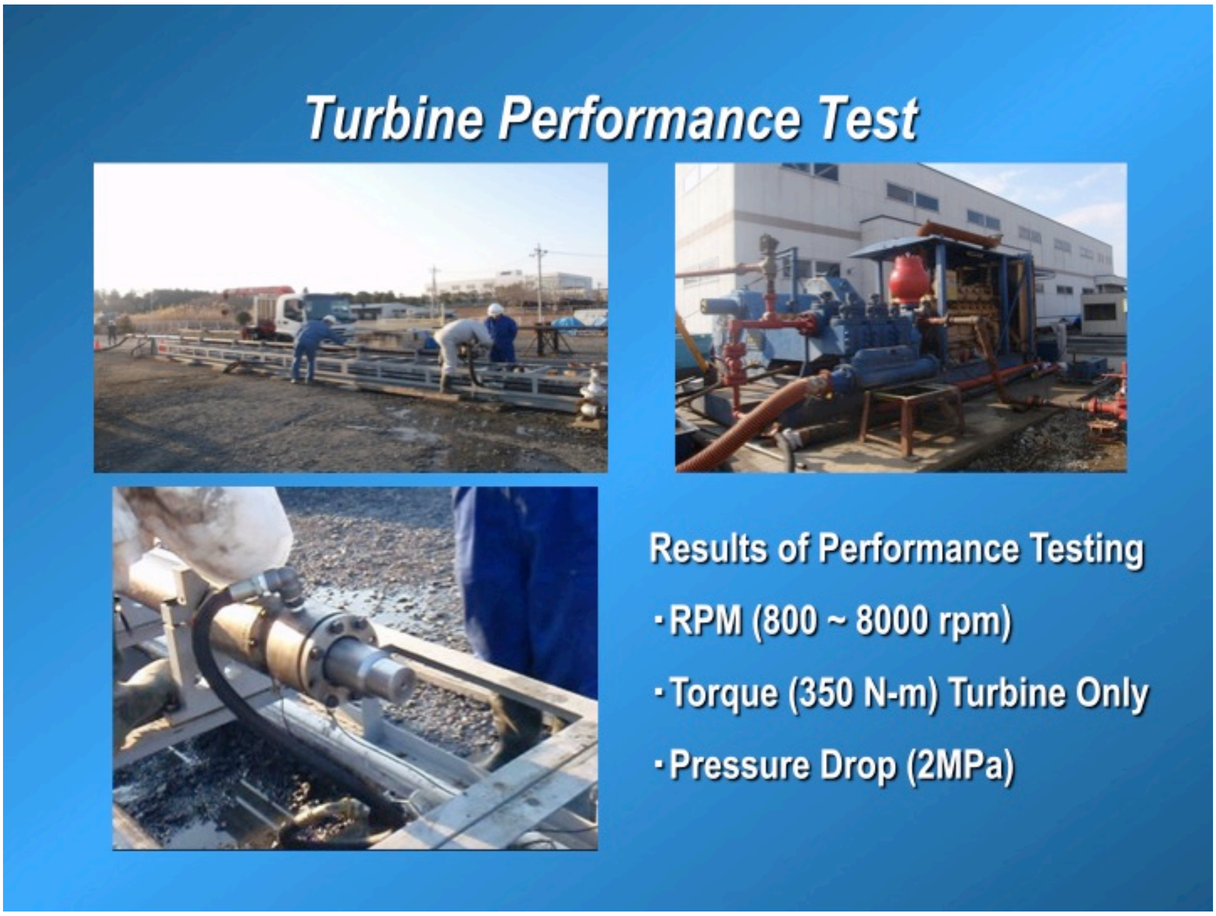
- Wireline Retrievable
- Core Bit Size (7-1/4"~8-1/2")
- Core Size (3.25") Length (15 ft)
- Diamond Bit Coring in Hard Formation

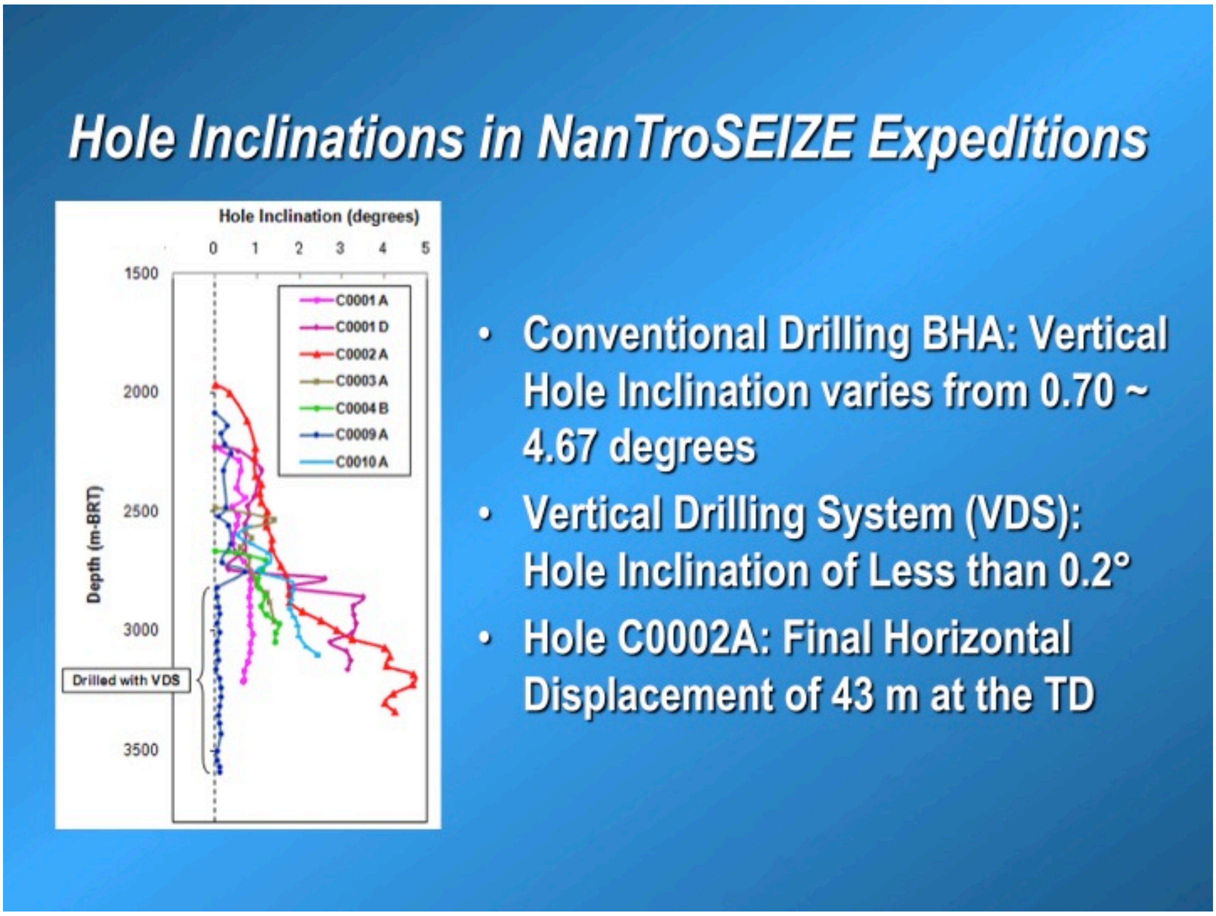
Turbo-Corer



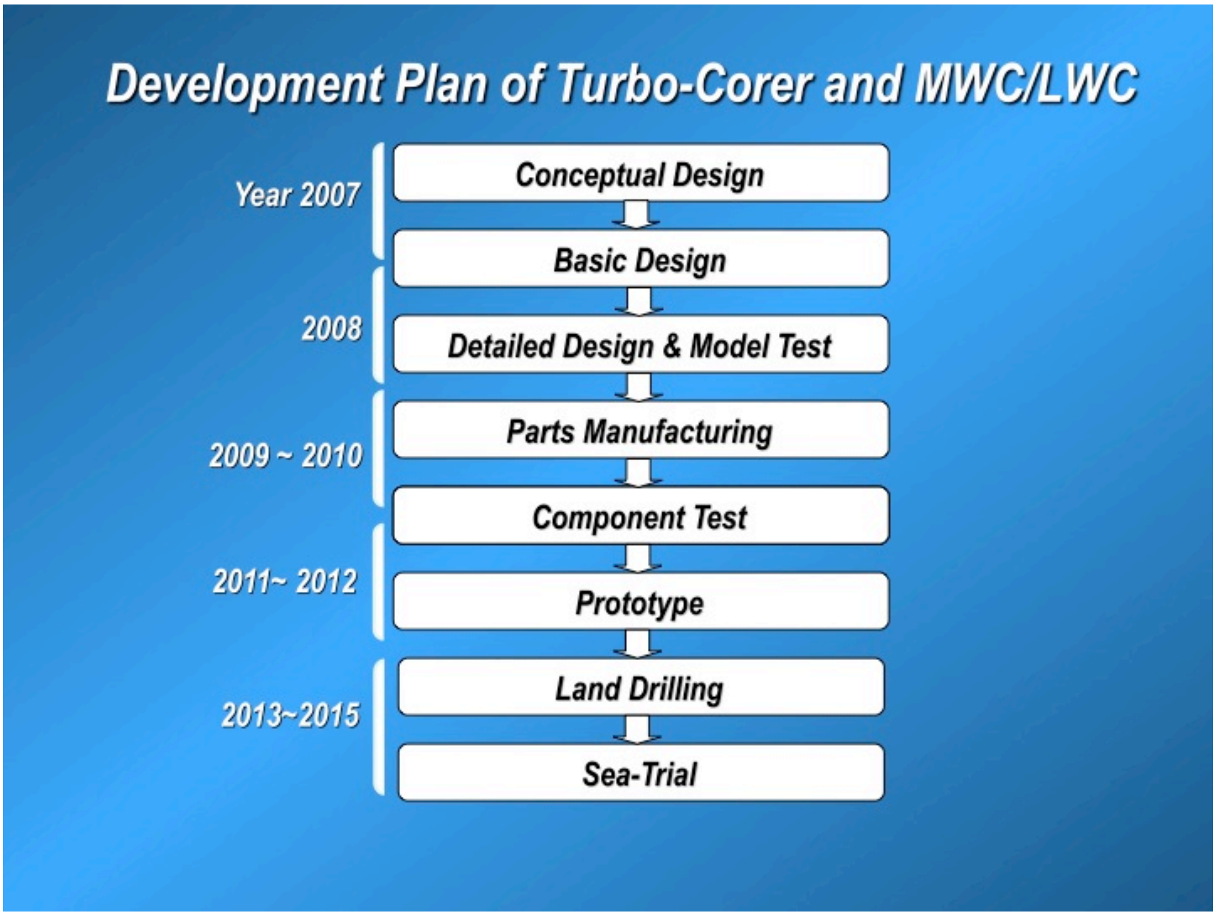
Target Specifications

Description	SI Unit	English Unit
Max. Coring Depth (Below Seafloor)	7000 (m)	23,000 (ft)
Formation Type	Medium ~ Hard	
Core Size	83.0 (mm)	3.25 (in.)
Core Length	4.5 (m)	15 (ft)
Core Bit Size	185 ~ 215 (mm)	7-1/4 ~ 8-1/2 (in.)
Operating WOB	50~100 (kN)	11~22 (k lbs-f)
Max. Operating Torque	7,500 (N-m)	5500 (ft-lbs)
Rotary Speed	100~400 (rpm)	
Max. Temperature	300 (deg.C)	572 (deg.F)
Flow Rate	600 ~ 1,200 (litter/min)	160 ~ 320 (GPM)
Mud Weight	1.0 ~ 1.8 (g/cm^3)	8.3 ~ 15 (PPG)


Turbine Performance Test
Results of Performance Testing
・RPM (800 ~ 8000 rpm)
・Torque (350 N-m) Turbine Only
・Pressure Drop (2MPa)


Hole Inclinations in NanTroSEIZE Expeditions
Hole Inclination (degrees)
0 1 2 3 4 5
1500
2000
2500
3000
3500
Depth (m-BRT)
C0001 A
C0001 D
C0002 A
C0003 A
C0004 B
C0009 A
C0010 A
Drilled with VDS
• Conventional Drilling BHA: Vertical Hole Inclination varies from 0.70 ~ 4.67 degrees
• Vertical Drilling System (VDS): Hole Inclination of Less than 0.2°
• Hole C0002A: Final Horizontal Displacement of 43 m at the TD


Development of Directional Control Coring System
Adjustable Bent Housing middle on the SD-RCB Assembly
New 8-1/2" Core Bits
Impregnated Diamond & PDC


Development Plan of Turbo-Corer and MWC/LWC
Year 2007
Conceptual Design
Basic Design
2008
Detailed Design & Model Test
2009 ~ 2010
Parts Manufacturing
Component Test
2011~ 2012
Prototype
2013~2015
Land Drilling
Sea-Trial

Drilling DEEP into HOT Oceanic Crust
Constraints and Challenges

David MAINPRICE
Philippe PEZARD

CNRS, Montpellier (France)

