The MoHole : a Crustal Journey and Mantle Quest

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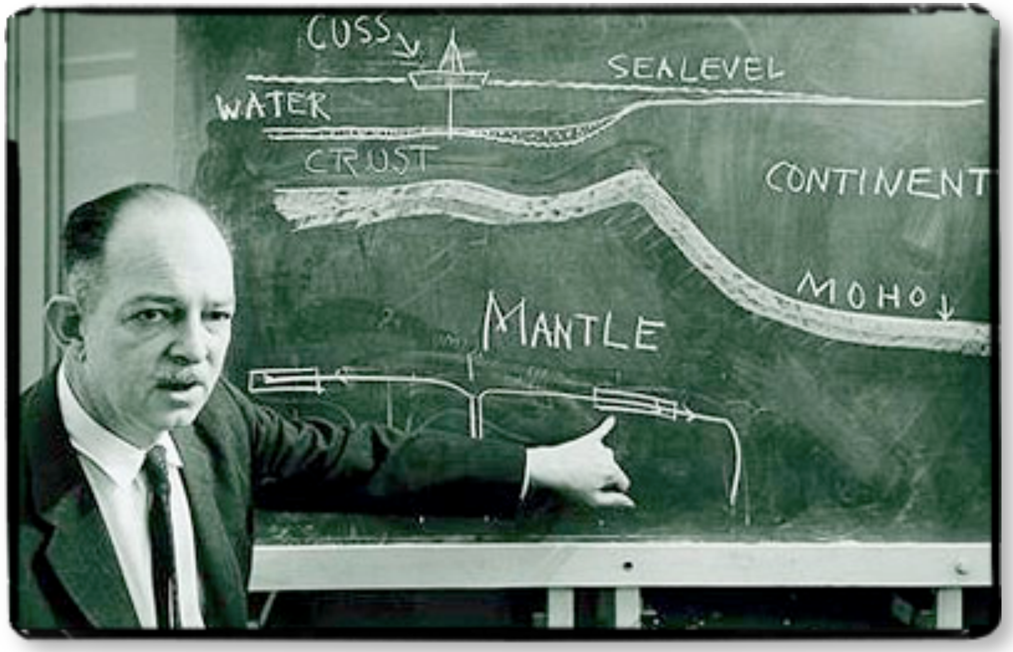
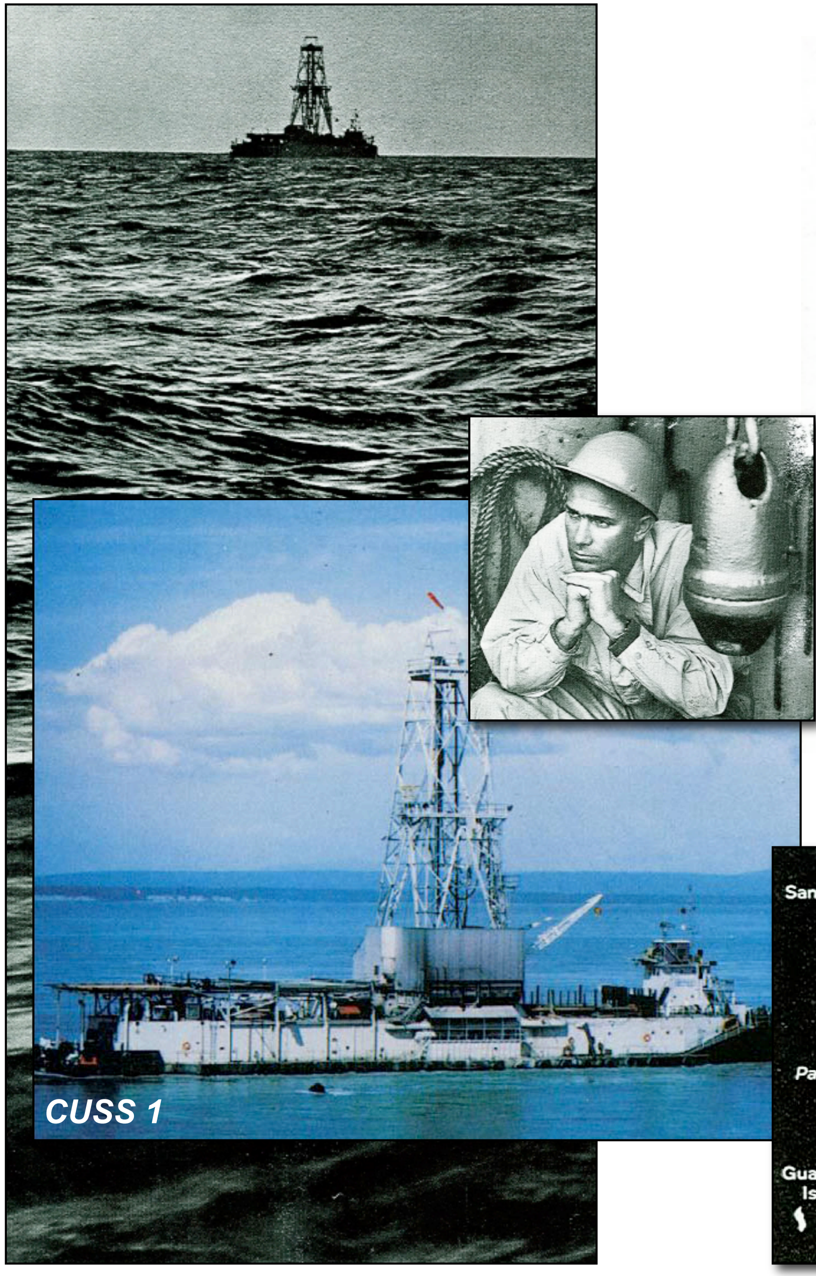
April 1958, meeting in the Great Hall of the NAS :
“What good will it do to get a single sample of the mantle?...”

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



Project "Mohole" 1957-1966



High Drama of Bold Thrust through Ocean Floor

AUTHOR STEINBECK AND PHOTOGRAPHER GORO ON DECK OF THE CUSS I

EARTH'S SECOND LAYER IS TAPPED IN PRELUDE TO MOHOLE

Last week Project Mohole (LIFE, April 7) made scientific history when its drilling barge, CUSS I (whose name is made up of the initials of oil companies who developed it: Continental, Union, Shell and Superior), pierced 601 feet into the sea floor to get core samples of the earth's never-before-penetrated second layer. On board to describe the extraordinary operation for LIFE was Novelist John Steinbeck, who is also an amateur oceanographer.

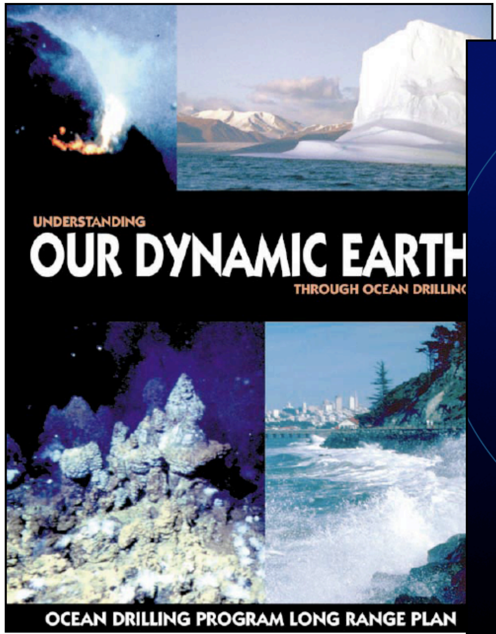
by JOHN STEINBECK

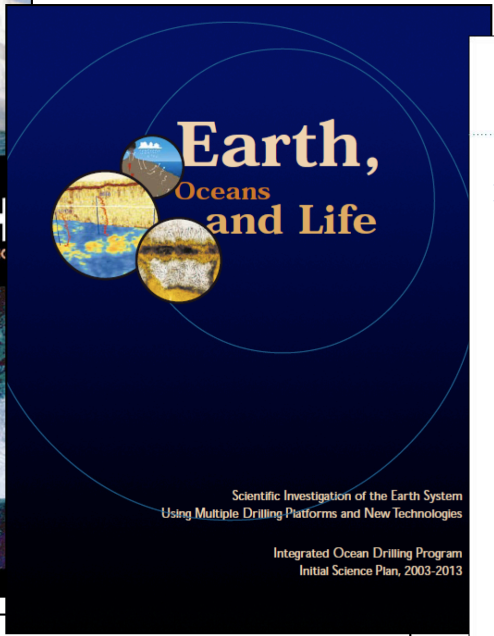
Life, April 14, 1961

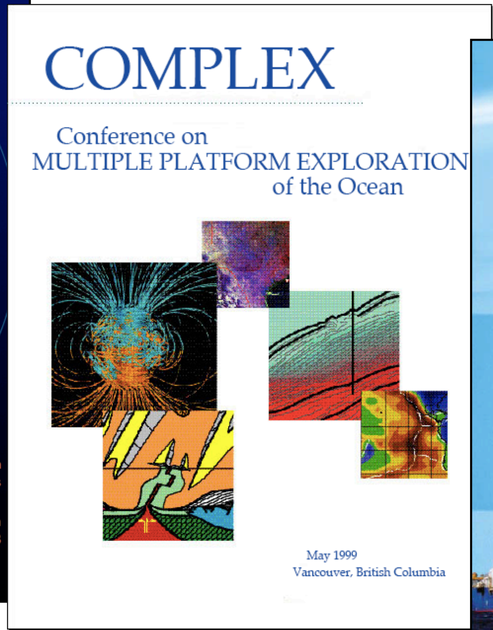
Offshore Guadalupe Island
March-April 1961

