Deep Sea Drilling Vessel
CHIKYU
マントル掘削
ULTRADEEP DRILLING 月より遠い道
Designed by K. Michibayashi

Frontiers of sampling the mantle by drilling to the Moho

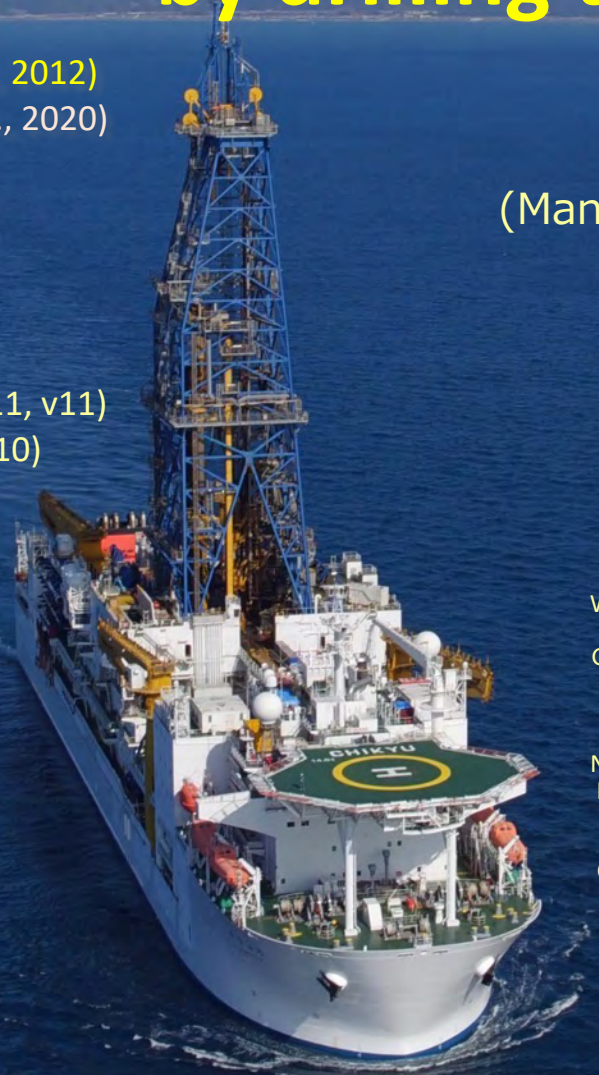
Natsue Abe
(Mantle Drilling Promotion Office, MarE3, JAMSTEC)
and
Susumu Umino (Kanazawa Univ.)

on behalf of the M2M Proponents

Shuichi Kodaira, Tomoaki Morishita, Katsuyoshi Michibayashi, Damon A.H. Teagle, Benoît Ildefons, Peter B. Kelemen, Olivier Alard, Shoji Arai, Ryo Anma, Chris Ballentine, Gary Acton, Jeffrey C. Alt, Wolfgang Bach, Neil R. Banerjee, Juan Pablo Canales, Mathilde Cannat, Richard L. Carlso, Rosalind M. Coggon, Laurence Coogan, Henry J.B. Dick, Toshiya Fujiwara, Yoshio Fukao, Jeffrey S. Gee, Kathryn Gillis, Takeshi Hanyu, Alistair Harding, Yumiko Harigane, (Erik Hauri), Eric Hellebrand, Ikuo Katayama, Jeffrey A.
Karson, Hiroyuki Kimura, Jun-Ichi Kimura, Juergen Koepke, Hidenori Kumagai, C. Johan Lissenberg, John Maclennan, Jinichiro Maeda, Christopher J. MacLeod, D. Jay Miller, Sumio Miyashita, Kentaro Nakamura, James H. Natland, Toshio Nozaka, Mladen Nedimovic, Yasuhiko Ohara, Eiji Otani, Philippe Pezard, Mark Rehkamper, Tetsuya Sakuyama, Takeshi Sato, Matthew O. Schrenk, Nobukazu Seama, Jonathan E. Snow, Eiichi Takazawa, Masako Tominaga, Takeshi Tsuji,Peter E. van Keken, Jessica M. Warren, Douglas S. Wilson,
Greg Moore, Steven D'Hondt, Laura Crispini, Brian Boston, Frieder Klein, Mikiya Yamashita, Michael Garcia, Michelle Harris, Yuki Kusano, Yohey Suzuki, Elizabeth Trembath-Reichert, Yasuhiro Yamada, Fumio Inagaki and many WS participants

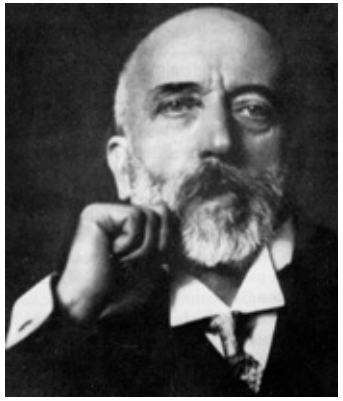
Two IODP Proposals:
- 805-MDP MoHole to Mantle (M2M: Umino et al., 2012)
- 951-Full Hawaiian North Arch Crust (Umino et al., 2020)

Workshops:
- Off Hawaii Drilling WS (Online, 2020 6-7)
- Kanazawa WS (2018.11)
- Mohole Tokyo WS (2012.2)
- Mantle Frontier WS (2010.10) Scientific Drilling (2011, v11)
- Kanazawa WS (2010, 6) & Scientific Drilling (2010, v10)
- INVEST WS & White Papers (2009.9)
- Southampton WS report (2009.7)
- Mission Moho WS (2006.9)



Mohole Project

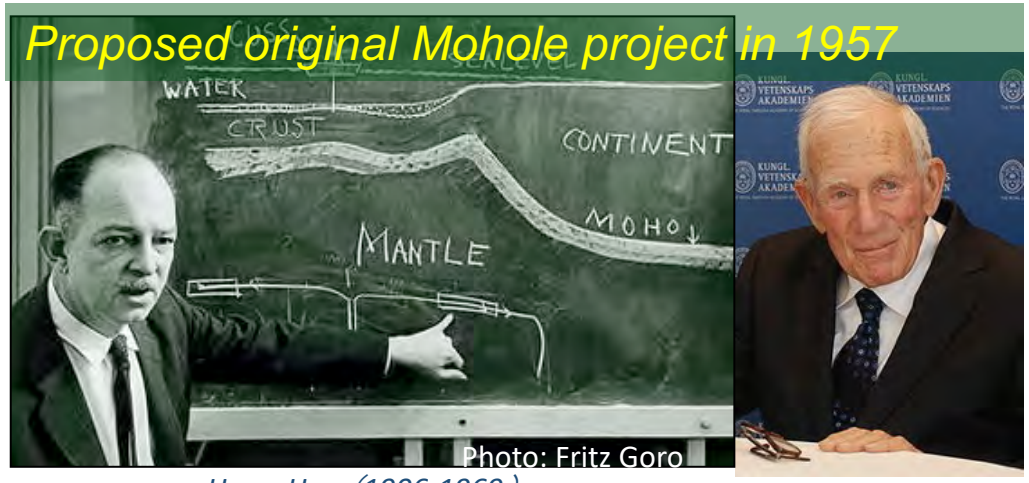
"Mohole" = "Moho" + "Hole"



Mohorovičić (1857-1936) discovered the "moho" discontinuity in October 8, 1909 (P-wave arrivals)