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SUBSURFACE

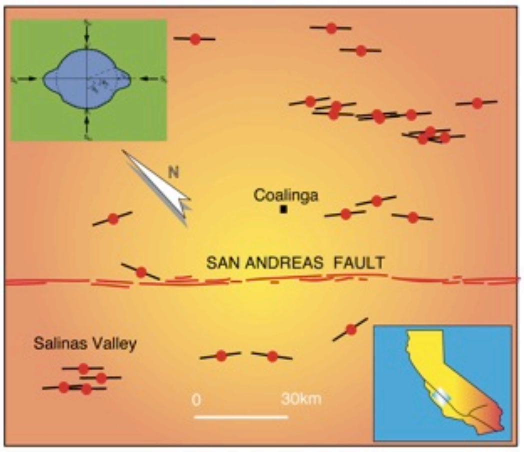
June 3, 2010, **Kanazawa (Japan)**

General remarks – stress state of a borehole wall rock

• ***We are considering horizontal stresses***

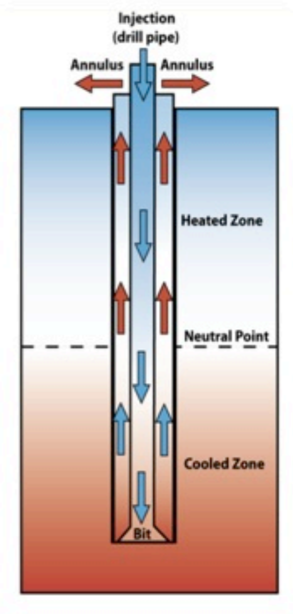
The stress state of the rock can be divided into 2 components

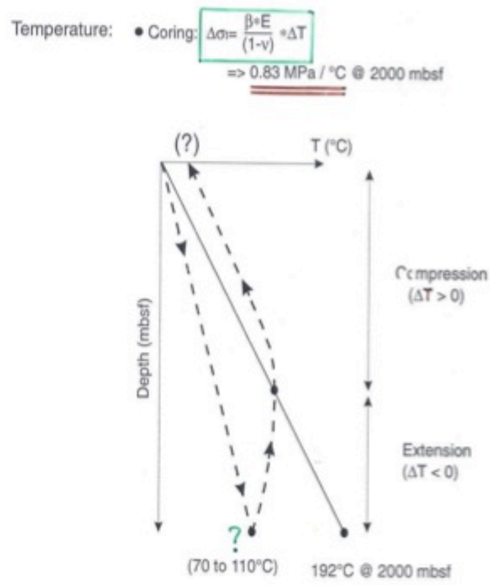
a) ***far field tectonic stress*** *that classically causes borehole break outs (e.g. around the San Andreas fault) –* ***site dependent !***



b) ***local thermo-elastic stresses*** *caused by changes in the temperature of the wall rock, which lead to brittle failure –* ***rock dependent !***

Modeling heat mining for 504B drilling
Numerical modeling of the drilling process

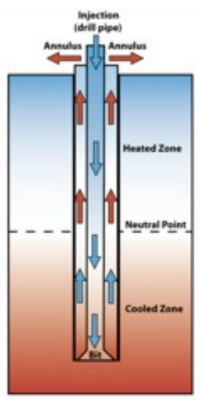


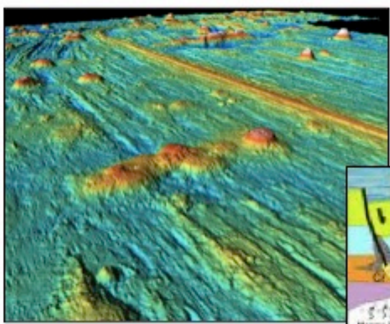


• **Numerical modeling with LOKI (finite difference)**

Drilling DEEP into HOT Oceanic Crust
Constraints & Challenges

- **THERMAL**
- **MECHANICAL**
- **TECHNOLOGY**





• **Heat mining process**

• **Structure** : heteregeneities (faults, …), physical properties
• **Dynamics** : pore pressure, stress (COSOD II; 1987)

• **High Temp (HT) logging tools**

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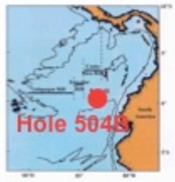
Drilling DEEP into HOT Volcanic Crust
What did we learn so far ?



- **At sea**

ODP (504B) **2111 mbsf** (192°C @ 2004 m)
Hole stopped in a crush zone
Unstable hole from the absence of telescopic casing
No particular problem in the upper crust (normal fault)
Numerous pipe shearing from small active faults
No hole deformation in "normal" drilling conditions
Important hole damages if intensive cooling
Poor core recovery (< 10% at base)

- **On land**

Kakkonda	**450°C**	World record in a geothermal context
ISOR	< 300°C	"Routine" drilling for the past 40 years !
IDDP	?	Large difficulties with heterogeneities so far

(and several other locations in the US, Italy, New Zealand, …)

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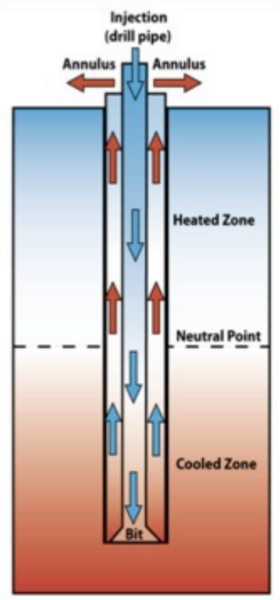
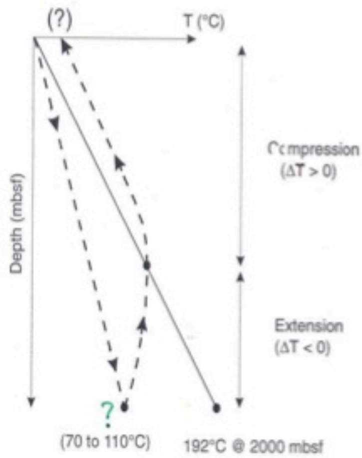
Modeling heat mining for 504B drilling
Numerical modeling of the drilling process

$\Delta T = T_{fluid} - T_{wall\ rock}$



Temperature: • Coring: $\boxed{\Delta\sigma_t = \frac{\beta \cdot E}{(1-\nu)} \cdot \Delta T}$

=> 0.83 MPa / °C @ 2000 mbsf



- **Numerical modeling with LOKI (finite difference)**

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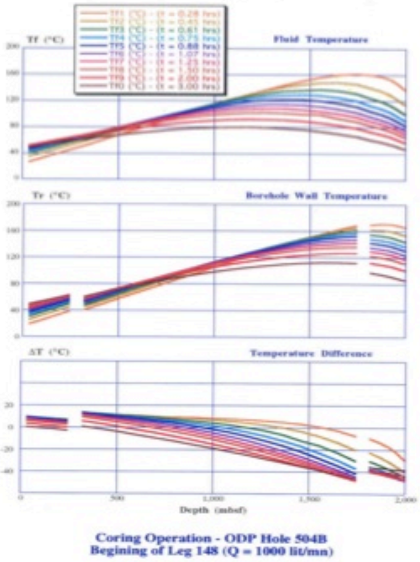
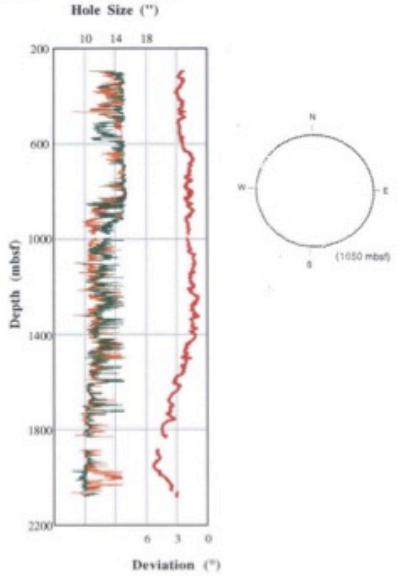
Modeling heat mining for 504B drilling
"Normal" drilling conditions with the JOIDES

Time from the moment the drill pump is started. $\Delta T = T_{fluid} - T_{wall\ rock}$





• **ΔT_{max} = 45°C at 2000 m (ΔS ~ 35 MPa) : stable hole**

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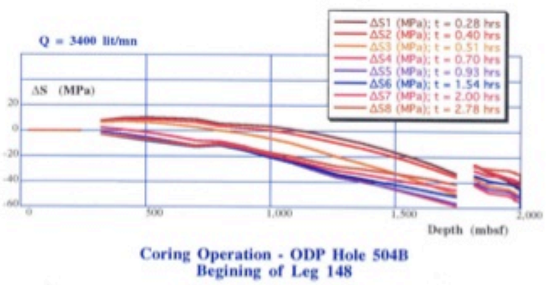
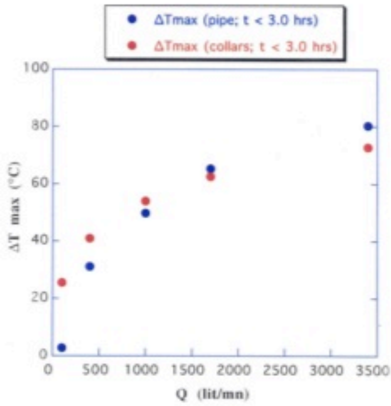
Modeling heat mining for 504B drilling
Influence of intense cooling (fishing, …)

$\Delta T = T_{fluid} - T_{wall\ rock}$

collars = base of the pipe

Time from the moment the drill pump is started.





• **If Q = 3400 liter/min at 2000 m :**

ΔT_{max} = 76°C (ΔS ~ 60 MPa) : tensile failure of the borehole

(basalt tensile rupture ranges from 50 to 70MPa after Bauer & Handin, 1985)

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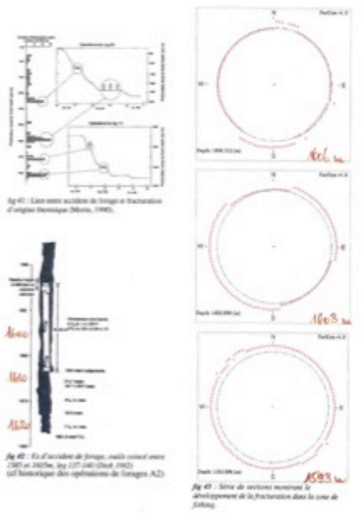
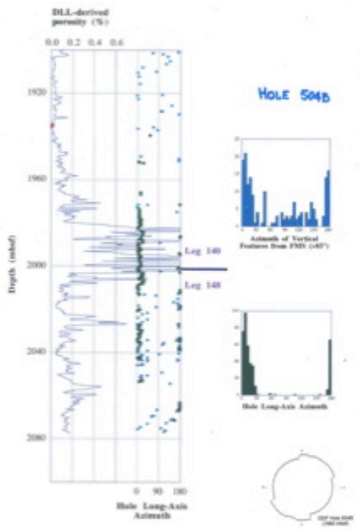
Modeling heat mining for 504B drilling
Influence of intense cooling (fishing, …)





Fishing pipe at 1620 m (ODP 140) *Hole cooling at 1980 m (ODP 148)*

- ***Radial, vertical and horizontal thermal ruptures***

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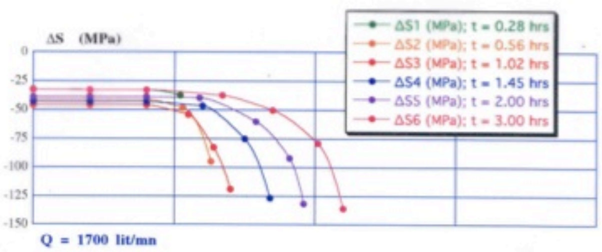
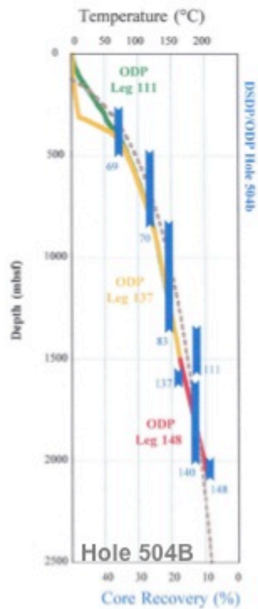
Modeling heat mining for 504B drilling
Influence of temperature on the coring process





Coring at 2000 m (T_{fluid} ~ 50°C & T_{rock} ~ 190°C) :

the drillbit progresses faster (50 to 100 cm/hr) than the heat (~6 cm/hour) in diabase => geothermal temperatures are being cored with 50°C fluid, generating a local temperature gradient of up to 150°C

- ***ΔS > 100 MPa : the basalt core is shattered** at the bit*
- ***the core recovery** decreases with depth & temperature*

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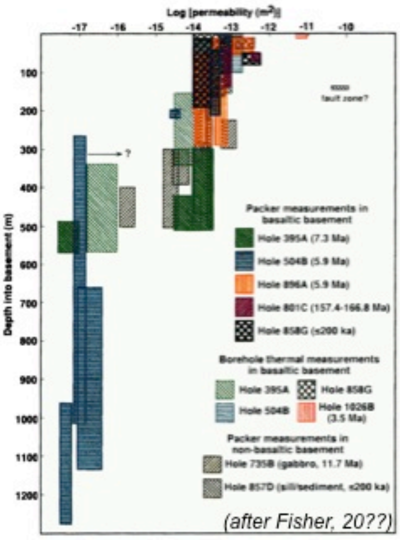
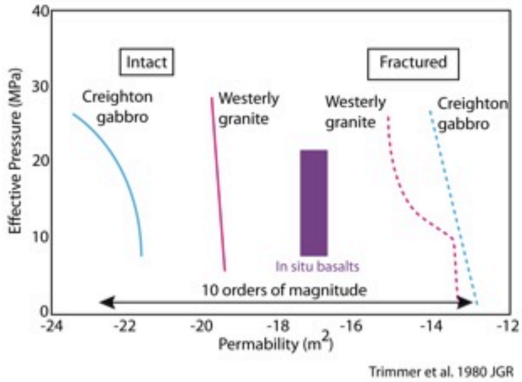
Heat mining efficiency in the deep oceanic crust
Influence of permeability on drilling conditions