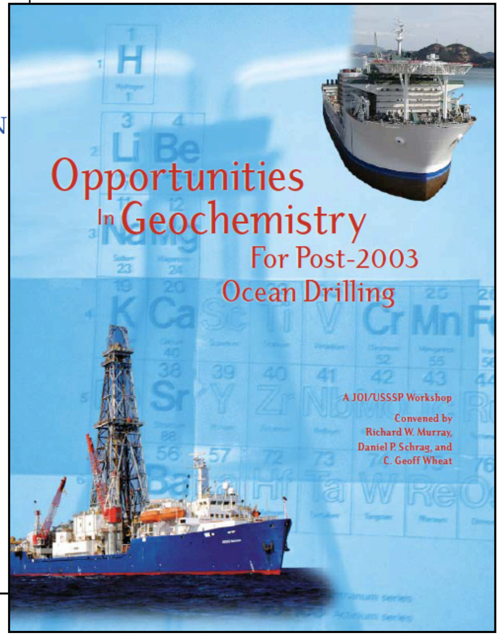
Dynamic positioning
~ 3500 mbsl
5 holes
Max depth 183 m, miocene sediments & ***~ 14 m of basalt***

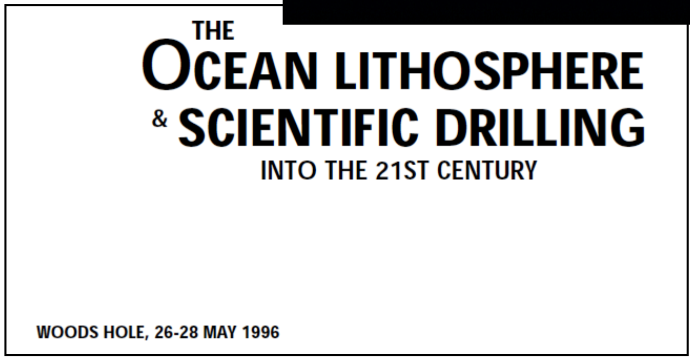
40 years of planning on deep drilling of the ocean lithosphere