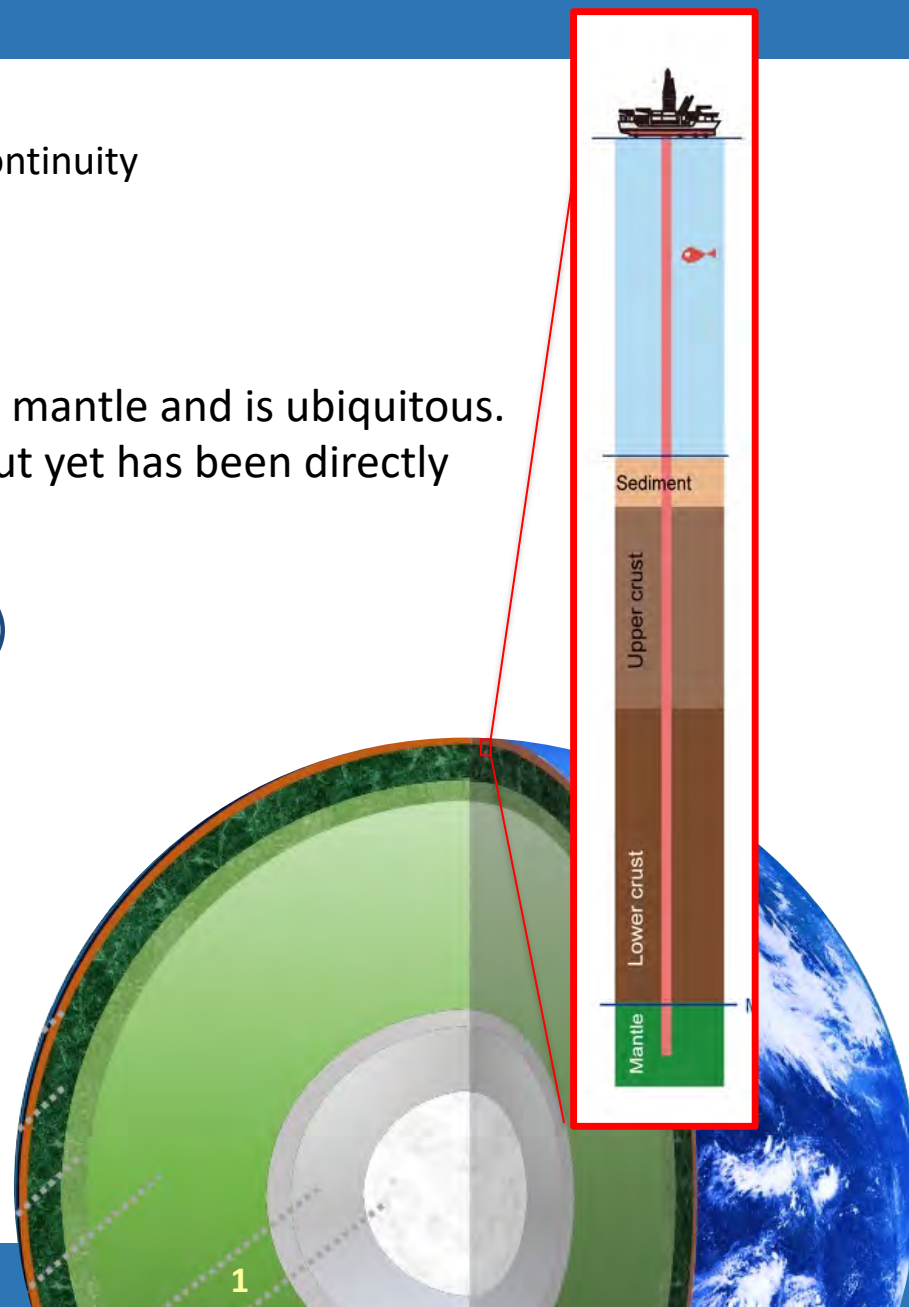
Moho is the boundary between Earth's crust and mantle and is ubiquitous. It is the outermost boundary in Earth's Interior but yet has been directly investigated.

Thick continental crust (~ 30 km) > Thin oceanic crust (~ 6km)

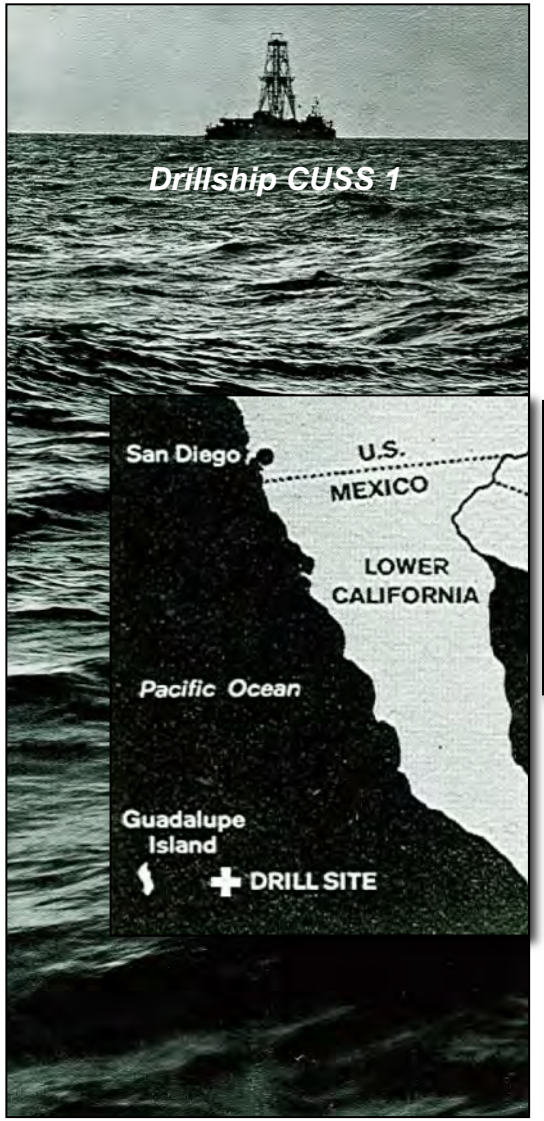


Harry Hess (1906-1969)

Walter Munk (1917-2019)



Project “Mohole” 1957-1966



Johna Steinbeck
Life,
14 April 1961

High Drama of Bold Thrust through Ocean Floor

EARTH'S SECOND LAYER IS TAPPED IN PRELUDE TO MOHOLE

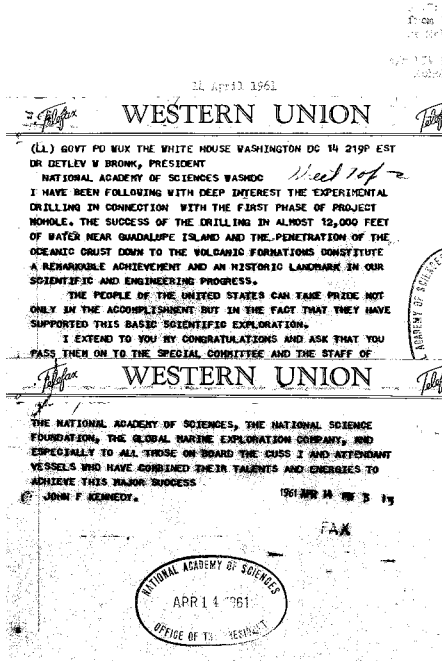
Last week Project Mohole (LIFE, April 7) made scientific history when its drilling barge, CUSS I (whose name is made up of the initials of oil companies who developed it: Continental, Union, Shell and Superior), pierced 601 feet into the sea floor to get core samples of the earth's never-before-penetrated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

by JOHN STEINBECK

AUTHOR STEINBECK AND PHOTOGRAPHER GORO ON DECK OF THE CUSS I

Offshore Guadalupe Island
March-April 1961

Dynamic positioning
~ 3500 m water depth
5 holes
Maximum penetration: 183 m,
Miocene sediments
~ 14 m of basalt