- except at shallow depth (and in faults), rock permeability is expected to be low and **drilling conditions <u>undrained,</u> further weakening** the borehole surface

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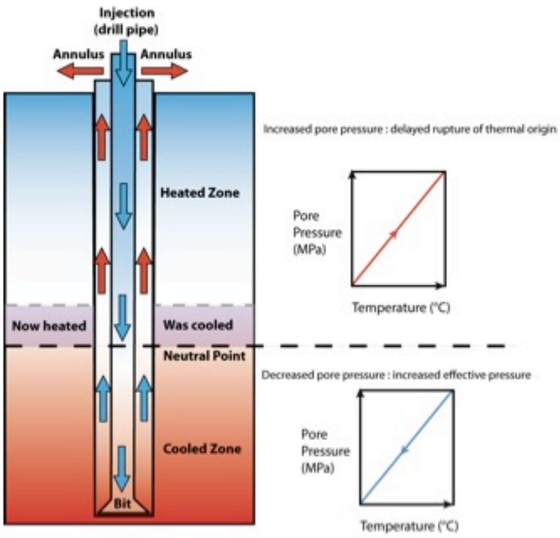
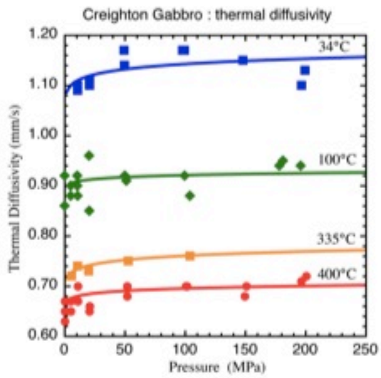
Heat mining efficiency in the deep oceanic crust
Influence of pore pressure and thermal diffusivity





- **an increased pore pressure** will delay the heat penetration into the rock, hence to **weaken the borehole surface**
- **the thermal diffusivity** is expected to decrease with increased temperature**, reinforcing the previous effect**

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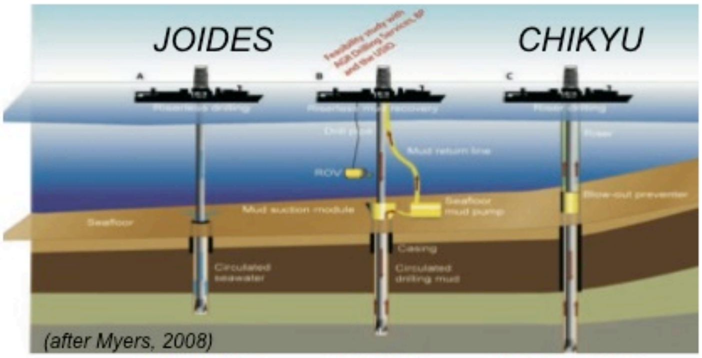
Managing heat stress while drilling the oceanic crust
Influence of drilling technology in the water column



POOR POOR BETTER

- ***RISER drilling*** *is the only way to keep the* ***drilling fluid hot*** *through the cold ocean (2°C from 600 m down), hence :*
  - ***- to reduce thermal stresses in the hole***
  - ***- to increase borehole stability & core recovery***
- ***Heat stress THM modelling while drilling*** *required to adjust the drilling parameters and thereby minimize the thermal stresses in the hole.*

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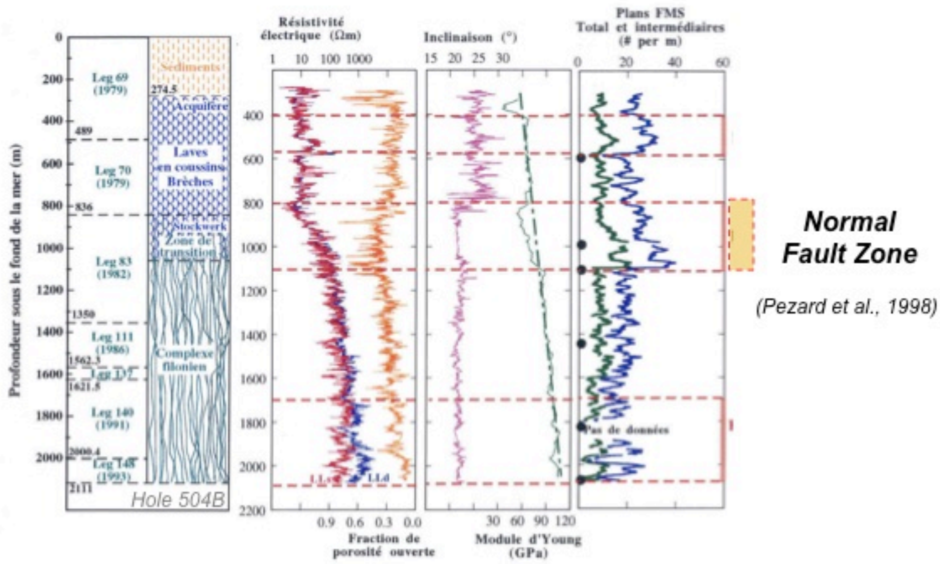
Drilling DEEP into the Oceanic Crust
Influence of the structure on borehole stability



- ***No major difficulty crossing a 300 m thick normal fault*** *at shallow depth into the crust (ODP Hole 504B)*

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Drilling DEEP into the Oceanic Crust

Basic HT logging tools requirements for MoHole drilling

- ***Temperature surveys :***
  - *to measure **in-situ temperature** when re-entering the hole*
  - *to provide **boundary conditions for** THM numerical **modeling***
  - *to prepare for drilling/logging **operations***
  - *to detect the presence of **fluid flow** into/out of the hole*
- ***Borehole stability control (from acoustic or ''BHTV'' images, in order to detect) :***
  - ***ruptures** of the borehole surface (origine, mapping, …)*
  - *identify the **rupture mode** (tensile, compressive ?)*
  - *detect and map **shear along active fault** planes*
  - *document changes with depth of the in-situ stress field*
  - ***plan ahead** drilling operations*
- ***Temperature and BHTV surveys should be run both at the beginning and at the end of each scientific drilling cruise** to minimize drilling accidents and lost time while at sea.*

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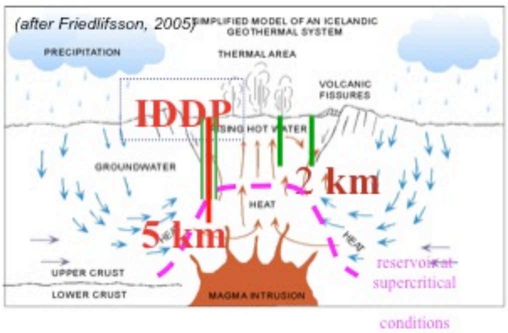
Drilling DEEP into the Oceanic Crust

New HT logging tools : HiTI EC project



HiTi
(2007-2010)

Coordinator :
***ISOR** (Iceland)*

Partners :
***CNRS** (France)*
***BRGM** (France)*
***CRES** (Greece)*
***CALIDUS** (UK)*
***OXATEC** (UK)*
***ALT** (Lux)*
***GFZ** (D)*

- ***HiTI objective** : to plan for **logging as part of IDDP,** to design, built and field test in Iceland **new High Temperature Instruments** for it.*
- ***Completed & tested so far by HiTI :***
  - ***BHTV images** (300°C) and **GR** (300°C) from ALT (wireline)*
  - ***production tool** (400°C) from CALIDUS (p, T, C_w tool)*
  - ***fiber optical monitoring** device (250°C) by GKZ (DTS)*
- ***To be completed in 2010 :***
  - ***DLL resistivity** (300°C) from CALIDUS (wireline)*
  - ***HT temperature** (320°C) from BRGM (wireline)*

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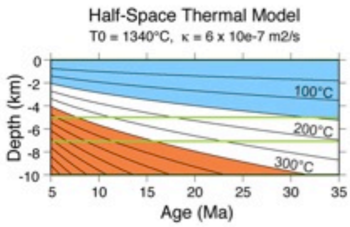
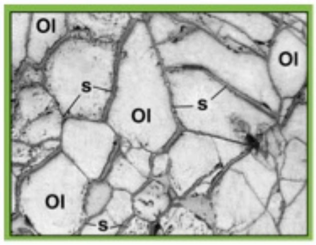
• Thermo-elastic stresses: caused by the anisotropy of thermal expansion and elasticity

*a) Due to **rapid** changes in wall rock temperature due cooling caused by the circulation of cold drilling fluids (classical phenomenon in Petroleum exploration), near the Moho temperatures are high.*

*b) Due to **slow** geological cooling, hot asthenosphere to cold lithosphere transition form mid-oceanic ridge axis (e.g. perdotite mantle rock) or cooling from the axial magma chamber (AMC) of a magmatic rock (e.g. oceanic crust composed of basalt or gabbro) – this is general ignored ! But it is is responsible for grain boundary cracking.. and can lead to fluid penetration (enhanced cooling, further cracking) and brittle failure.*





Thermo-elastic stresses and grain boundary cracking due to slow geological cooling

The stress intensity factor for tensile mode 1 cracks on a grain boundary (Fredrich and Wong 1986 JGR), depends on;

Physical conditions :
pressure (Pc), temperature change $\Delta T = (T_{plastic} - T_{wall\ rock})$, is the temperature at which the elastic stress were set to zero.

Mineral physical properties :
For isotropic elasticity (Young's modulus (E), Poisson's ratio (υ) and thermal expansion anisotropy

Microstructural parameters :
flaw size (a), grain size (L=grain size/2)

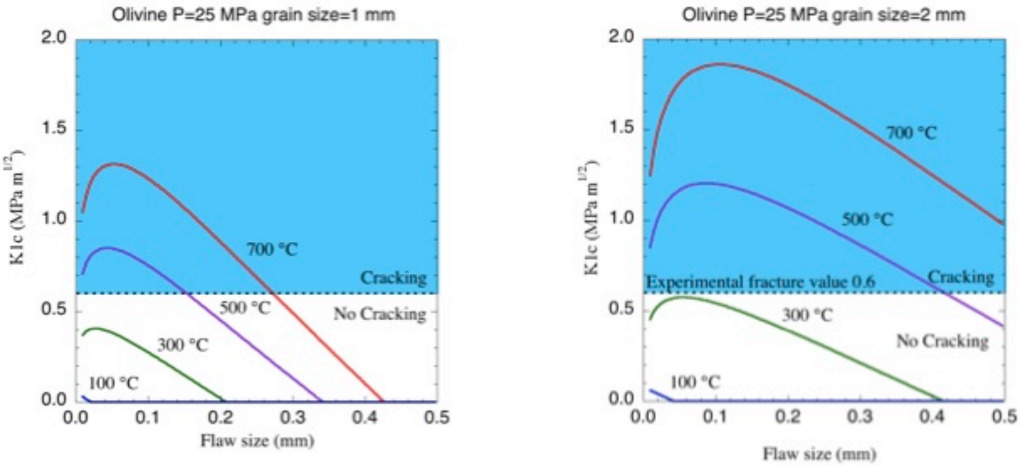
$$K_{1c} = \sqrt{\frac{2}{\pi a}} \int_0^a \left(\frac{\sigma_{yy}(x)\sqrt{x}}{\sqrt{a-x}} \right) dx - P_c \sqrt{\pi a}$$

where

$$\sigma_{yy}(x) = \frac{E\,\Delta\alpha\,T}{2\pi\left(1-\upsilon^2\right)} \left\{ \frac{4L^2}{4L^2+\left(2L-x^2\right)} - \frac{4L^2}{4L^2+x^2} + Ln\left[\frac{2L-x}{x}\right] - \frac{1}{2}Ln\left[\frac{4L^2\,(2L-x)^2}{4L^2+x^2}\right] \right\}$$

Thermo-elastic stresses and grain boundary cracking due to slow geological cooling

Illustration of the method to olivine, predicting more cracking for larger grain size and high temperature differences. Under cooling from $T_{plastic}$ (≈ 900°C) – $T_{wall\ rock}$ (≈250°C) at Moho gives ΔT = 650°C



Drilling DEEP into HOT Oceanic Crust : Constraints & Challenges

- ***In-situ thermal stresses :***
  - *can be reduced from **RISER** drilling,*
  - *can have a major and negative impact on **core recovery,***
  - *will be reduced from **real-time THM modeled** before and during, drilling to define drilling parameters and anticipate failures,*
- ***Borehole instabilities :***
  - *can be detected and monitored from **repeated BHTV logging,***
  - *can be reduced from **real-time THM modeling,***
  - *will be gradually eliminated with **telescopic casing** strings,*
- ***Site structure and heterogeneities :***
  - *can be detected and monitored from **repeated BHTV logging,***
  - *have not proven in the past to offer major difficulties in the ocean,*
- ***HT logging equipment :***
  - *a basic set was developped by HiTI to cover hole stability needs,*
  - *this set requires further tools development to obtain a comprehensive description of the crust at T > 200°C.*

Géosciences Montpellier
SUBSURFACE

ICELAND DEEP DRILLING PROJECT

What is IDDP?