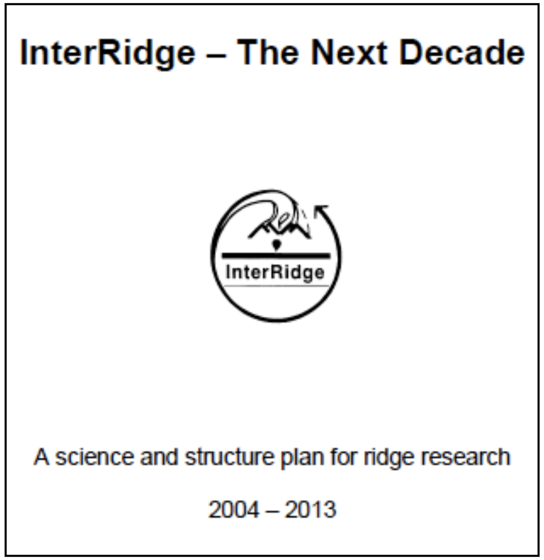




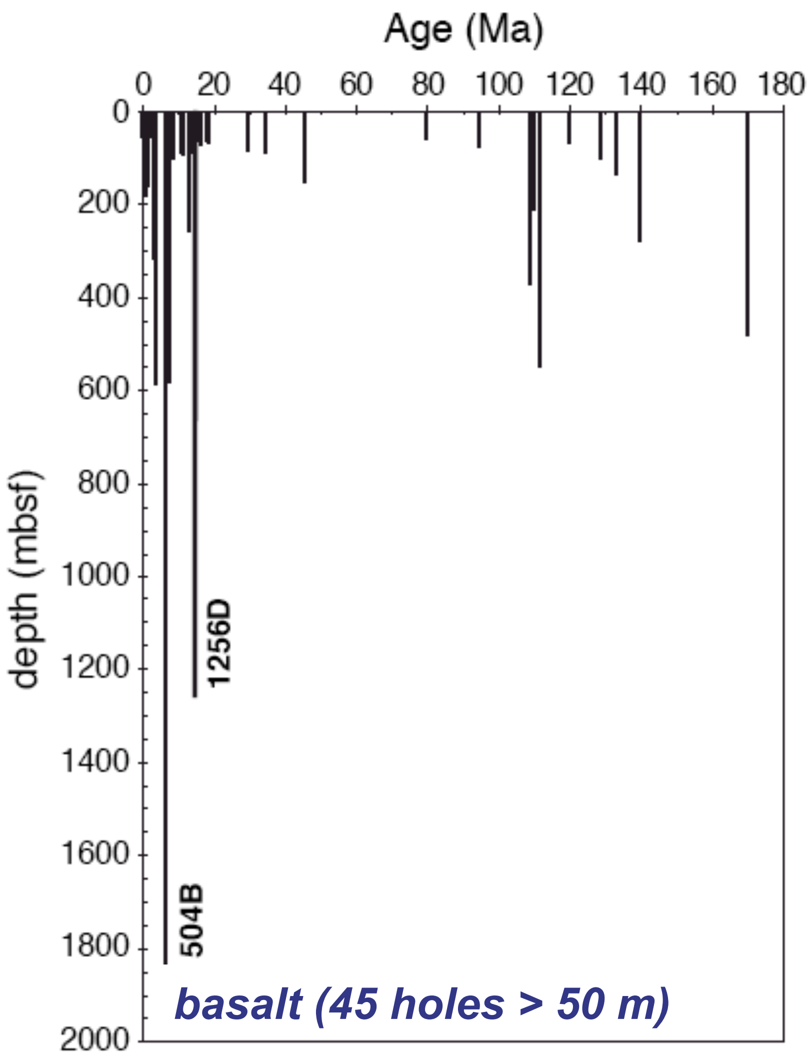


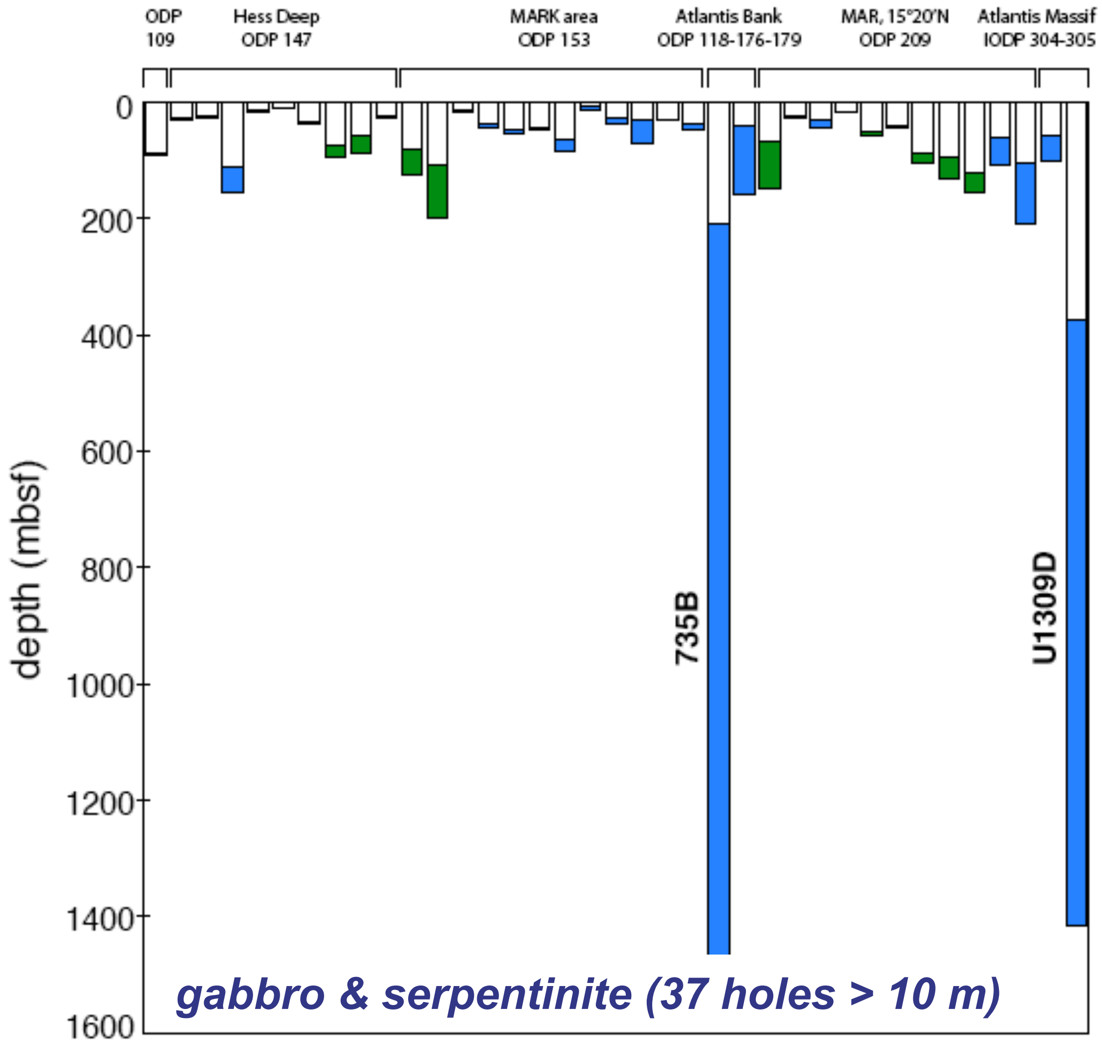






Oceanic basement drilling 1968 - 2005





Ildefonse et al., 2007

Not enough !!   ~3% of DSDP/ODP/IODP cumulated depth

No continuous section of ocean crust !

Scientific planning 2006-2010

- ***Mission Moho Workshop***

Formation and Evolution of Oceanic Lithosphere
Portland, Sept. 2006
www.iodp.org/mission-moho-workshop

- ***Mission Moho Proposal***

Submitted to IODP in April 2007
www.missionmoho.org

- ***Melting, Magma Fluids and Life meeting***

Challenges for the next generation of scientific ocean drilling into the oceanic lithosphere
Southampton, July 2009
www.interridge.org/WG/DeepEarthSampling/workshop2009

- ***INVEST Meeting***

IODP New Ventures in Exploring Scientific Targets
Bremen, Sept. 2009
www.marum.de/en/iodp-invest.html (report available at www.iodp.org)

- ***MoHole Workshop***

A crustal Journey and Mantle Quest
Kanazawa, June 2010
campanian.iodp.org/MoHole

Full penetration of fast-spread crust

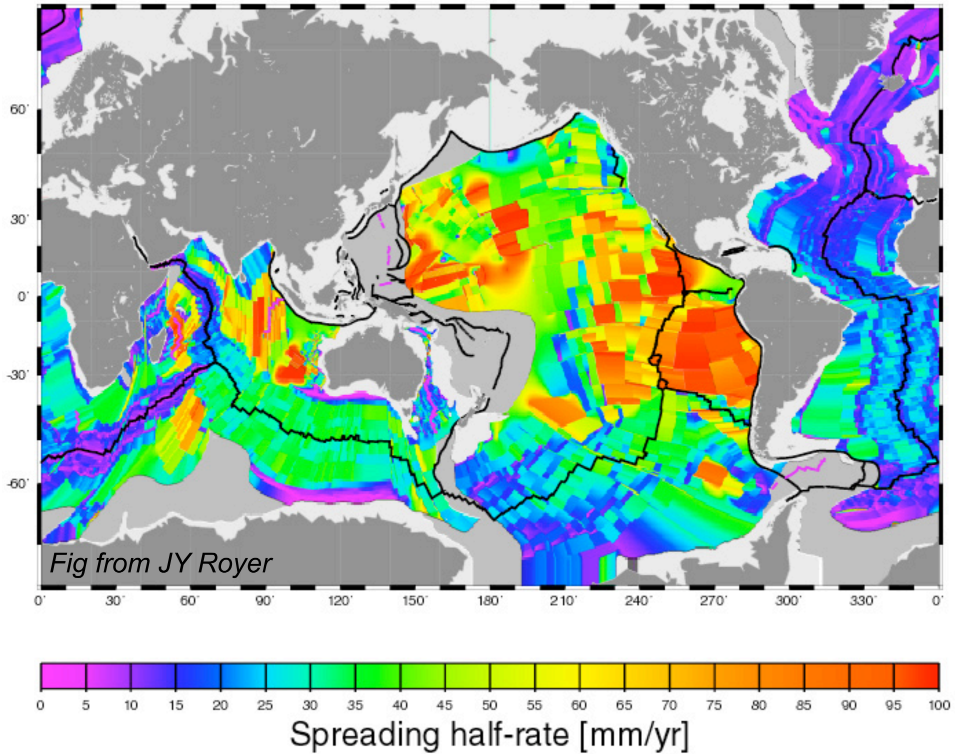
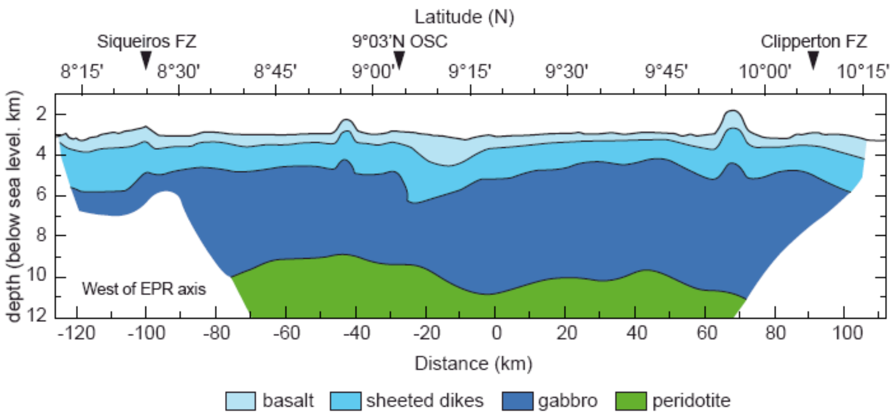
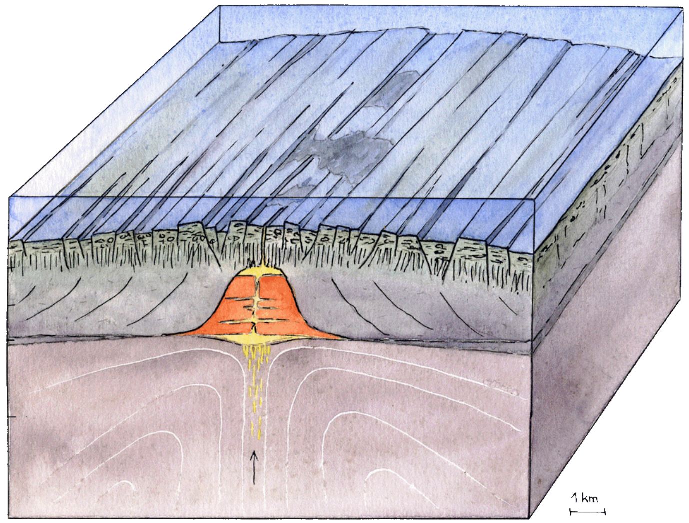


Fig from JY Royer

- Relatively uniform and continuous
- ~20% of modern ridges
  ~50% of modern ocean crust
  ~30% of Earth's surface
- Majority of crust subducted into mantle in past ~200 Ma