WESTERN UNION

(LL) GOVT PD WUX THE WHITE HOUSE WASHINGTON DC 14 219P EST
DR DETLEV W BRONK, PRESIDENT
NATIONAL ACADEMY OF SCIENCES WASHDC
I HAVE BEEN FOLLOWING WITH DEEP INTEREST THE EXPERIMENTAL DRILLING IN CONNECTION WITH THE FIRST PHASE OF PROJECT MOHOLE. THE SUCCESS OF THE DRILLING IN ALMOST 12,000 FEET OF WATER NEAR GUADALUPE ISLAND AND THE PENETRATION OF THE OCEANIC CRUST DOWN TO THE VOLCANIC FORMATIONS CONSTITUTE A REMARKABLE ACHIEVEMENT AND AN HISTORIC LANDMARK IN OUR SCIENTIFIC AND ENGINEERING PROGRESS.
THE PEOPLE OF THE UNITED STATES CAN TAKE PRIDE NOT ONLY IN THE ACCOMPLISHMENT BUT IN THE FACT THAT THEY HAVE SUPPORTED THIS BASIC SCIENTIFIC EXPLORATION.
I EXTEND TO YOU MY CONGRATULATIONS AND ASK THAT YOU PASS THEM ON TO THE SPECIAL COMMITTEE AND THE STAFF OF

WESTERN UNION

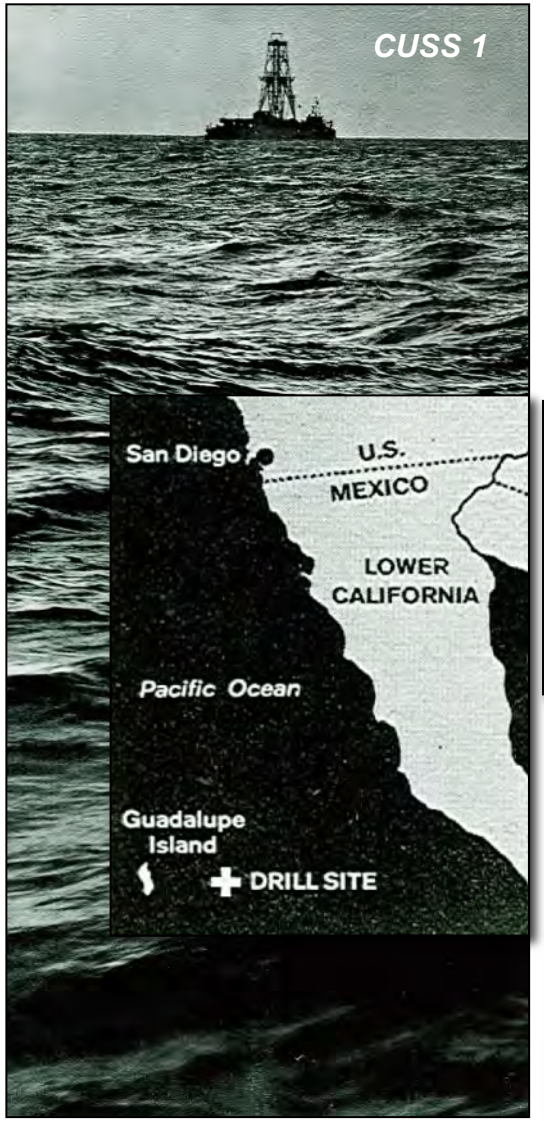
THE NATIONAL ACADEMY OF SCIENCES, THE NATIONAL SCIENCE FOUNDATION, THE GLOBAL MARINE EXPLORATION COMPANY, AND ESPECIALLY TO ALL THOSE ON BOARD THE CUSS I AND ATTENDANT VESSELS WHO HAVE CONTRIBUTED THEIR TALENTS AND ENERGIES TO ACHIEVE THIS MAJOR SUCCESS
JOHN F KENNEDY.

FAK

NATIONAL ACADEMY OF SCIENCES
APR 14 1961
OFFICE OF THE PRESIDENT

The first sampling of oceanic basaltic crust achieved by the Cuss 1 team received a personal letter of congratulations from President Kennedy.

Project “Mohole” 1957-1966



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March-April 1961

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~ 3500 m water depth
5 holes
Maximum penetration: 183 m,
Miocene sediments
~ 14 m of basalt

1966, the U.S. Congress issued a formal cease and desist order.

This frontier has been a symbolic goal for many geoscientists over decades but was beyond the reach of available technology at the time.

40 years later…, D/V Chikyu was built and would become feasible.

The Upper mantle anisotropy

Peridotite mantle

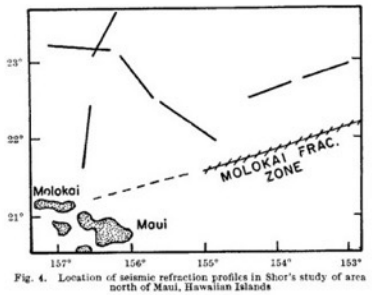


Fig. 4. Location of seismic refraction profiles in Shor's study of area north of Maui, Hawaiian Islands

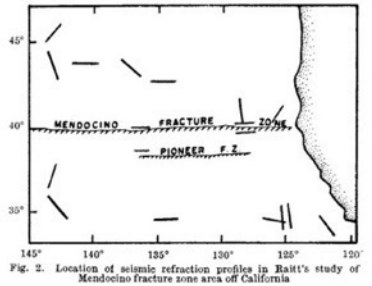


Fig. 2. Location of seismic refraction profiles in Raitt's study of Mendocino fracture zone area off California

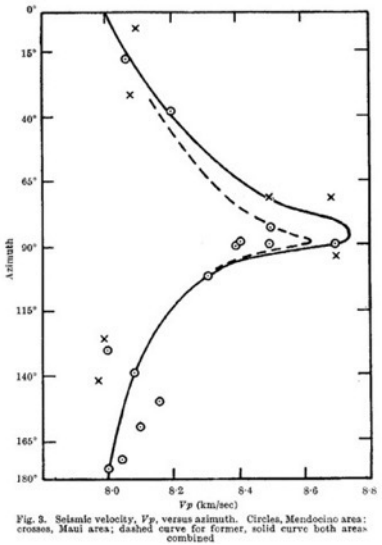
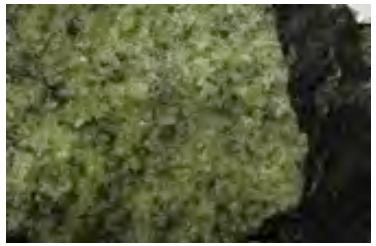


Fig. 3. Seismic velocity, V_P, versus azimuth. Circles, Mendocino area; crosses, Maui area; dashed curve for former, solid curve both areas combined

Two rock types have Vp > 8.0km/s and density ~ 3.2g/cm^3



Peridotite:
Ultrabasic rock (SiO2<45wt%)
Olivine dominant (>40%) with possible strong anisotropy

or

Eclogite (Gt+Cpx):
Basic rock (SiO2 45~53wt%; basaltic component)
Garnet dominant with isotropic

Photo by @tatsukix

Evidence of the peridotitic upper mantle:

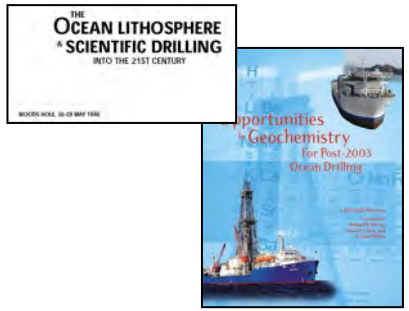
Hess (1964; Nature) found the upper most mantle has a strong anisotropy of the seismic velocity. It was observed during the site survey at two Mohole site (Hawaii and Baja California).

After this, Ringwood & Green (1966) demonstrated by high-P experiment that the oceanic Moho is much shallower than the pressure of the phase transition between Gabbro/Eclogite, which is deeper than 36km.

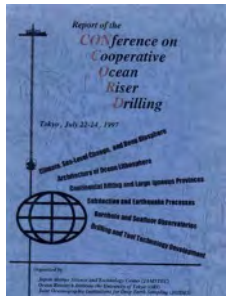
Now we believe the upper mantle is composed of peridotite.
It is the result of the Mohole study at the beginning.