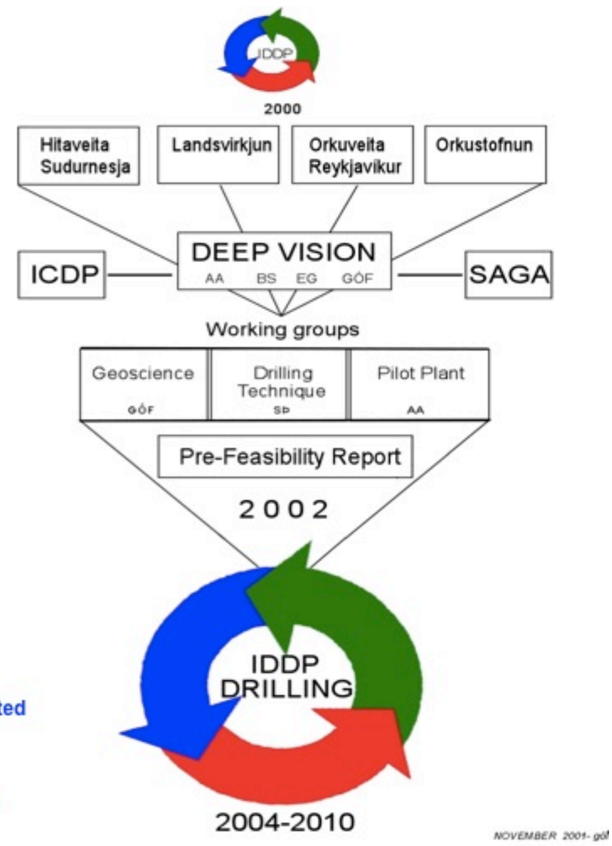
IDDP is a long-term geothermal research program, established in year 2000
The goal is to improve the economics of geothermal energy by producing supercritical fluids from 4-5 km depth

International Scientific Continental Drilling Program (ICDP) supported meetings and 2 Workshops in 2001 and 2002
(PI's: GÓF - Wilfred A. Elders and Seiji Seito)

A team of international scientists was established with some 60 research proposals and about 100 - 150 international scientists, engineers and their students from at least 15 countries

Status 2005 : Requests for funds for scientific drilling granted by ICDP (1.5 M USD) and by US NSF (3.0 M USD)

Candidate drillhole: RN-17 was drilled late in 2004 and completed to 3.1 km depth in February 2005. This well was flow tested in November 2005, and subsequently lost in February 2006 upon cleaning. Cost 4-5 M USD



IDDP Consortium Since 2008

HS ORKA HF
Landsvirkjun
Orkuveita Reykjavíkur
ALCOA
ORKUSTOFNUN National Energy Authority
Statoil
National Science Foundation
icdp

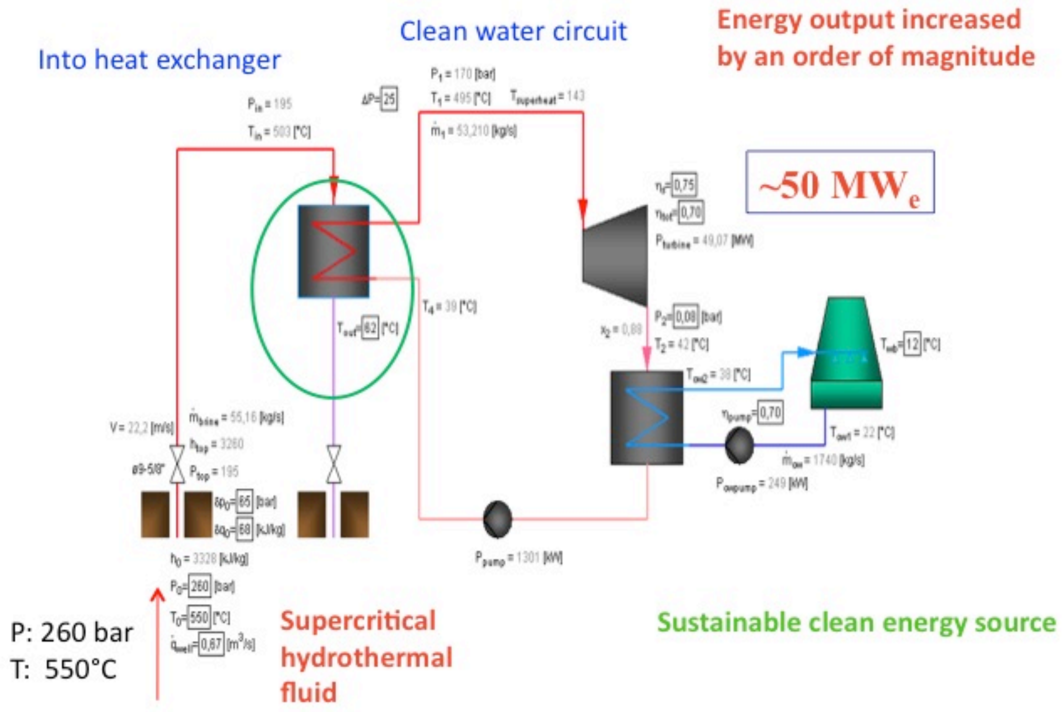
Principal Science Investigators:
www.icdp-online.org
Gudmundur Omar Fridleifsson, HS orka hf
Wilfred A. Elders, University of California at Riverside
And a team of international scientists

Why are the energy companies interested ?

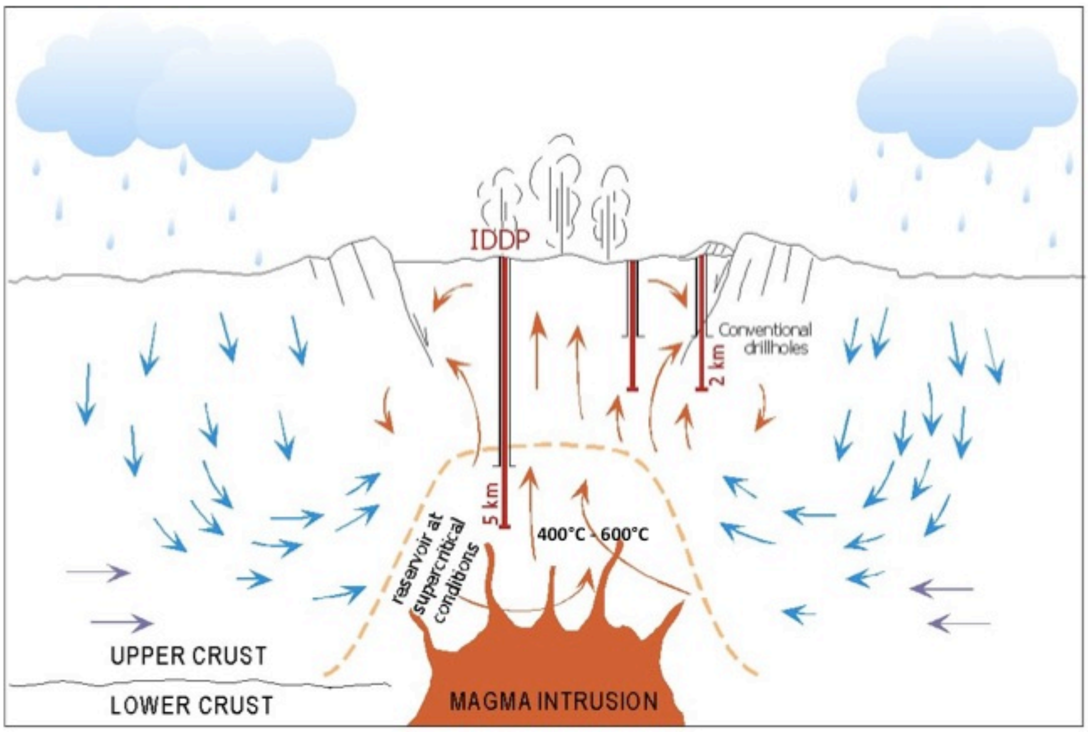
Electric Power Generation

	Conventional dry-steam well	IDDP well
Downhole temperature	235 °C	430 - 550 °C
Downhole pressure	30 bar	230 - 260 bar
Volumetric rate of inflow	0.67 m^3/s	0.67 m^3/s
Electric power output	~ 5 MW_e	~ 50 MW_e

This comparison is based on the same volumetric flow rate of inflowing steam



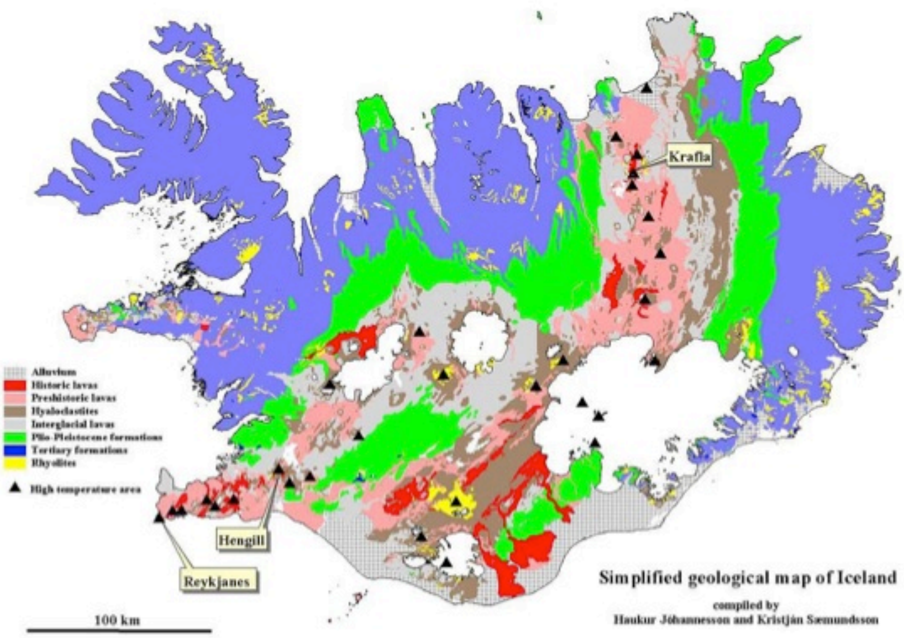
By drilling deeper we should reach supercritical conditions



Iceland Deep Drilling Project (IDDP)

- The plan for IDDP is to drill three (3) wells 4.5-5.0 km into the roots of high-temperature geothermal systems in Iceland and seek to reach supercritical conditions >374°C and >22.1 MPa.
- A generic well to achieve the above objectives was designed to serve the dual purpose of a production- and a science well.

Proposed three IDDP sites



Production vs. scientific well

Design premises:

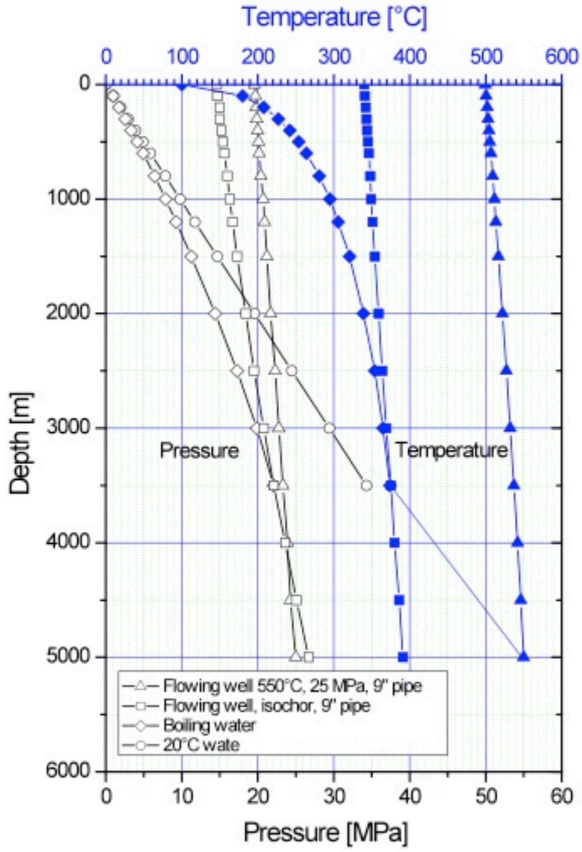
- The well should be of sufficient diameter to be suitable as a production well.
- Coring should be done in the expected transition to and inside the supercritical zone, to the extent that science funds would allow.
- Several well designs and coring systems were considered and the conclusion was that the final section below 3500 m should be drilled 8 ½" and 10 m long spot cores collected, rather than the initial idea of continuous coring (HQ) below 2400 m in a 4" diameter hole.

Expected geological conditions

- The T&P basis of the casing design were boiling point depth (BPD) curve to the Critical Point (~3500 m) and a maximum temp. of 500°C in the well. Lithostatic pressures not expected.
- The wells are to be drilled within three (3) geothermal fields with more than 30 wells each, <3000 m each. Drilling there has been trouble-free, with a few exceptions, and the geological conditions are well known down to 2.5 km.
- The lithology is composed of basaltic lava formations and sub-glacial hyaloclastite formations above ~ 1.5 km depth, and more frequent intrusive rocks, of different type, below that depth.

T&P design premises

- The static reservoir T&P, the undisturbed conditions at depth.
- Well flowing T&P, dynamic profile.
- Predictions were also made of circulation temperatures for each section of the well at different rig pump flow rates during drilling.



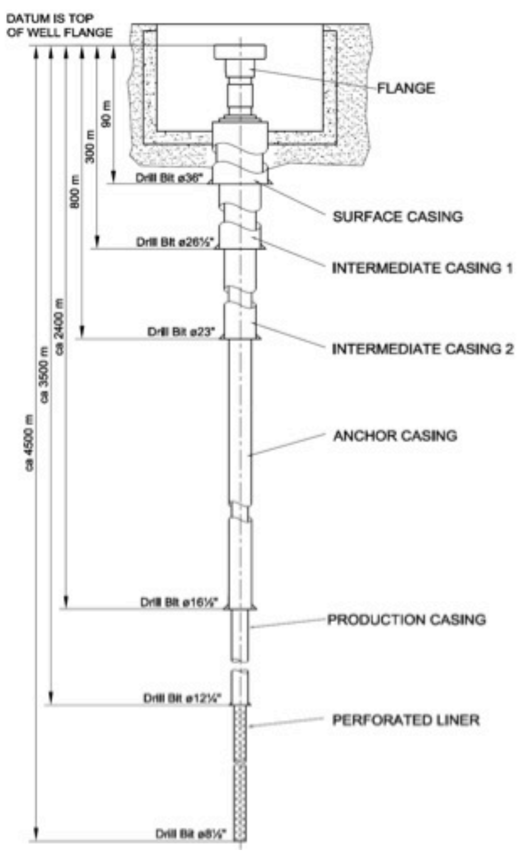
Conclusions

- The drilling of the IDDP well is a major step for geothermal drilling. Compared to existing HT drilling in Iceland in the past:
  - Extend drilling depth from 3 km to 4.5 km
  - Temperature from 340°C to 400-500°C
  - Cementing casing to twice the depth before.
  - Larger hole and casing sizes.
  - More coring and at extreme temperatures.
  - Four times the cost of a conventional well.