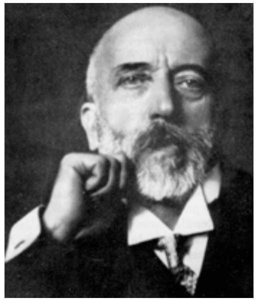


Ildefonse, 2007; after Canales et al., 2003

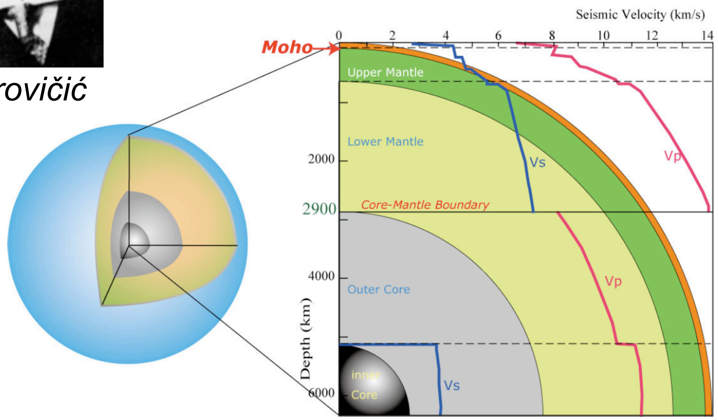


C. Laverne

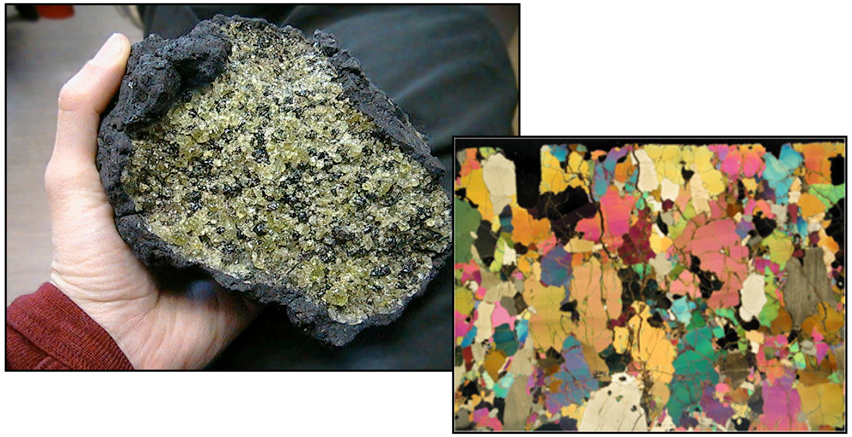
Scientific rationale



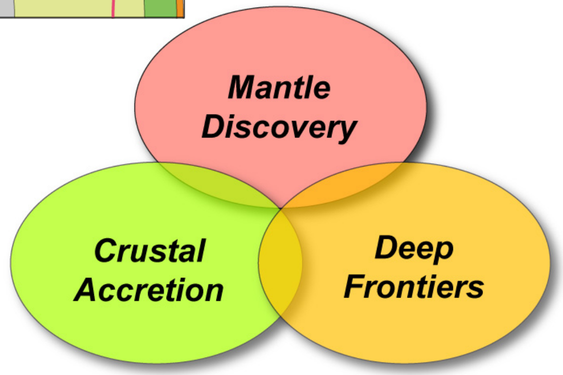
A. Mohorovičić

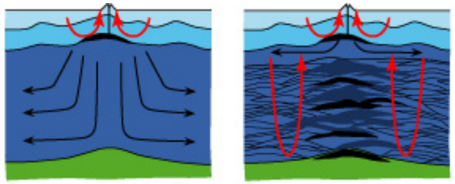


Breakthrough the outermost discontinuity of Earth's interior

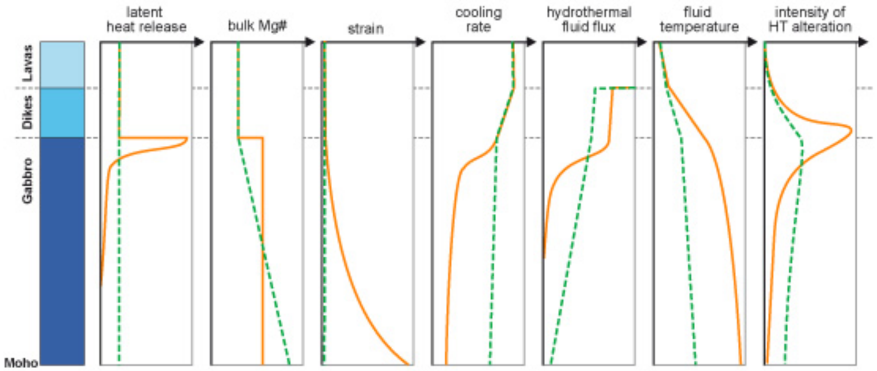


Obtain physical properties and chemical composition of ***in-situ*** upper mantle

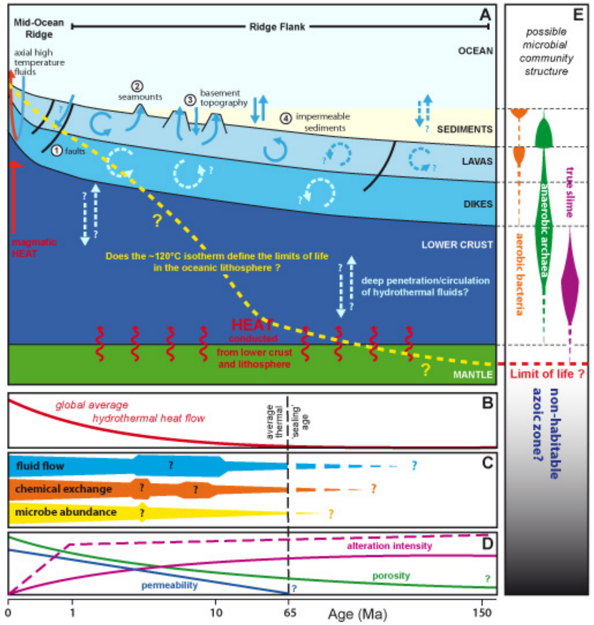




Conductive or Convective Cooling

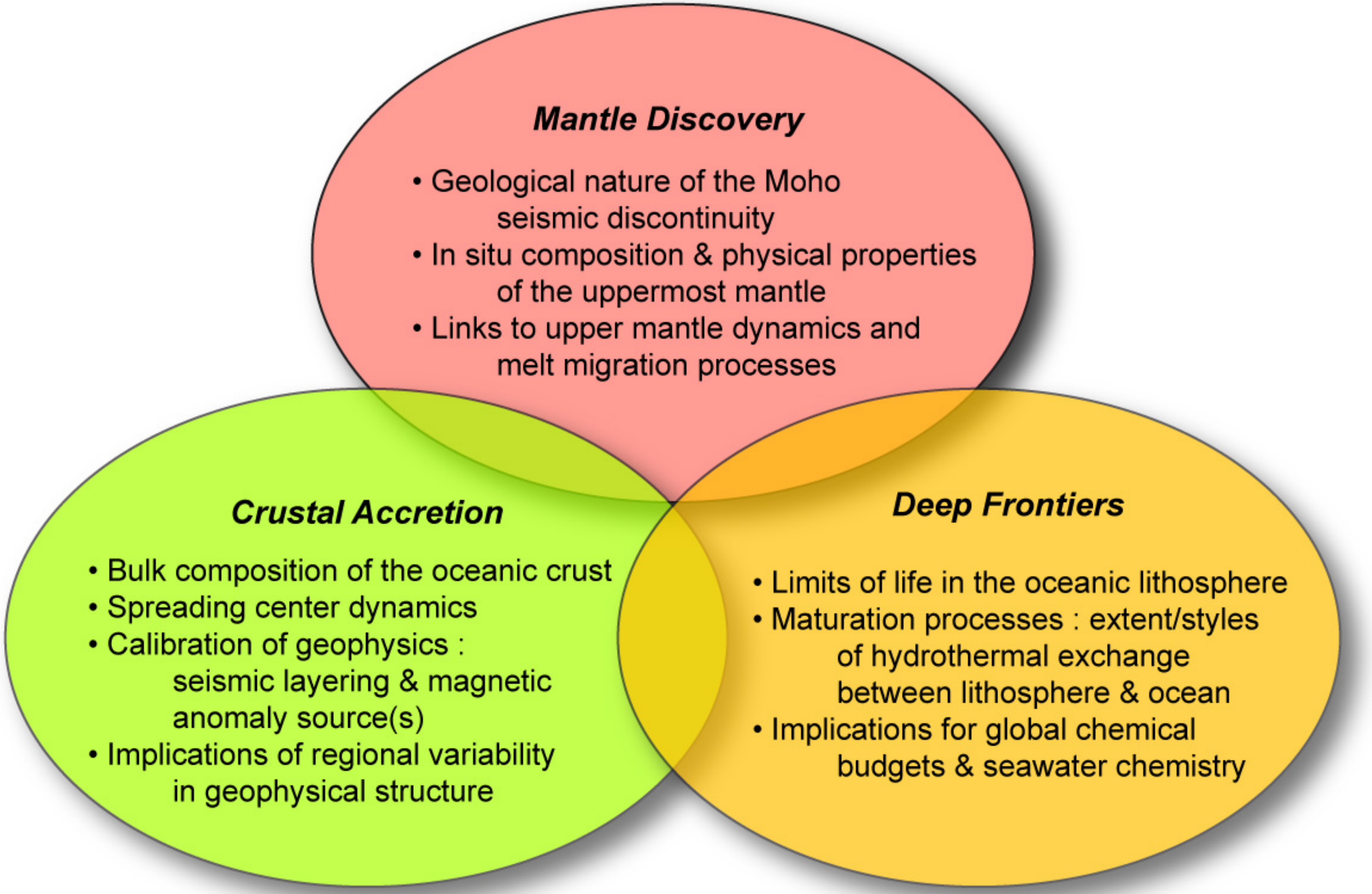


Test accretion and cooling models with drill cores



Document maturation/composition of crust and limits of life

Scientific rationale



Primary inhibitor : Absence of in situ samples

MoHole workshop 2010

Kanazawa, Japan, 3-5 June 2010

Report available at campanian.iodp.org/MoHole

- *Identify a limited number of potential MoHole sites in the Pacific in fast-spread crust, where the scientific community will focus geophysical site survey efforts over the next few years*