History of scientific ocean drilling

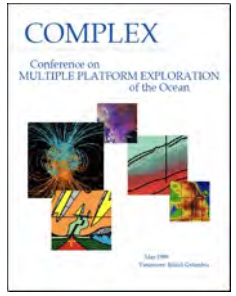
WSs to initiate IODP



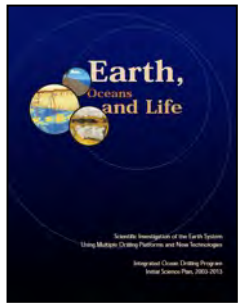
1997 Tokyo



1999 Vancouver

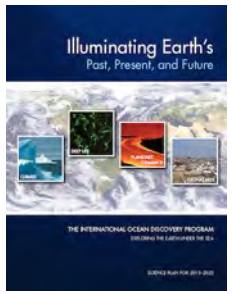


Science Plans

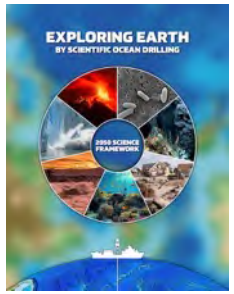


IODP Phase I SP
(2003-2013)

IODP Phase II SP
(2013-2023)



2050 Science Framework



1961 Project Mohole

1968 Deep Sea Drilling Project

1975 *Japan joined DSDP*

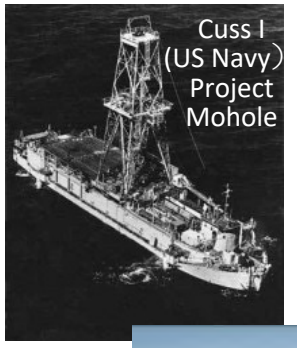
1983 Ocean Drilling Program
with 21 member countries

1985 D/V JOIDES Resolution launched

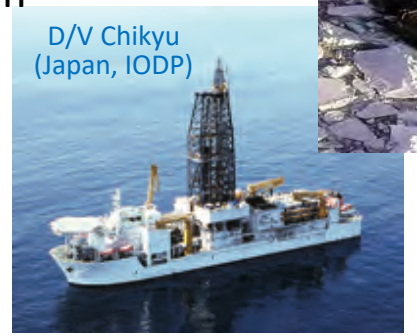
2003 Integrated Ocean Drilling Program
w/25 countries (IODP Phase I)

2005 D/V Chikyu launched

2013 International Ocean Discovery
Program (IODP Phase II)



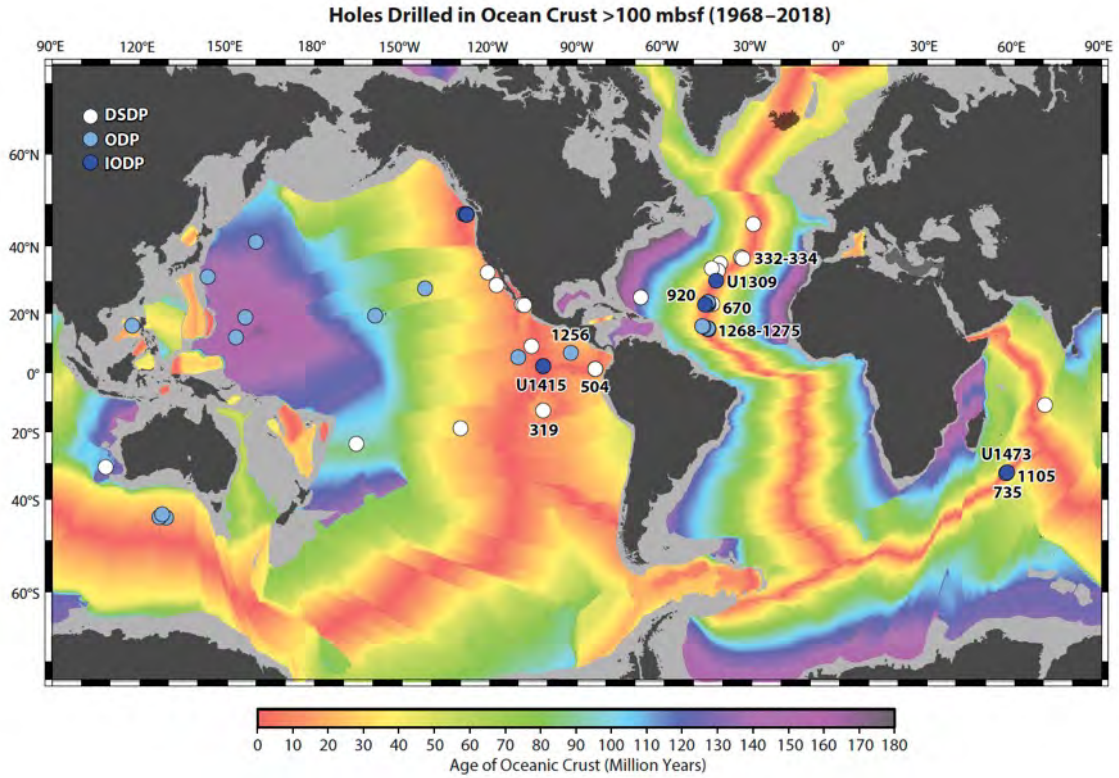
Mission
Specific
Platform
(ECORD, IODP)

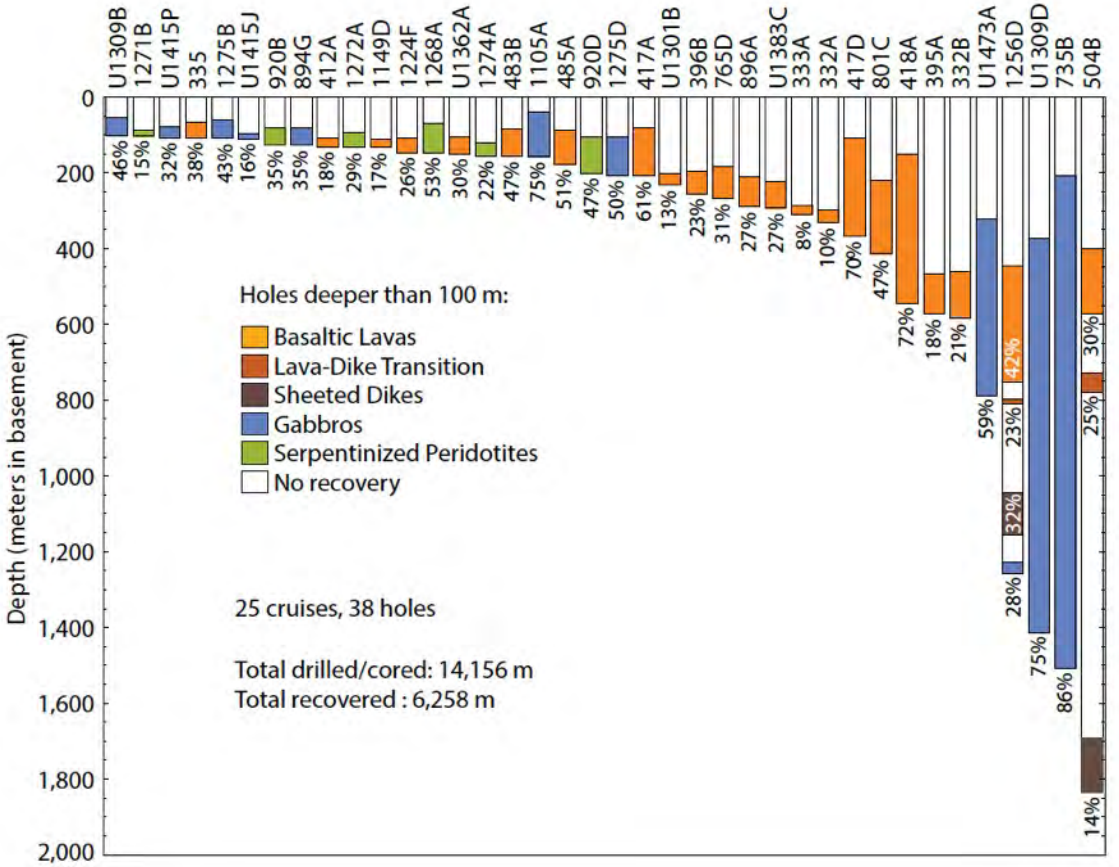


2024 Scientific Ocean Drilling (2050 Science Framework)

Drill holes in oceanic crust (>100m, 1974-2018)

Michibayashi et al., Oceanography, 2019.