New challenges

- Risk of intersecting magma and acid fluids, as have been encountered at Krafla over the past few years.
- Greater depths and temperatures than before.
- Circulation temperatures and life of bits.
- Cementing of long casing strings where formation temperatures are high and losses are to be expected.
- Cement design and mud program.
- Casing and connection strength.
- Wellhead temperature and pressure.

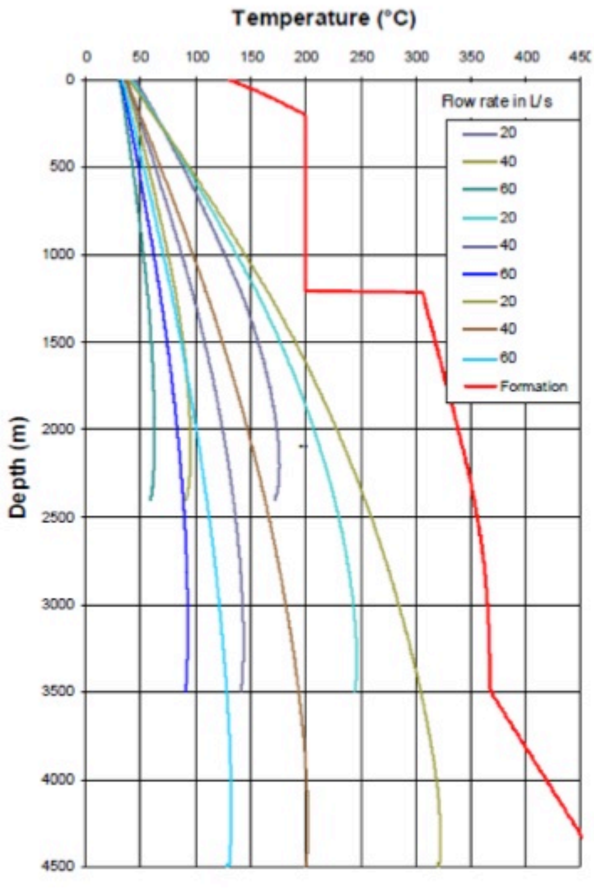
IDDP-1 WELL DESIGN



For Coring at Extreme Temperatures, a New Core Barrel was designed and operationally tested for the Iceland Deep Drilling Project

Expected circulation temperatures of IDDP-1

The return temperatures
for 20, 40 and 60 L/s
are shown for:
2400 m
3500 m
4500 m



Design features of the core barrel

- Spot-coring barrel to collect 10 m long cores.
- Diamond impregnated bit 8 ½" od x 4" core.
- Matrix allows for a rotational speed (RPM) between 70 and 160 RPM – actual 70-110 RPM.
- Weight on bit (WOB) should be between 5.4 – 11.4 tonnes – actual 3-10 t.
- Flushing (water) 30 – 40 L/s – actual 25-30 L/s.
- Float valve in core barrel head.
- Temperature logger embedded inside barrel.

Trial run of IDDP core barrel in RN-17B

- Well RN-17B was in December 2008 being reconditioned by sidetracking it out of well RN-17 at 930 m depth below the production.
- Spot coring was performed at 2800 m depth.
- Rock formation: basalt intrusions.
- Well diameter 12 ¼", inclined 35°.
- Formation temperature is 315°C.
- There were losses near bottom that aided the cooling of the well.

Týr at well RN-17B on Reykjanes

Briefing meeting. Crew 6 persons

Temperature Recording

The Temperature Probe (memory tool) assembled in its housing is attached to the inner core barrel head assembly.

Maximum Temperature Strips made of wax were also inserted into the barrel

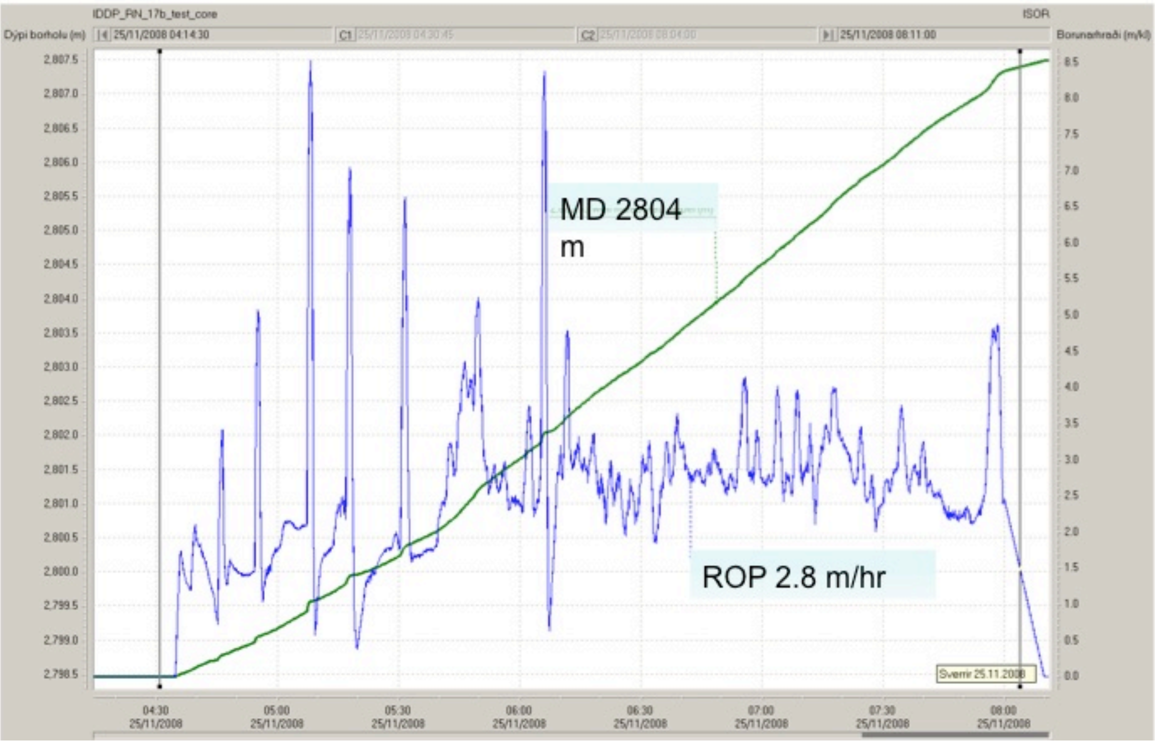
The assembled Core Barrel ready for shipping to the Rig site

New spot coring equipment built and tested in 2008 at Reykjanes within in well RN-17B – supported by ICDP

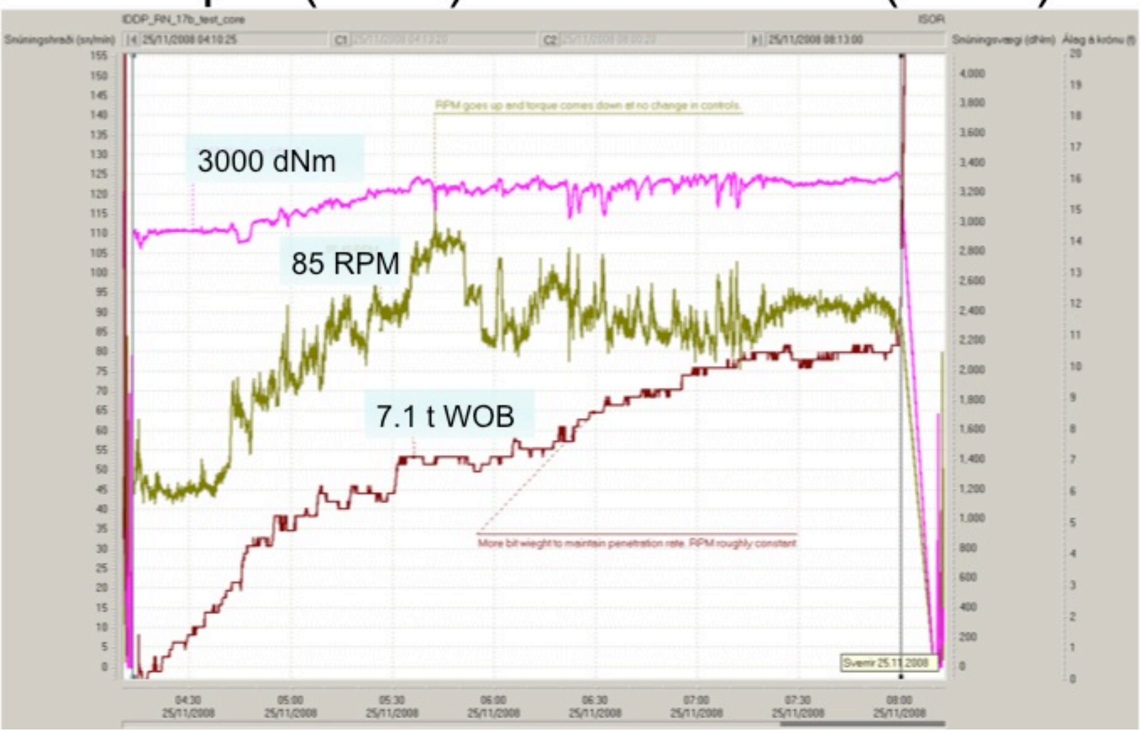
New design of core bit – 40 l/s

Six boxes, 1.65 m each, full of 4" drill core recovered from 2500 m depth in RN-17B in 2008

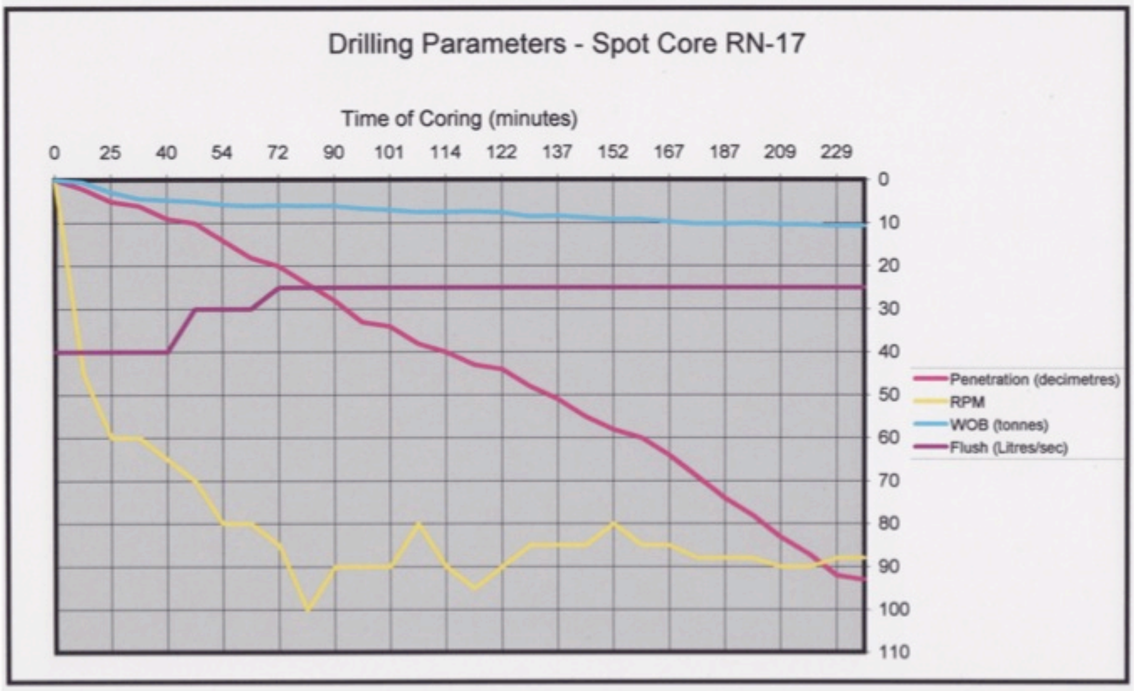
Measured Depth and ROP



Weight on bit (WOB) (tonnes) Torque (dNm) and revolution (RPM)