- *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*

Requirements for deep penetration site

- *Crust formed at **fast-spreading rate** (>40 mm/yr half rate)*

- ***Simple tectonic setting** with very low-relief seafloor and smooth basement relief. Connection to the host plate active constructive and destructive boundaries would provide important scientific information*

- *Crustal seismic velocity structure should not be anomalous relative to current understanding of **"normal" fast-spread Pacific crust**, indicative of layered structure*

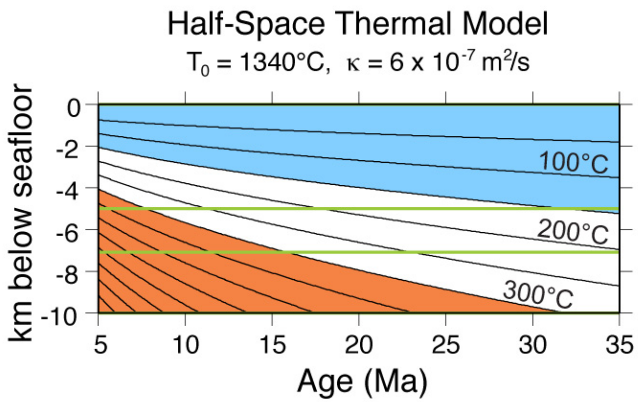
- ***Well-imaged Moho***
  - *Sharp, strong, single-reflection Moho imaged with Multi-Channel Seismic (MCS) techniques*
  - *Strong wide-angle Moho reflection (PmP), as observed in seismic refraction data, with distinct and clearly identifiable sub-Moho refractions (Pn).*

- *Clear upper mantle seismic anisotropy*

- *Crust formed at an original latitude greater than ±15°.*

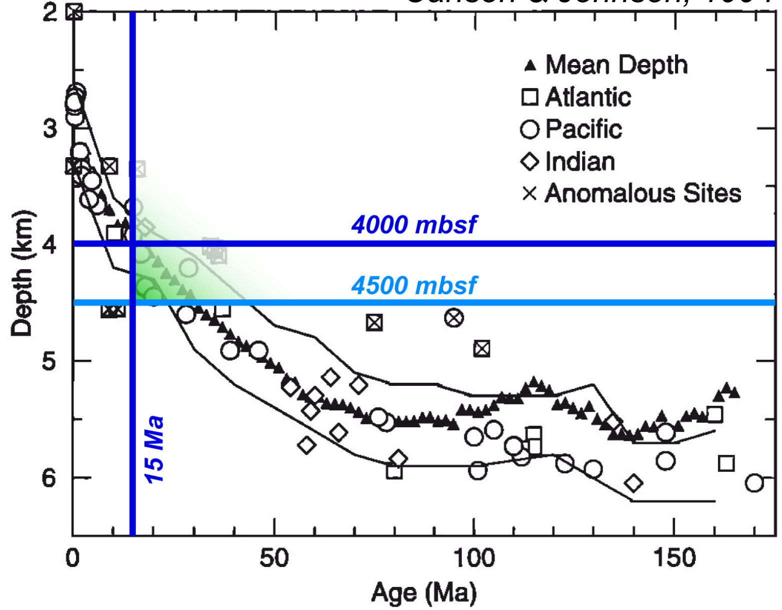
- *Location with relatively high upper crustal seismic velocities indicative of massive volcanic formations to enable the initiation of a deep drill hole*

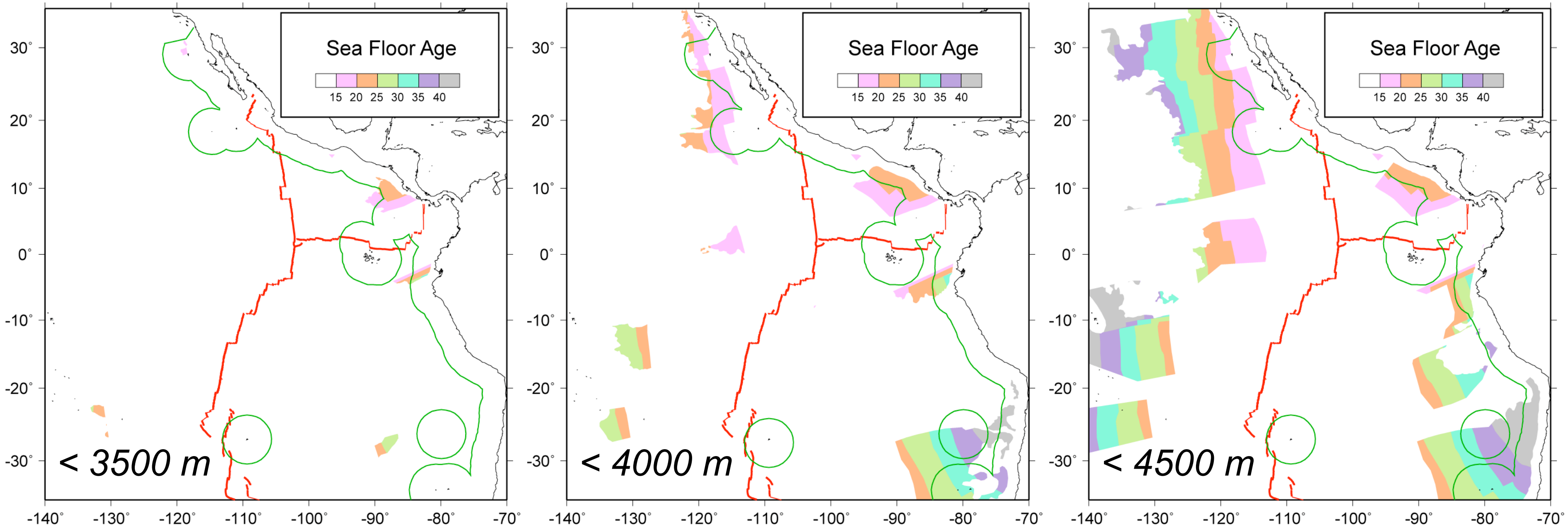
The trade-off of depth and temperature in choosing a site