Hard rock ~ 3% of drill cores, 97% sediment

- *Small amount of cores*
- *No full crustal section*

Mantle Drilling

D/V Chikyu

Proposed *MoHole to Mantle (M2M)* in 2012

Received 25 March 2012

IODP Proposal Cover Sheet **805-MDP**

☒ New ☐ Revised ☐ Addendum

Please fill out information in all gray boxes *Above For Official Use Only*

Please check if this is Mission proposal ☐

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

Contact Information:

Contact Person:	Katsuyoshi Michibayashi		
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E-mail:	sekmich@ipc.shizuoka.ac.jp		

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

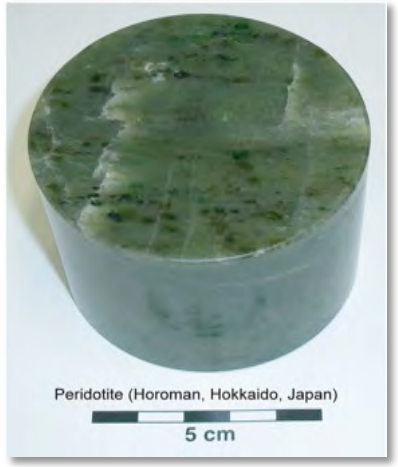
IODP Proposal (805-MDP: Umino et al.)

MoHole To the Mantle (M2M)

IODP Proposal (805-MDP: Umino et al.)

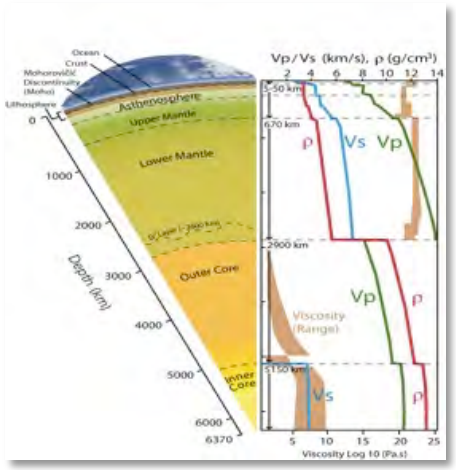
4 main Science targets

1. Sample Return



Structure and composition of convecting mantle, obtaining in-situ mantle sample

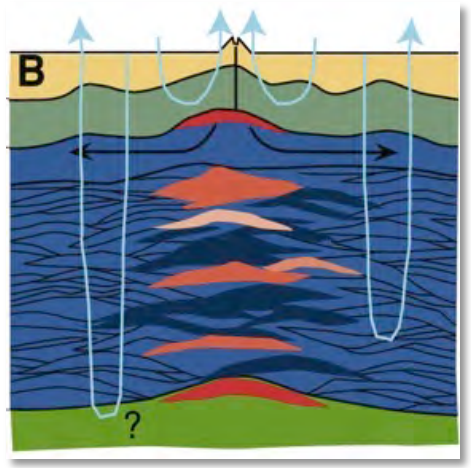
2. Naturel of Moho



Geological meaning of Moho and seismic layers in the crust

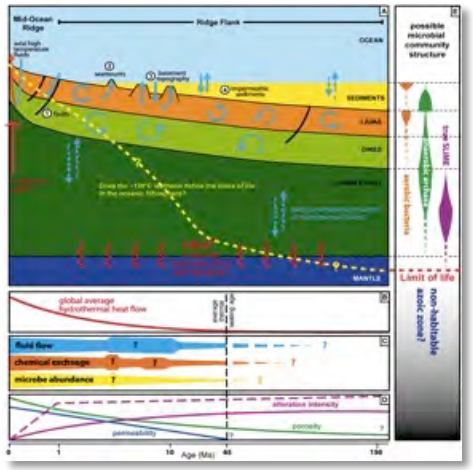
10 fundamental questions

3. Crust formation



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

4. Frontier and limits of life



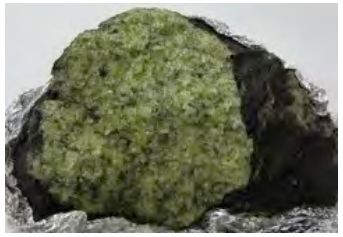
Lithosphere aging, chemical fluxes, and limits and controlling factors of life

1 Sample Return

Obtain the first in-situ samples of Earth's mantle

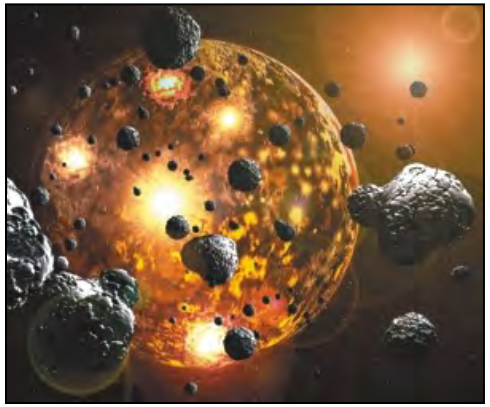
- Estimation Gap: basalt and mantle

Mantle composition is commonly estimated by basalt composition, which is produced as a partial melt of the mantle peridotite. There is a large gap of the concentration between basalt (MORB) and abyssal peridotite.



- *Compositional and isotopic heterogeneity*
- *Volatiles contents (CO_2, H, …)*
- *Contribution to global carbon budget*
- *Melt migration processes*
- *Physical properties (rheology, seismic anisotropy, …)*

Temperature and viscosity of mantle



Late veneer

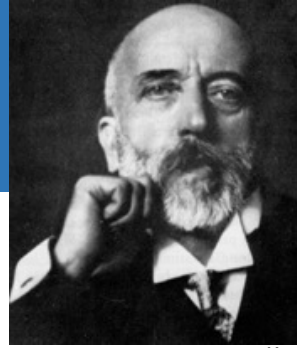
- Estimation Gap: whole earth

Need samples & measurement

Up to 0.7 wt% (carbon) and 0.02 wt% (H_2O) on the earth's surface
vs. av. 3.2 wt% (carbon) and 2 wt% (water) in whole Earth estimated from C1 chondorite

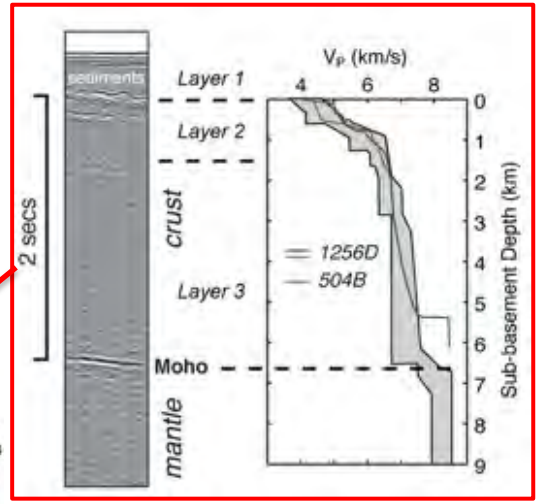
How much CO_2 in the lithospheric oceanic mantle ? (10 ppm > ~10^{20} tons for 10km)