Drilling Parameters recorded during the Coring Run RN-17B



Core securely held in Catcher

Core boxed for examination

Length of core:
9 m

Coring rate:
2.6 m/hr

Core recovery:
100 %

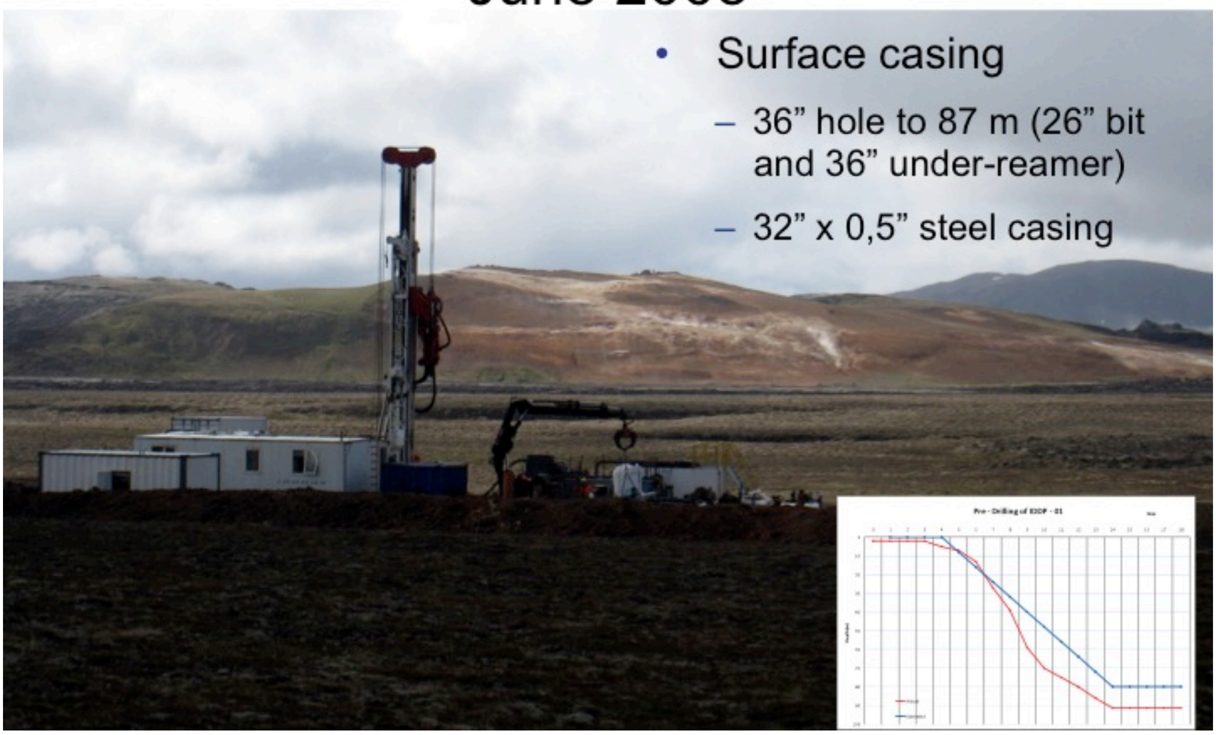
Conclusions

- The barrel performed very well in spite of being deployed in an oversize and inclined hole. Thus slower RPM and less WOB.
- No pilot-hole drilled nor junk-basket run.
- Bit cooling was effective <80°C – top drive rig.
- Coring rate of penetration 2.6 m/hr.
- 100% core recovery was achieved (9.3 m).
- Overall time for tripping and coring 2 days.

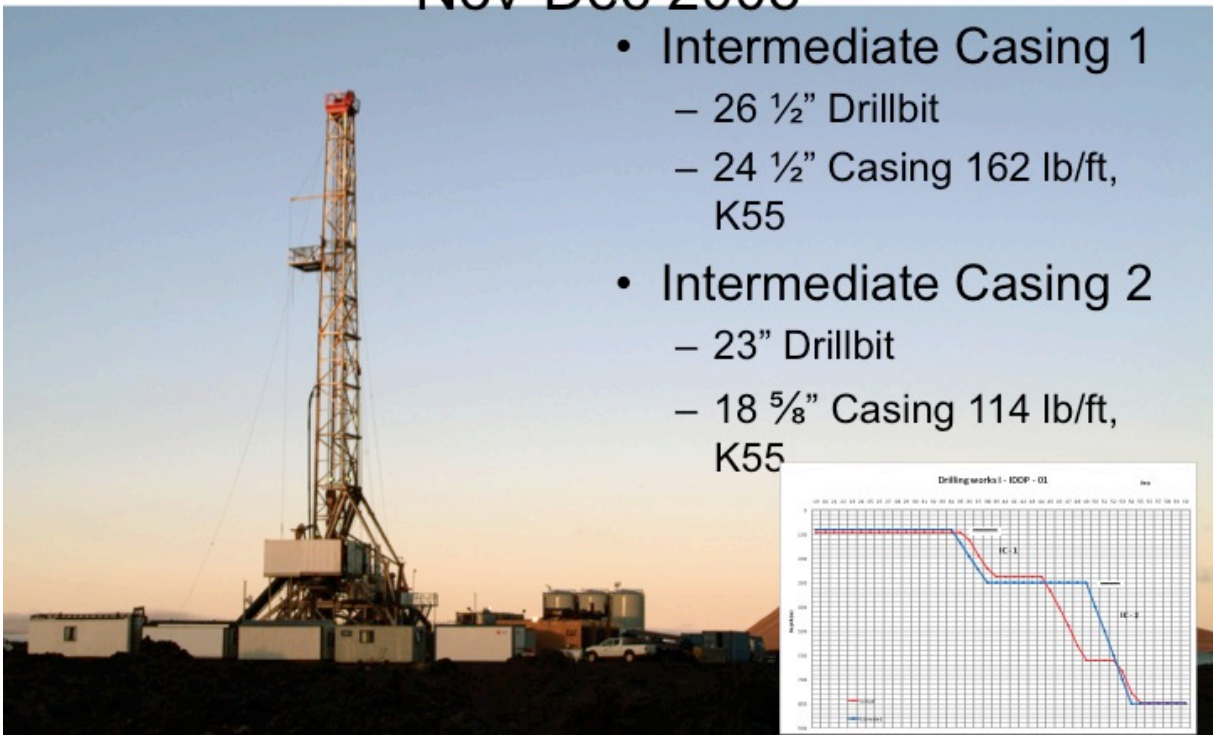
Drilling Operations at the first Iceland Deep Drilling Well (IDDP)

IDDP #1 Krafla

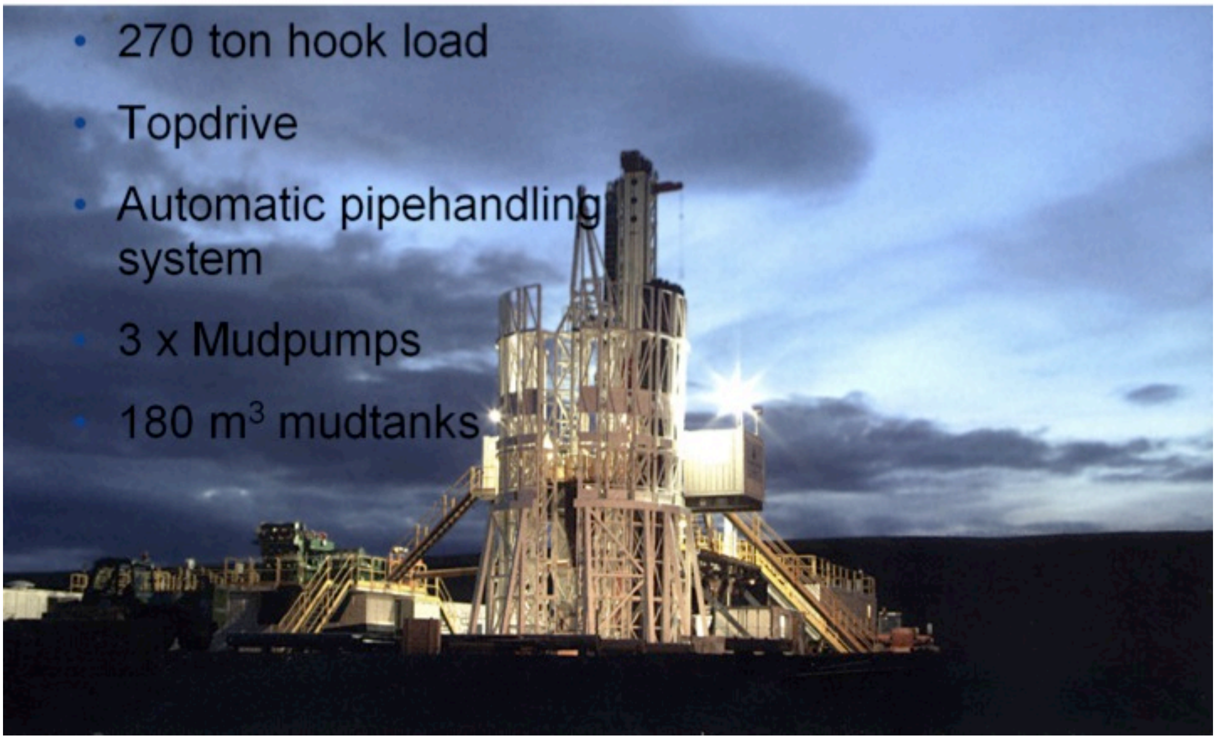
Saga Rig 0-87 m
June 2008

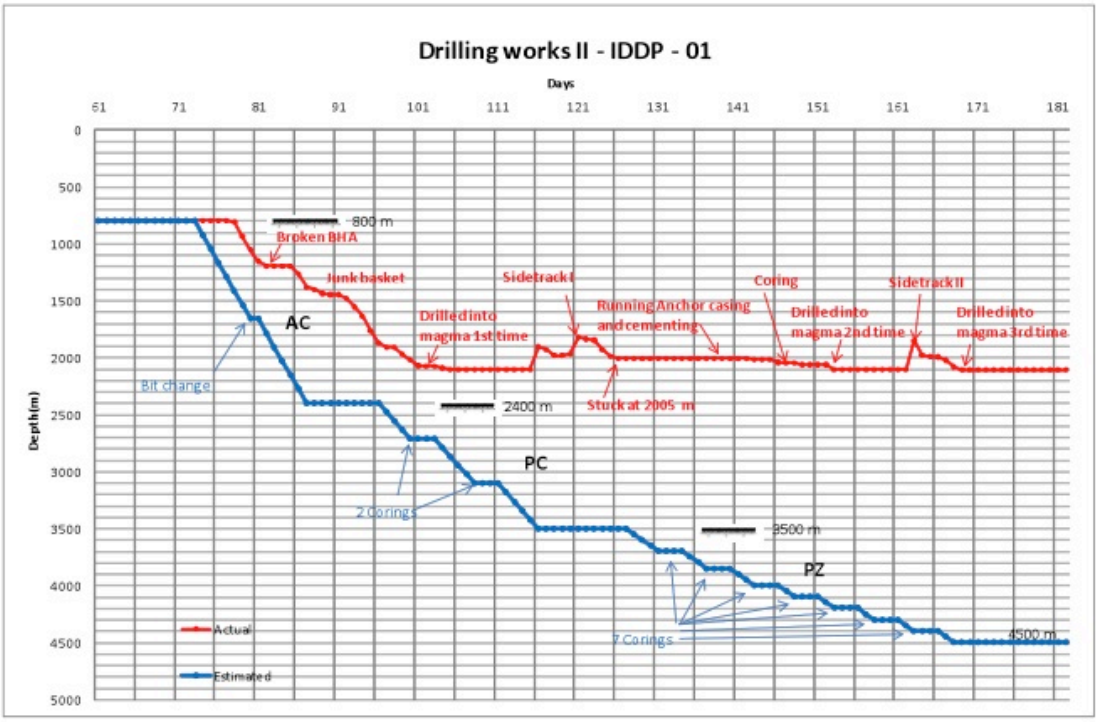


Jötunn Rig 87-260-796 m
Nov-Dec 2008



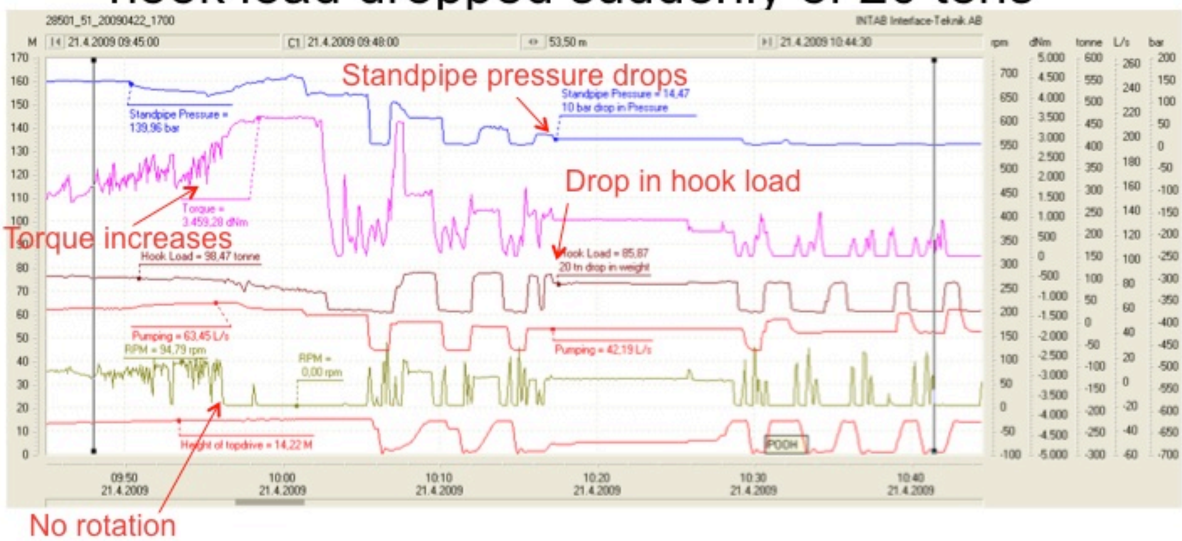
Týr Rig 796 m - final depth
March-July 2009