- ***<~250°C (15-20 Ma)***
- ***Shallow (≤4000-4500 mbsf)***

Carlson & Johnson, 1994

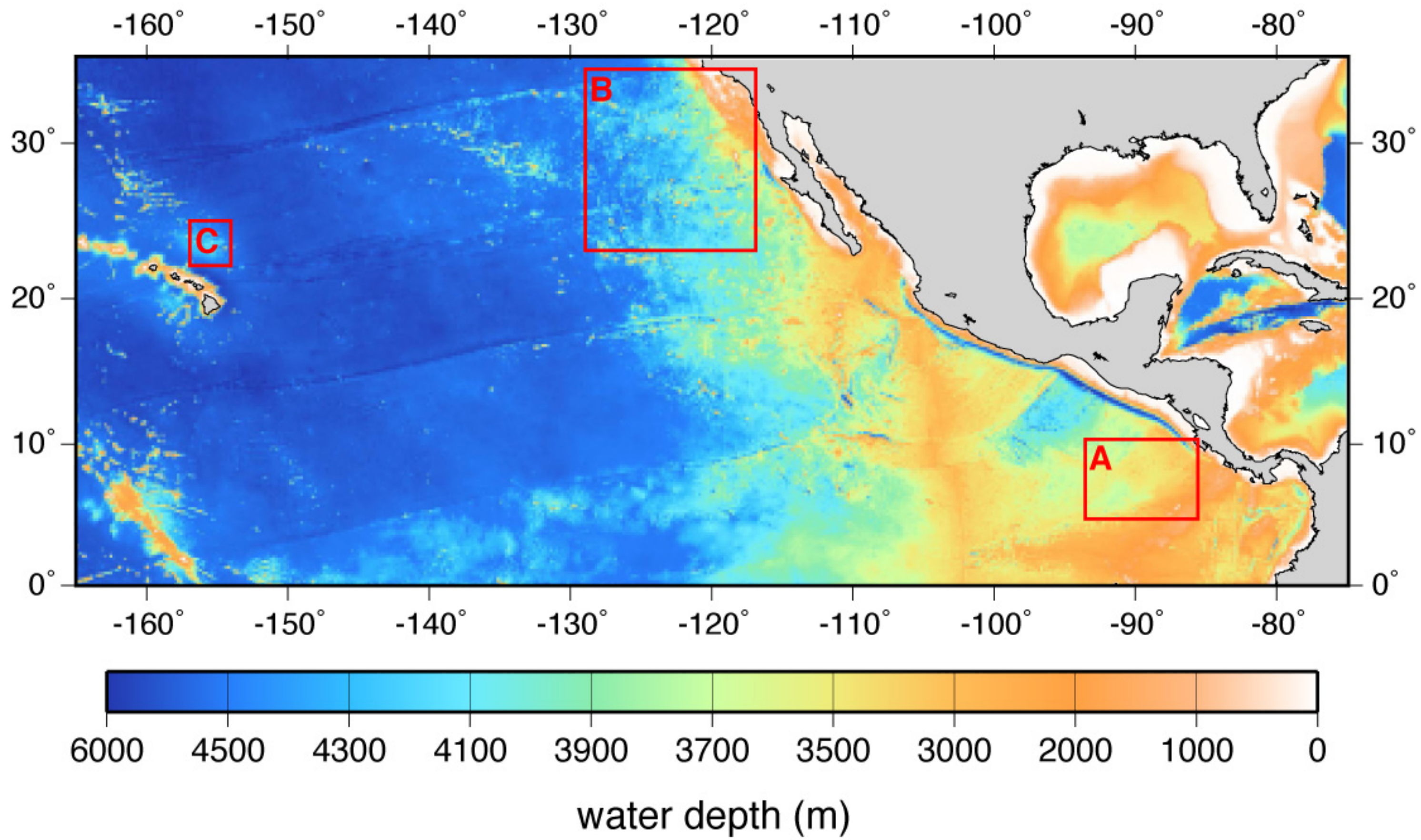




Figs by D. Wilson

Potential Target Regions for the Mohole in the Eastern Pacific

Selected project areas



A - Cocos plate (including IODP site 1256)

B - Off Southern/Baja California (including "deep tow" site)

C - North of Hawaii, in flexural arch

Large scale geophysical surveys : finding the right project area

3 areas need additional geophysical data to evaluate the feasibilty of a MoHole

First survey (JAMSTEC) in 2011 : off Southern/Baja California area

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.*

Scope and costs of surveys too large to be conducted by a single nation or funding agency; ***international collaboration is required***

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

Drilling deep is difficult…

DSDP Leg 70

ODP Leg 140

ODP Leg 176

ODP Exp 309-312

All we need to do is…

- *Stabilize the vessel to drill/core/log in water depths ~12,000 feet (3600 m) and more*
- *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 funding and stay within time and financial constraints*

Need to learn how to drill deep (hole stability, HT, …)

Technology Planning and Development

Technology selection and engineering development

Engineering efforts :

- *As soon as possible, in conjunction with site survey operations*
- *Must be directed to ensure that the scientific goals of the MoHole project are achieved*

Different items listed in Kanazawa :

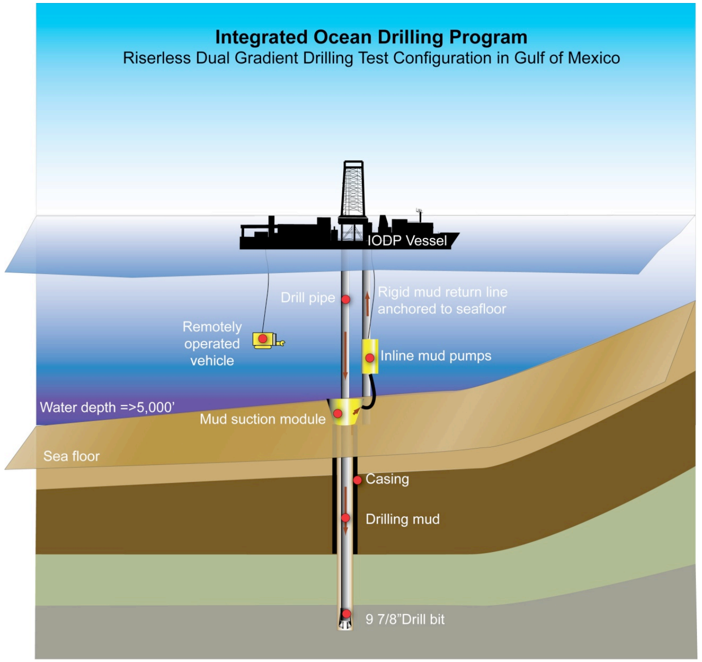
- ***Continuous mud circulation (Riser, RMR, …)***
- *Logging and coring in HT formations*
- *Drill bits (specifically designed for abrasive, hard rocks)*
- *Drill string (high tensile strength)*
- *Drilling mud (developed for HT environment)*
- *Casing/cementing materials and strategies (specifically designed, ideally to the bottom of the hole)*

- *Post-drilling experiments (VSP, …)*
- *Long-term monitoring (fluid monitoring, microbiology incubation, …)*

We need a management/scoping team asap

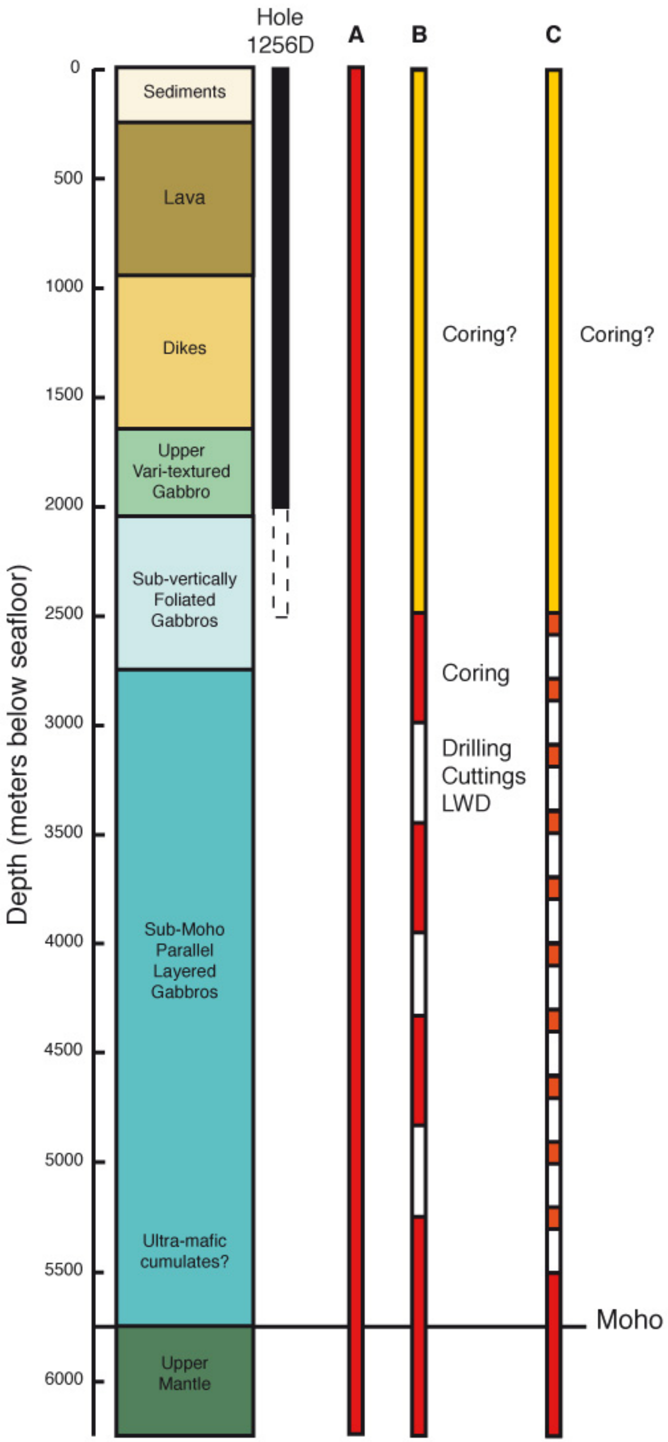
Technology selection and engineering development