2. Geological nature of Moho?

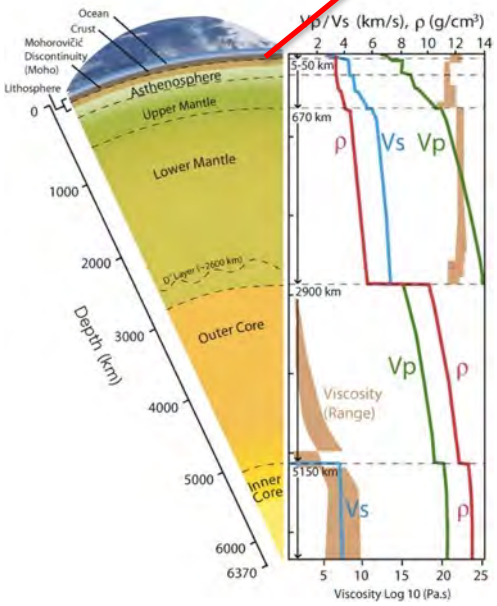


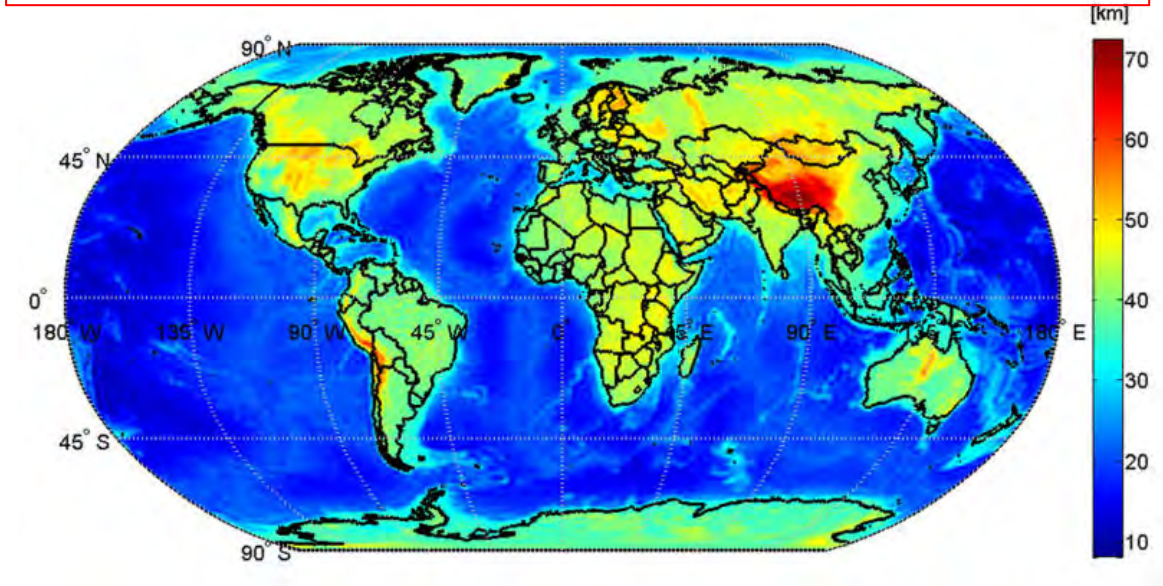
Andrija Mohorovičić

6 km thick ubiquitous oceanic crust = 10 km – 4km water depth



Seismic imaging of Pacific lithosphere

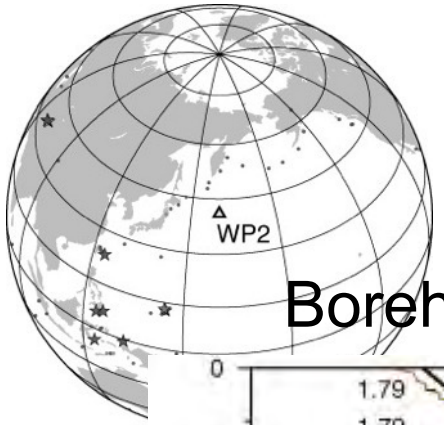




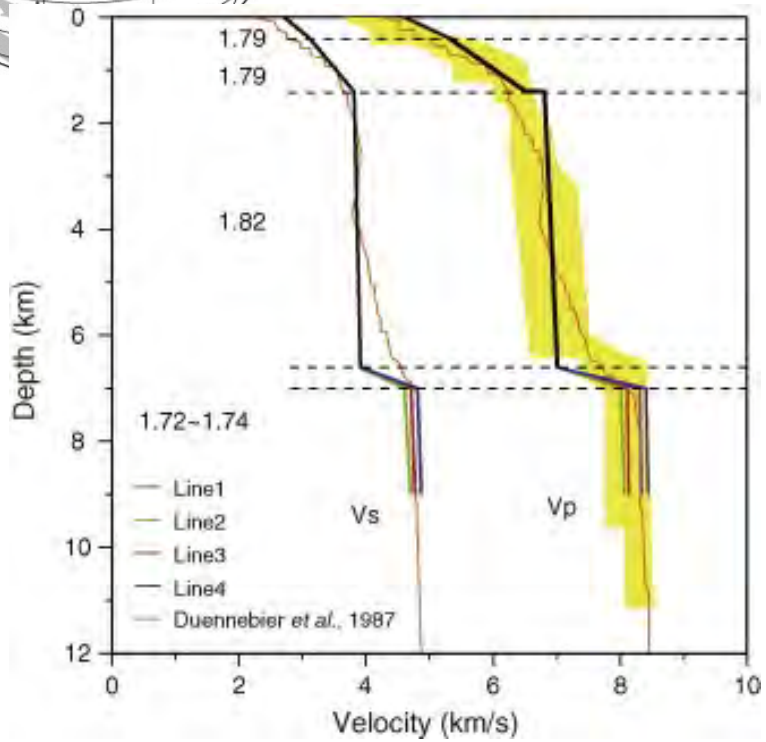
Global map of Moho depth (from GOCE data, 2012)

- *Is the Moho the interface between :*
  - *magmatic crust & residual mantle ?*
  - *magmatic rocks of different compositions ?*
  - *serpentinized mantle & fresh mantle ?*
  - *mantle + magmatic intrusions & mantle ?*

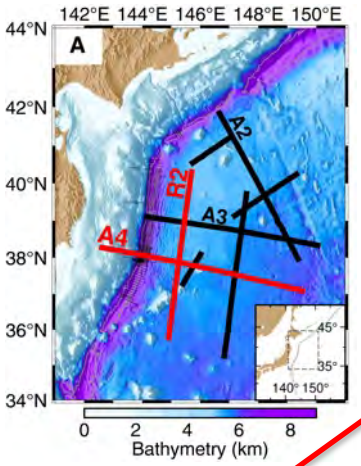
2. Geological nature of Moho?