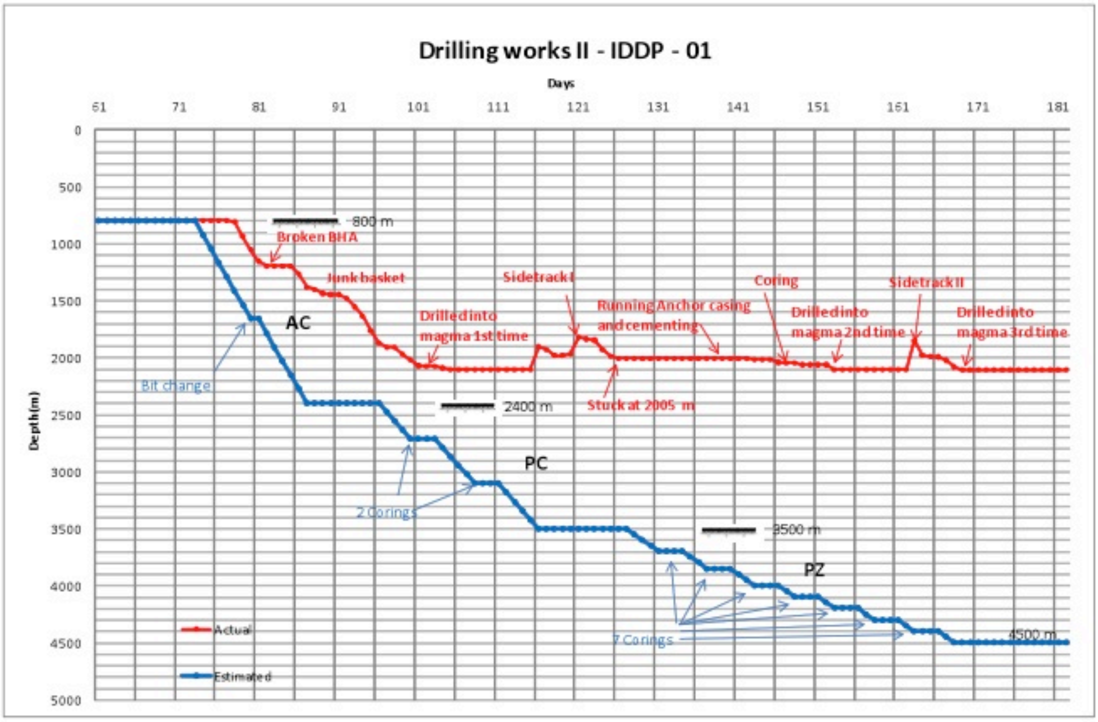




2009-04-21
Stuck at 2101 m depth

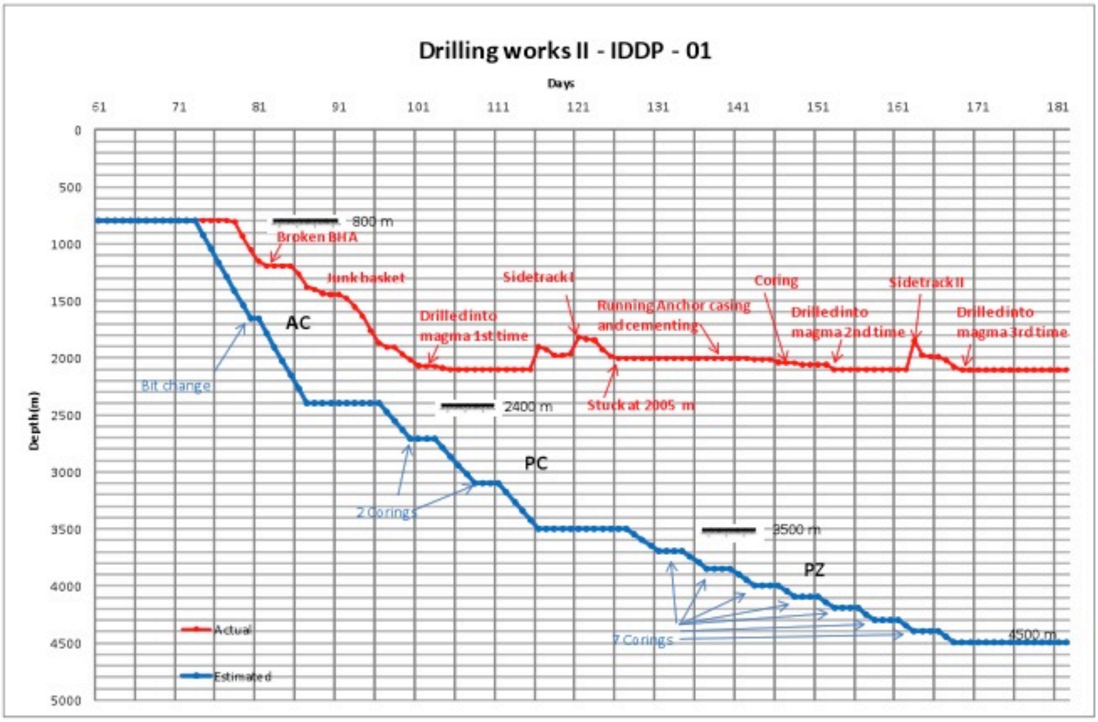
- Pulled out three singles for reaming when hook load dropped suddenly of 20 tons





2009-06-02
Coring

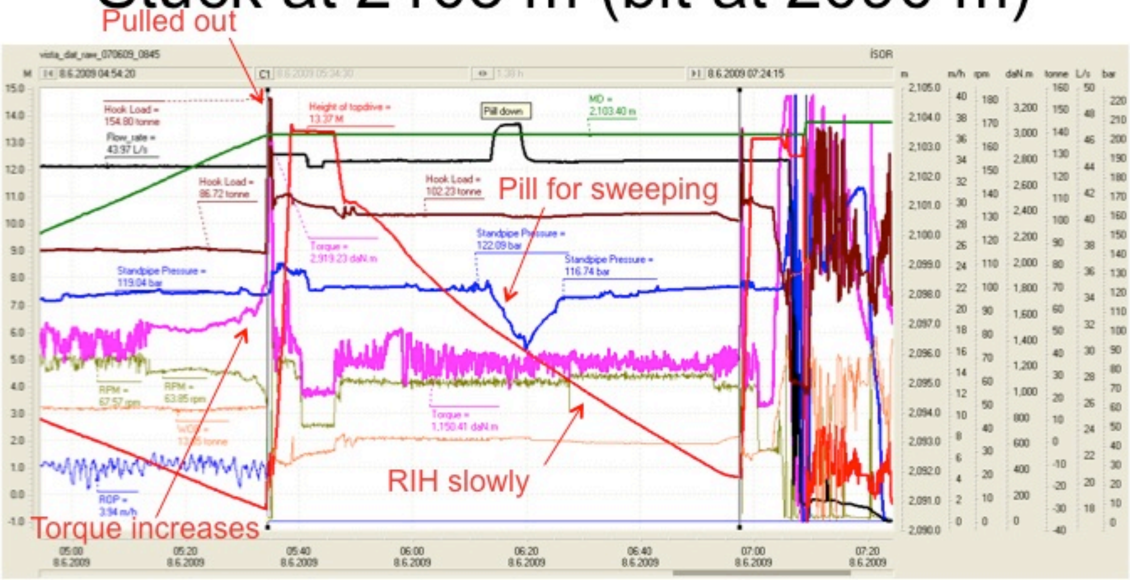
- **Decided to drill a spot core (9 m) from 2040 m.**
- **Known loss zones from previous track.**
- **Managed to drill 2 m until no penetration observed. No core inside the barrel.**



2009-06-08
Stuck at 2103 m

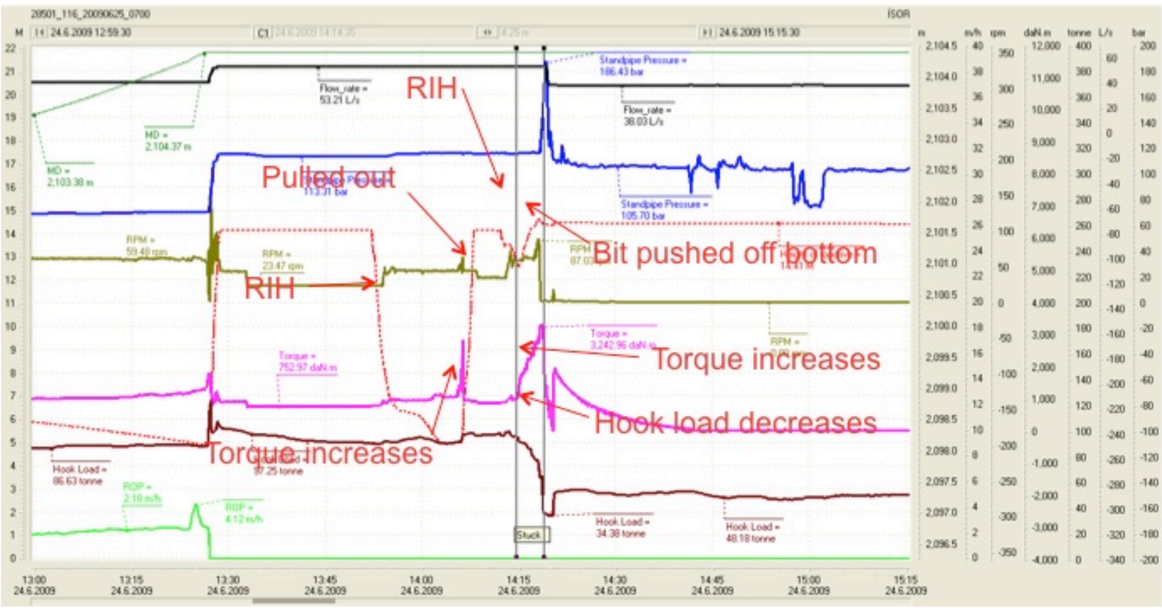
- Continued drilling until the string got stuck at 2103 m.
- Managed to get loose by pulling 160 tons.
- Circulated for 1 ½" hour.
- RIH again slowly and when the bit was on bottom the torque increased and the string was stuck.
- Returns lost imediately and the string was blocked for circulation.

2009-06-08
Stuck at 2103 m (bit at 2090 m)



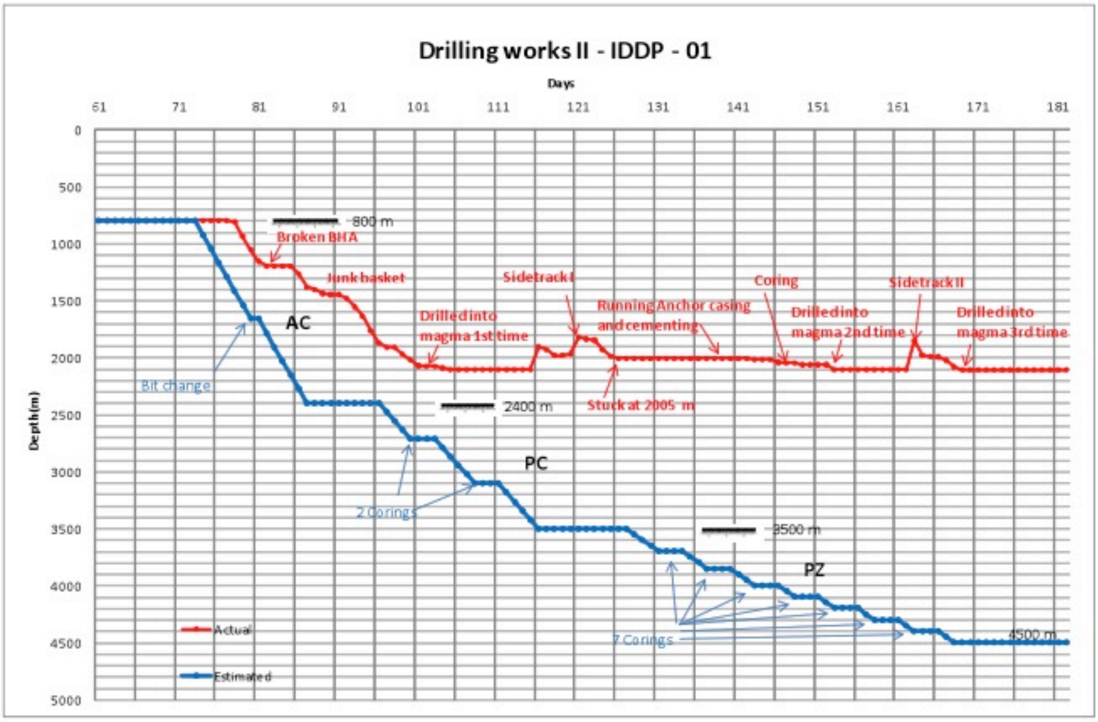
2009-06-08
Stuck in Magma at 2104 m

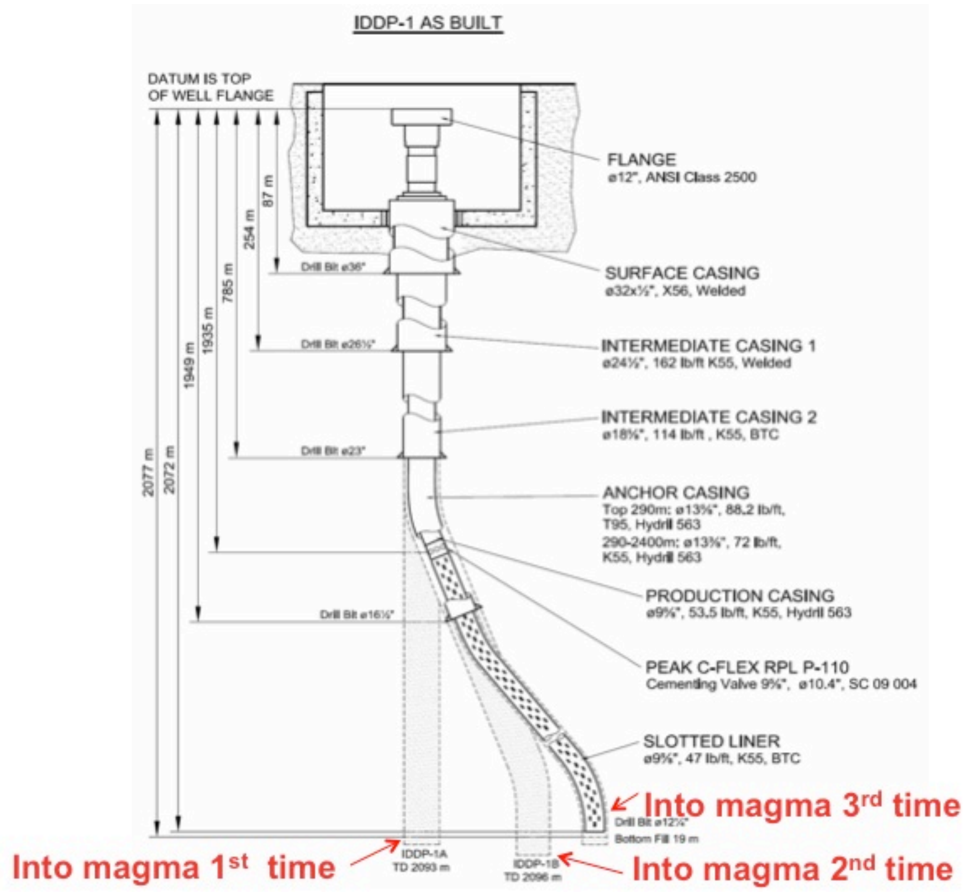
- The Hook load decreases by 50 tons!