D/V Chikyu



Myers, 2008, 2009

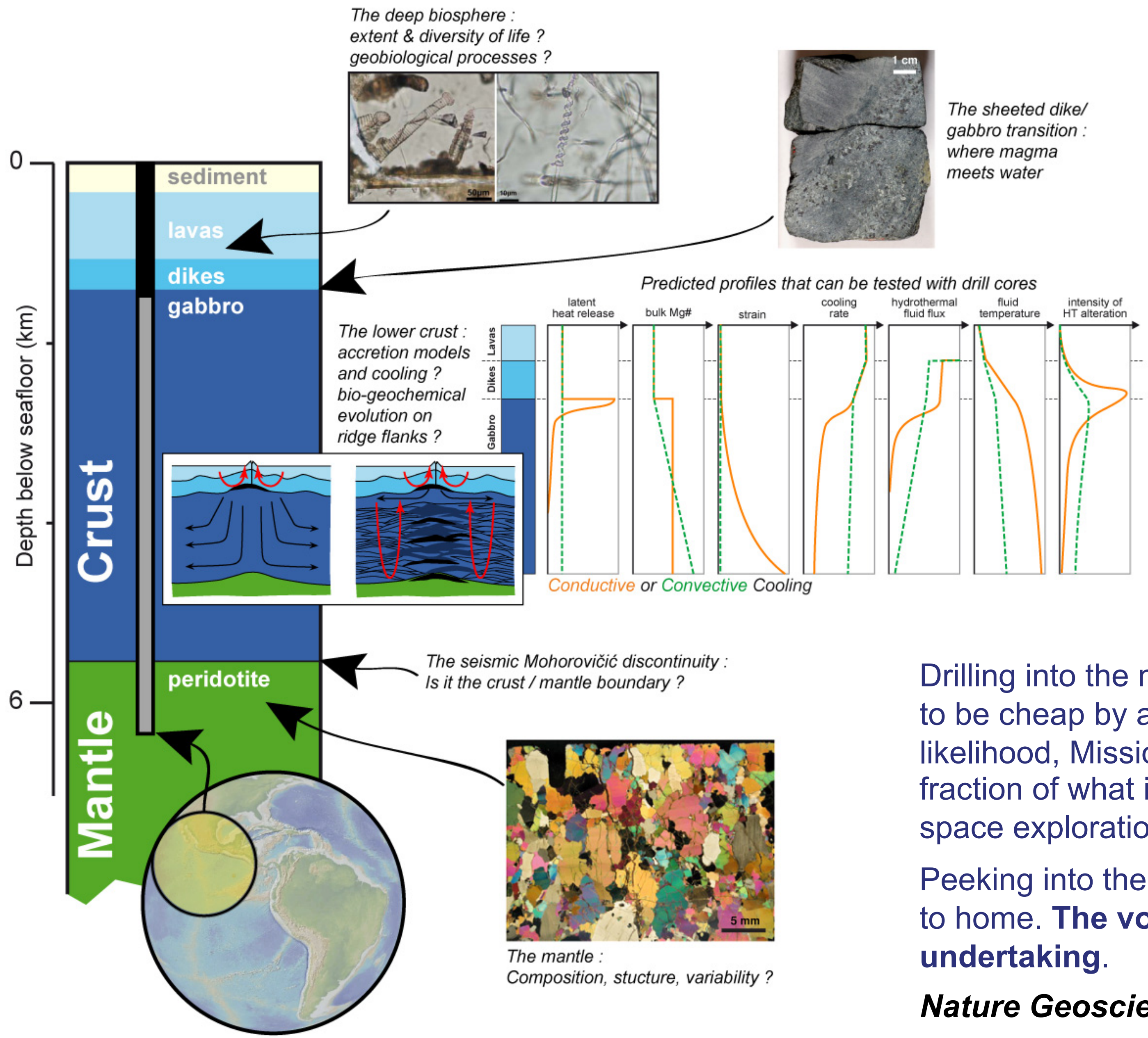
	Riser and BOP (CFRP riser or other material)	Surface BOP plus SID(ESG)	RMR	RMR with EGS (SID)	Free Standing Riser	BOP-less
Cost	1	3	3	2	2	3
Risk	3	3	2	3	3	0
Lead time	1	3	2	2	1	2
Flexibility	1	3	3	3	2	2
Feasibility	2	3	3	3	2	2
Environmental / Safety	3	3	2	2	3	0
Heat tolerance	2	2	2	2	2	2
Deployment time	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



Keys for success

- *Many of our primary scientific goals will require **continuous core samples***
- *Core samples for **microbiological studies** (avoid and/or control chemical and microbiological contaminations)*
- *Continuous, comprehensive suite of **geophysical logs & borehole experiments***
- *Integrate core/log/survey data in a comprehensive **synthesis study of the Project Area***
- *Engage of a **broad range of scientific communities***
- *Develop required technology and engage industry*
- *Improve **public support** and understanding of the project (dedicated, dynamic and engaging MoHole web page, …)*

The MoHole - モホール計画



Drilling into the mantle is not expected to be cheap by any means. But in all likelihood, Mission Moho will only cost a fraction of what is currently spent on space exploration…

Peeking into the Earth's interior is closer to home. **The voyage is well worth undertaking**.

Nature Geoscience, Editorial, Nov 09

Ildefonse et al., Sci. Drill., in press

The MoHole

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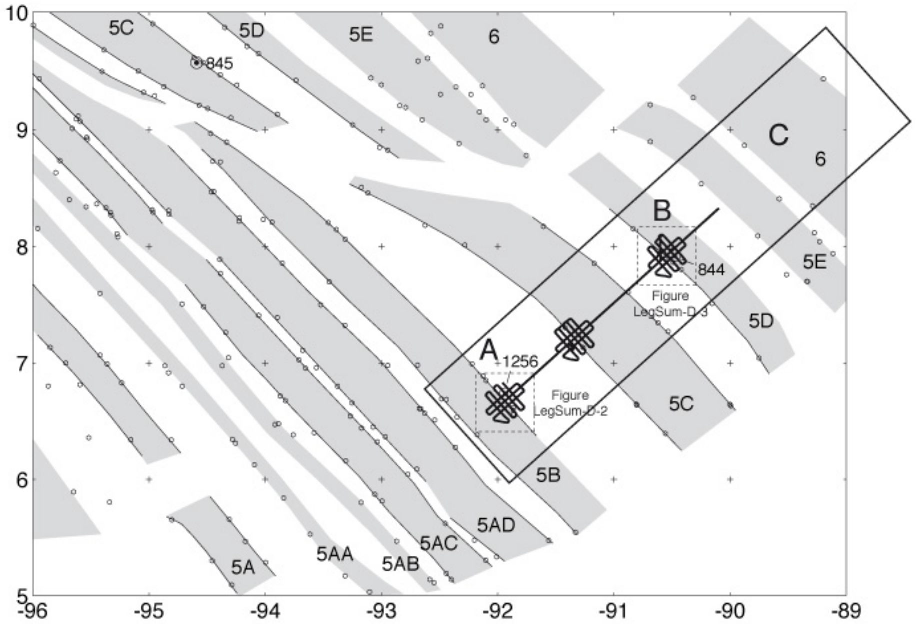
Timeline

	FY2009	FY2010	FY2011	FY2012	FY2013	FY2014	FY2015	FY2016
General	*INVEST* *Phase II SP writing*	1) Kanazawa WS (June) 2) Washington WS (September) **Roadmap (Mohole PMT?)**	JR Hole 1256D Exp. 335 (April-May) PMT start (?)				**Site Decision WS** **CDEX preparation start (?)** ⟷	
Characterization of Prospective Site-Data Acquisition	*R/V Kilo Moana @Hawaii bathymetry*	International Site Survey Team	R/V KAIREI off-Mexico ⟷	Site 1256 or Hawaii	Site 1256 or Hawaii	Mexico, 1256 or Hawaii 2D 3D seismic (?)	3D seismic (?)	
Data Analysis, & Sample Strategy Development		Sampling Strategies WG		Reconnaissance data analysis	2D data analysis		3D data analysis	
Technology development		Technology Roadmap & team(?)						