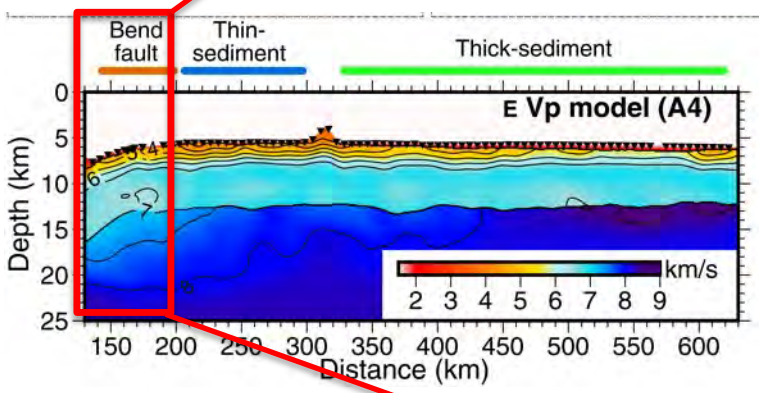


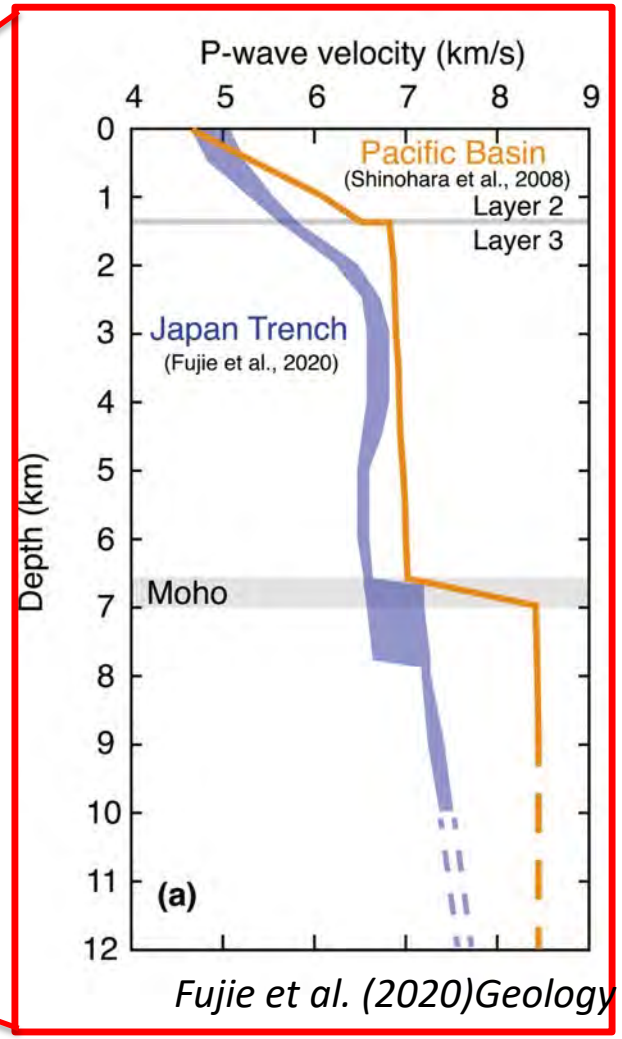
Borehole seismometer



Shinohara et al. (2008)PEPI





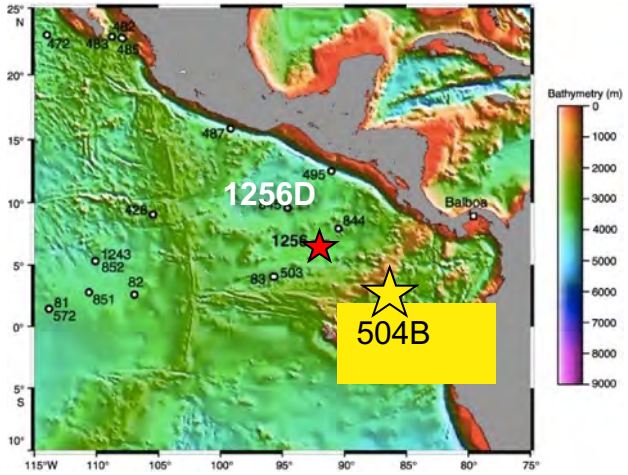


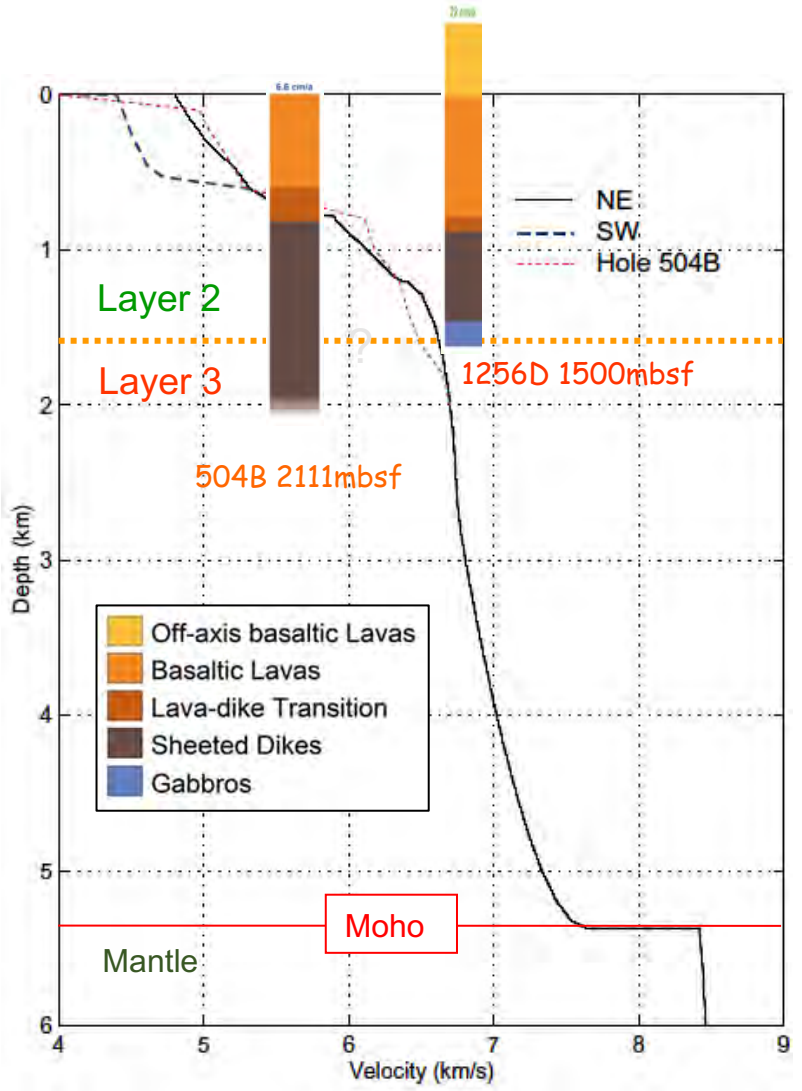
Fujie et al. (2020)Geology

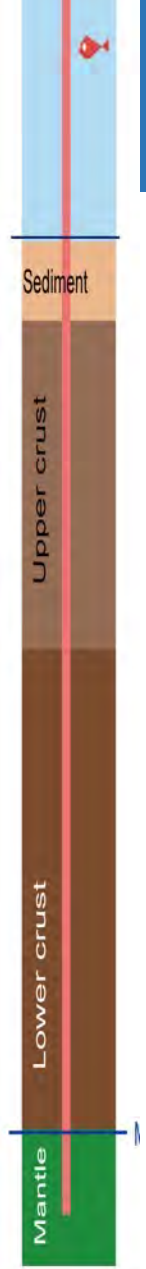
Need samples to test the hypothesis

2. Geological nature of Moho?

What is the upper/ lower crust boundary?



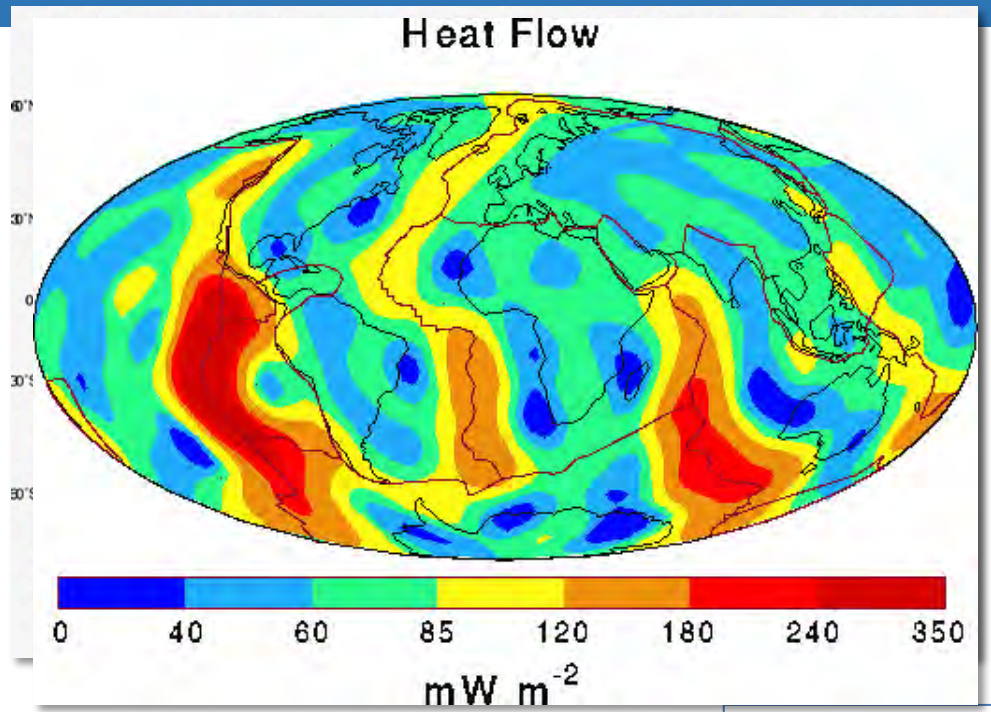




- Gabbro/Layer2 <= Hole 1256D
- Sheeted /Layer 3 <= Hole 504B.