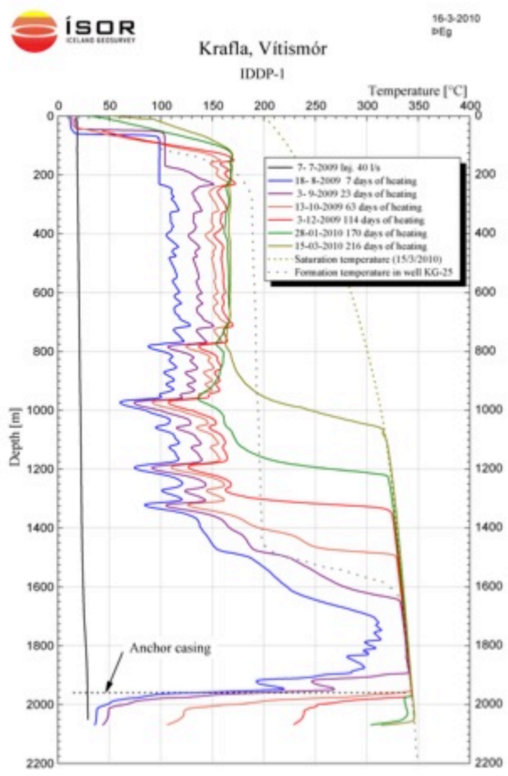


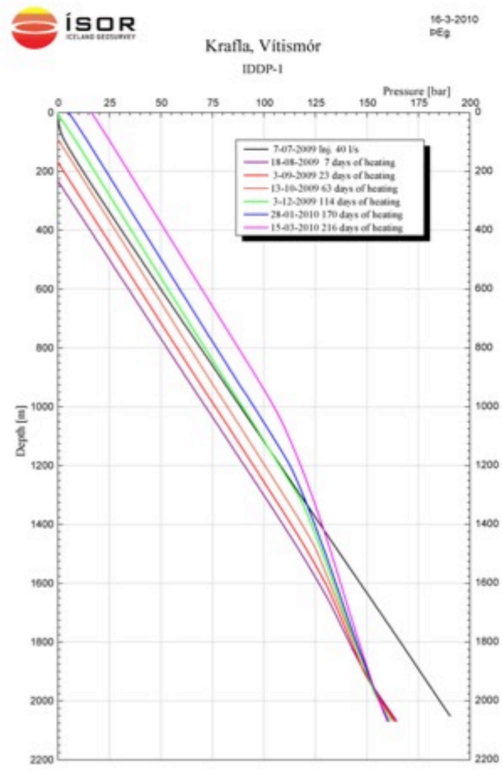
2009-06-24
Stuck in Magma!

- At 2100 m the bit was pulled up to casing and the well was cleaned. No fill was on bottom.
- At 2104 m the torque increased and the ROP doubled from 2 m/hr to 4 m/hr.
- The hook load decreased by 40 tons.
- Managed to keep circulation and returns.
- Quenched glass in the returns.
- Proof of Magma.



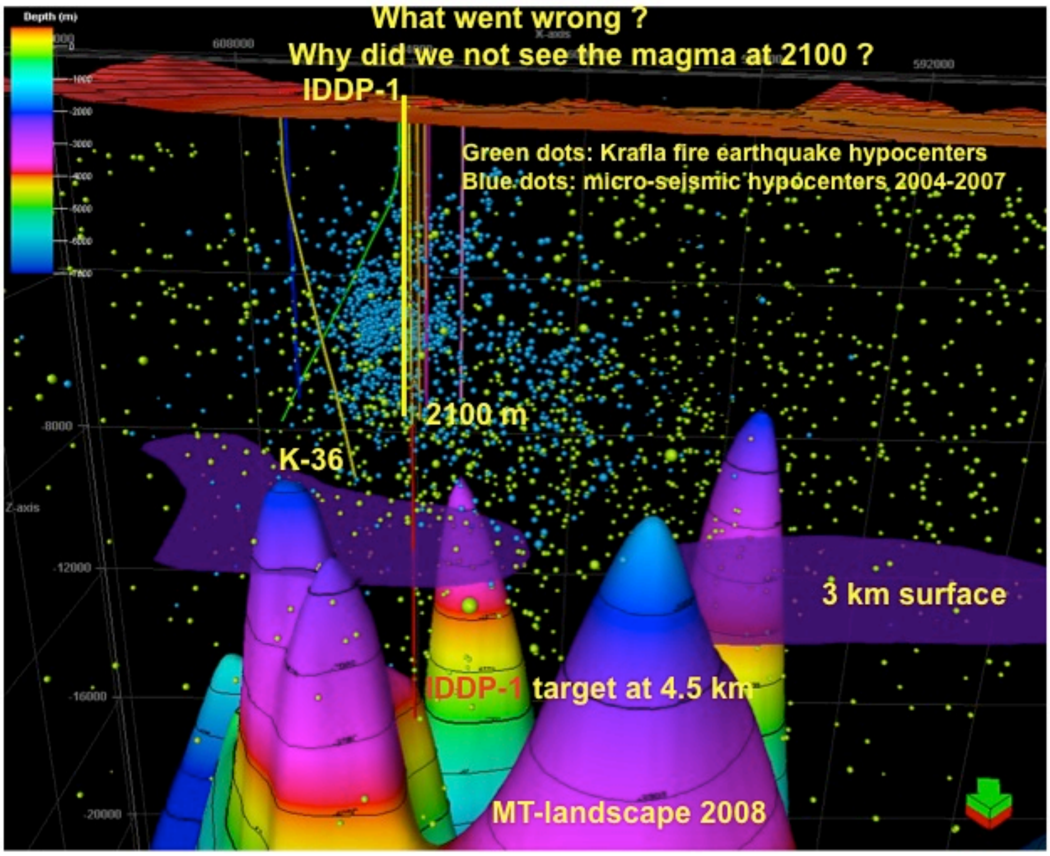

IDDP-1 AS BUILT
DATUM IS TOP OF WELL FLANGE
FLANGE
ø12", ANSI Class 2500
SURFACE CASING
ø32x½", X56, Welded
INTERMEDIATE CASING 1
ø24½", 162 lb/ft K55, Welded
INTERMEDIATE CASING 2
ø18⅝", 114 lb/ft , K55, BTC
ANCHOR CASING
Top 290m; ø13⅜", 88.2 lb/ft, T95, Hydril 563
290-2400m; ø13⅜", 72 lb/ft, K55, Hydril 563
PRODUCTION CASING
ø9⅝", 53.5 lb/ft, K55, Hydril 563
PEAK C-FLEX RPL P-110
Cementing Valve 9⅝", ø10.4", SC 09 004
SLOTTED LINER
ø9⅝", 47 lb/ft, K55, BTC
87 m
254 m
785 m
1935 m
1949 m
2072 m
2077 m
Drill Bit ø36"
Drill Bit ø26½"
Drill Bit ø23"
Drill Bit ø16½"
Drill Bit ø12¼"
Bottom Fill 19 m
IDDP-1A
TD 2093 m
IDDP-1B
TD 2096 m
Into magma 1st time
Into magma 2nd time
Into magma 3rd time

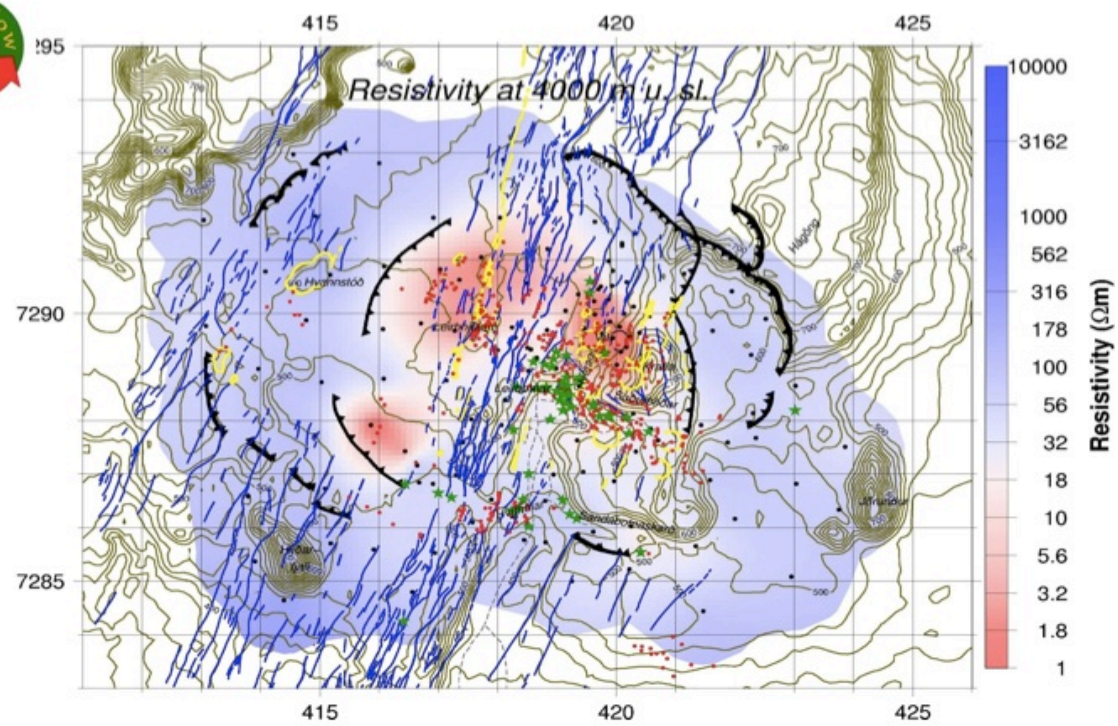

ÍSOR
ICELAND GEOSURVEY
16-3-2010
Krafla, Vítismór
IDDP-1
Temperature [°C]
Depth [m]
7- 7-2009 Inj. 40 l/s
18- 8-2009 7 days of heating
3- 9-2009 23 days of heating
13-10-2009 63 days of heating
3-12-2009 114 days of heating
28-01-2010 170 days of heating
15-03-2010 216 days of heating
Saturation temperature (15/3/2010)
Formation temperature in well KG-25
Anchor casing


ÍSOR
ICELAND GEOSURVEY
16-3-2010
Krafla, Vítismór
IDDP-1
Pressure [bar]
Depth [m]
7-07-2009 Inj. 40 l/s
18-08-2009 7 days of heating
3-09-2009 23 days of heating
13-10-2009 63 days of heating
3-12-2009 114 days of heating
28-01-2010 170 days of heating
15-03-2010 216 days of heating

Future scenario 1:

- Flow test IDDP-1 – as scheduled:
  1 Phase 1 test - small scale test (4”) **We are here now !**
  2 Phase 2 test - full scale test (10”)
  3 Pilot test for energy production
- Depending on result:
  1 Phase 1 successful – go to phase 2 (chemistry and flow OK)
  2 Phase 2 successful – go to phase 3 (chemistry and flow OK)
  3 Phase 3 successful – produce the well:
  (i) as a conventional steam producer for the 7 bar inlet pressure to turbine
  (ii) at higher pressure - into a high-P steam turbine
  (iii) into a heat exchanger to mitigate chemical problems (cont. pilot study)





The magma chamber(s) in Krafla seen by MT-resistivity survey 2005-2007

IDDP Plan in 2008

- IDDP -1 well at Krafla 2008-2009
  - **Landsvirkjun** drills a well to 3.5 km
  - IDDP Consortium deepens the well to 4.5 km
- IDDP-2 well at Hengill, 2010
  - **Reykjavik Energy** drills a well to 3.5 km
  - IDDP Consortium deepens the well to 5 km
- IDDP-3 well at Reykjanes, 2011
  - **HS Orka** drills a well to 3.5 km
  - IDDP Consortium deepens the well to 5 km

Current Status
IDDP1 15-20MWe and still heating up

Into magma at 2.1 km
(potential EGS)

Postponed until later

Being considered for 2011

- Wells at Hengill and Reykjanes are back-up for the IDDP science program