	FY2017	FY2018	FY2019	FY2020	FY2021	FY2022	FY2023
General	CDEX preparation ⟷	**Start Drilling** ⟷				**Reaching the Mantle**	Borehole & Post-drilling research
Science							
Technology & Operation							

Cocos Plate



- *Superfast spreading rate (>200 mm/yr)*
- *15 to 25 Ma*
- *Crustal thickness ~5 km*
- *Some MCS and wide-angle OBS data*

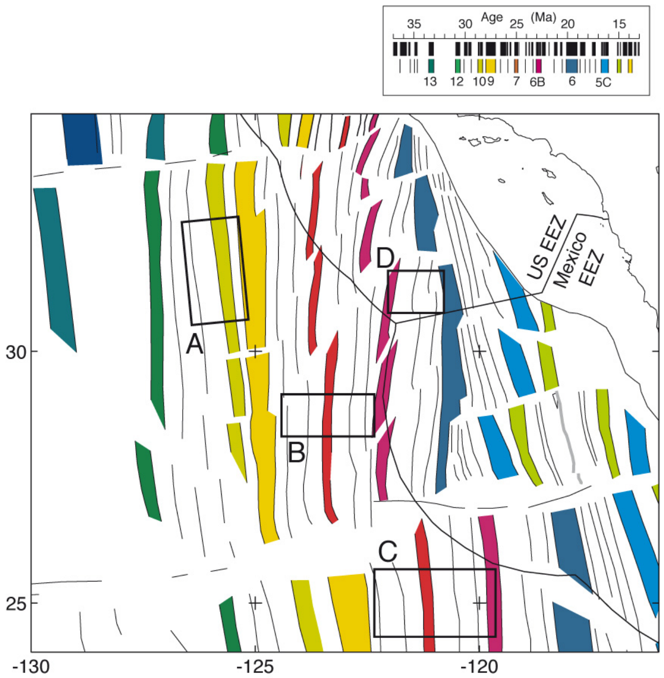
PROS

- *Shallowest water depth*
- *Well-known tectonics*
- *Sits within a corridor that includes a complete tectonic plate life cycle*

CONS

- *Highest Moho T*
- *Faster than present-day fastest spreading rate*
- *Near equator*

Off Southern/Baja California



- Spreading rate 110 mm/yr
- 20 to 35 Ma
- No modern geophysical data

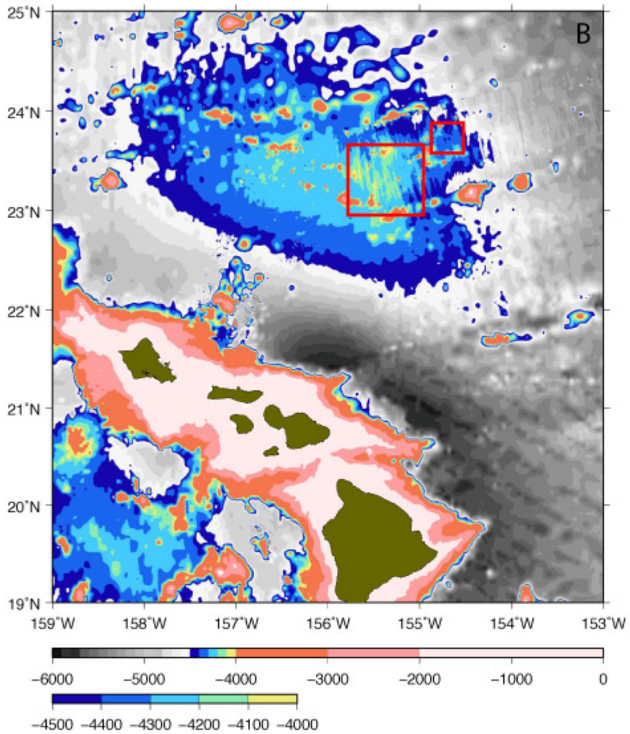
PROS

- Large range of water depth
- Modest Moho T
- higher latitude

CONS

- Few data available
- Off-ridge volcanism

Hawaii



- *Spreading rate ~ 70-80 mm/yr*
- *~ 80 Ma*
- *In flexural arch*

PROS

- *Lowest T*
- *Nearby a large port*

CONS

- *Deepest water*
- *Near large Hotspot*
- *Close to arch volcanism*
- *Near equator*
- *Lowest end of fast-spreading rates*

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.

Recommended detailed surveys:

- *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.*

The MoHole in Nature

Experts draw up ocean-drilling wish list

BREMEN
Earth scientists have laid the groundwork for the future of ocean drilling. More than 500 scientists — almost twice as many as organizers had initially expected — gathered last week in Bremen, Germany, to discuss priorities and research goals for the second phase of the Integrated Ocean Drilling Program (IODP), which is expected to begin in late 2013.

Since ocean drilling began in the 1960s, sediment and rock cores retrieved from the seabed have provided information about everything from plate tectonics to Earth's climate history. Much more remains to be discovered, scientists said at the meeting.

"We're not done," says Alan Mix, a marine geologist at Oregon State University in Corvallis. "Actually, we ain't seen nothing yet."

Researchers have generated a detailed wish list for new ocean-drilling projects, which will be boiled down into a science plan for the 2013–23 period by a group yet to be appointed. The finalized science plan will then be forwarded to funding agencies in Japan, Europe and North America, which currently support the IODP to the tune of around US$200 million per year.

Mix says that targets might include the role of greenhouse gases in transitions between cold and warm climates, and the magnitude, speed and locations of resulting sea-level changes. A more ambitious project would be to relaunch the effort to drill through Earth's crust and into its mantle. A 1960s attempt to drill through the sea floor into this boundary, known as the Mohorovičić discontinuity, or 'Moho', failed.

> "We need to explain why what we are doing matters."

The Japanese IODP vessel, the *Chikyu*, is already outfitted with technology to drill down some 7,000 metres into the crust, and there are plans to refit the vessel over the next three years with drilling and core-recovery technology to allow it to drill even deeper.

"Japan will lead the Moho project," says Asahiko Taira, the Yokohama-based executive director of the Japan Agency for Marine-Earth Science and Technology, which oversees Japan's ocean-drilling operations. "It's a classic geological quest, and definitely one of our prime targets."

"The journey down is equally important to the things we may find at the bottom," adds Benoît Ildefonse, a geologist at France's National Centre for Scientific Research (CNRS) based in Montpellier, France. "Recovering rocks from near Moho will, for the first time, allow us to test our ideas and models about how the crust forms."

The deepest sea-floor holes drilled so far include a 2,111-metre-deep hole drilled during the 1970s and 1980s off Nicaragua, and a 1,500-metre-deep hole drilled in 2005 in the Cocos plate in the eastern Pacific Ocean. The latter, performed by the US vessel *JOIDES Resolution*, was the first continuous retrieval of core from Earth's upper crust. Following a $130-million refurbishment, the 30-year-old ship is now capable of drilling 2,000 metres into the sea floor in waters as deep as 7,000 metres.

IODP leaders say they are increasingly aware of the need to explain the societal relevance of

Nature, Oct 21, 2009 (about the INVEST meeting) editorial

An epic voyage in the making

The plan to drill through the entire oceanic crust is ambitious and exciting, and well worth the expense.

The exploration of even the outermost fringes of our Solar System has long crossed over from the realm of fantasy to that of reality. But the human quest to explore our planet's interior — magically expressed in Jules Verne's epic *A Journey to the Centre of the Earth* — lags far behind. Unlike the leap into space, gravity defying as it may be, a voyage into the planet's bowels faces the sheer resistance of drilling through kilometre after kilometre of dense rock.

Human innovation, though, is only fuelled by such challenges. Indeed, penetrating the oceanic crust and traversing the crust–mantle boundary (the Mohorovičić discontinuity, or Moho) is the principal objective of the ambitious Mission Moho initiative, discussed at the September workshop of the Integrated Ocean Drilling Programme (IODP) in Bremen, Germany.

The first attempt at accomplishing this daunting task — made in the 1960s — was unsuccessful, and the hole reached a depth beneath the sea floor of less than 200 m. But it showed that drilling in the deep ocean was possible, and inspired subsequent missions that have managed to drill deeper. The data and insights gained from such projects have radically altered our understanding of the evolution of the oceanic crust and uppermost mantle.

However, so far no deep-sea drill has managed to reach beyond 1.5 km beneath the sea floor, which is only about one fourth of the typical distance from the sea floor to the Moho. As a result, much of our knowledge about the deeper parts of the oceanic crust and the uppermost mantle comes from observations of slices of oceanic plates that have been shoved on to continents by plate tectonic processes.

But geological exposure is incomplete as a rule, and remnants of the mantle that have ended up on the continents are not pristine. More importantly, the diverse processes that went into the construction and modification of oceanic crust and uppermost mantle cannot be directly observed in such outcrops, but can only be inferred. Drilling through the oceanic lithosphere is expected to fill in the gaps in our understanding of processes ranging from mantle melting to hydrothermal alteration.

Mission Moho is still in its infancy, and its success will depend on technological feasibility as well as budgetary considerations. The former may not be an obstacle for too long. Recently developed technology is likely to allow drilling through sea floor that lies at depths of over 4 km beneath the sea surface: this will enable the relatively thin oceanic crust along a mid-ocean ridge to be targeted. In contrast, current technologies can negotiate a water depth of only about 2.5 km.

Drilling into the mantle is not expected to be cheap by any means. But in all likelihood, Mission Moho will only cost a fraction of what is currently spent on space exploration: compare, for example, the current IODP annual budget of about $200 million (*Nature* **461**, 578–579; 2009) with that of NASA (over $15 billion for 2009). Peeking into the Earth's interior is closer to home. The voyage is well worth undertaking. ❐

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