A seismic boundary
≠ Lithological boundary

3. Formation of the oceanic crust , the mode of accretion



(Degree 12 Spherical Harmonic) after Pollack et al. (1993)

Japan, Chile etc

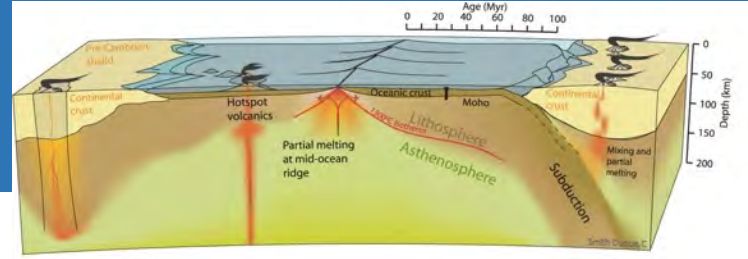
Yellowstone, Kilimanjaro etc

Hawaii, Canary, Azores, Tahiti Islands etc

	Magma production rate (km3/yr)			Producing rate (%)
	Extrusive	Intrusive	Total	
MOR	3	18	21	60-80
Subduction	0.4-0.6	2.5-8.0	2.9-8.6	8.6-33
Intraplate (continent)	0.03-0.1	0.1-1.5	0.13-1.6	0.4-6.2
Intraplate (ocean)	0.3-0.4	1.5-2.0	1.8-2.4	5.4-9.3
Total	3.7-4.1	22.1-29.5	25.8-33.6	

Magma production rate in Cenozoic: *Data from McBurny* (1993)

3. Formation of the oceanic crust



- **A reference site** of the continuous deep hole into the mantle layer
- Mid ocean ridge : **the biggest heat radiator** from the earth interior
- **The pattern of the hydrothermal** circulation in deep is controlled by formation processes of the oceanic crust
- **Bulk crust composition**

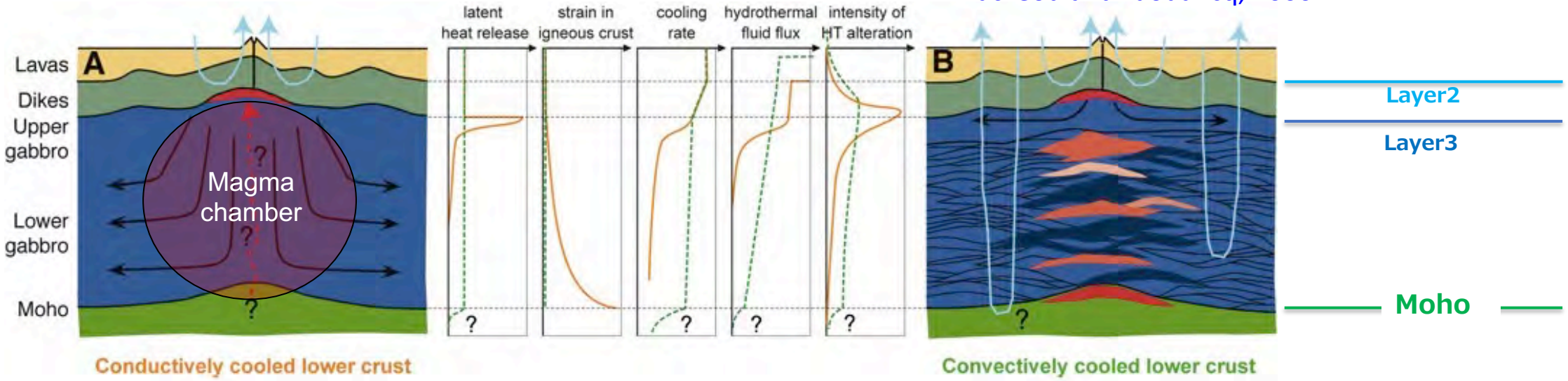
Two endmember models of crust accretion

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



and the outermost

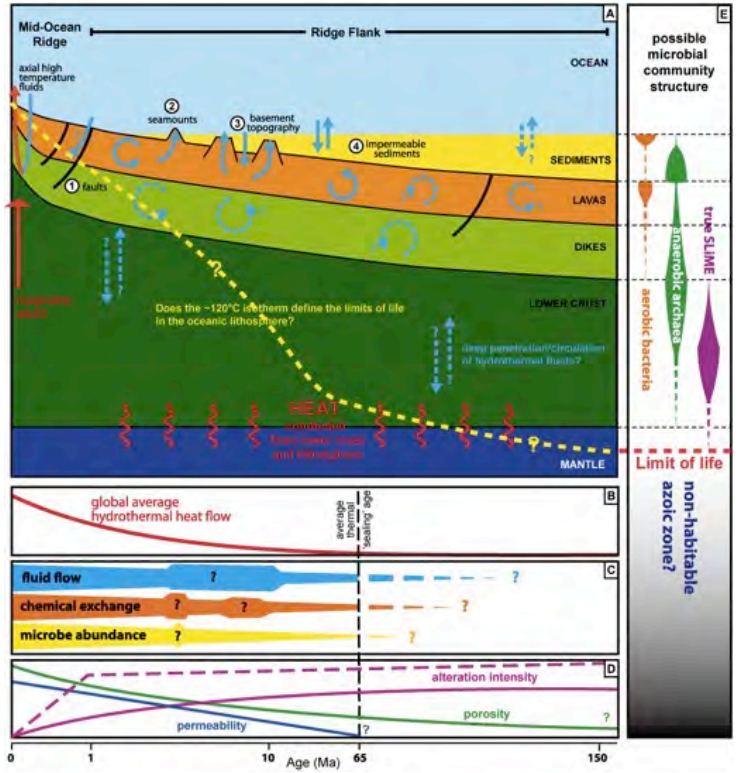
Moho is the only boundary to reach, observe and describe in-situ melt migration system.

4. Limits and controlling factors of life

Hydrological-Geochemical-Microbiological Feedbacks

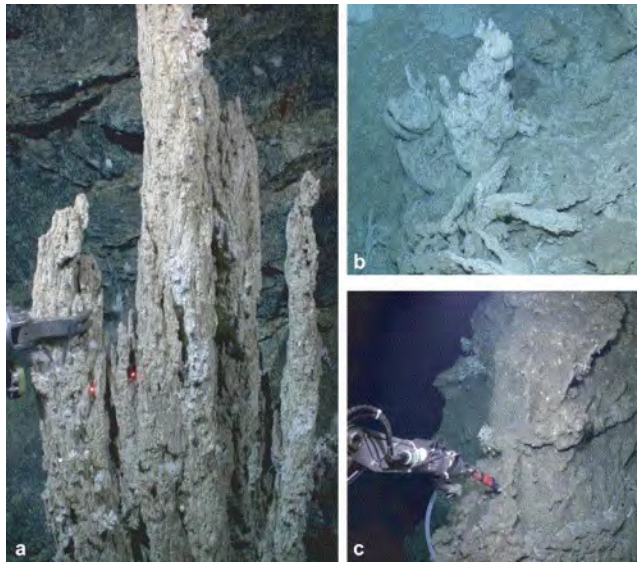
MoMARDREAM Cruise, 2008

Reaction front of lithosphere - seawater



M2M proposal (Umino et al., 2012)

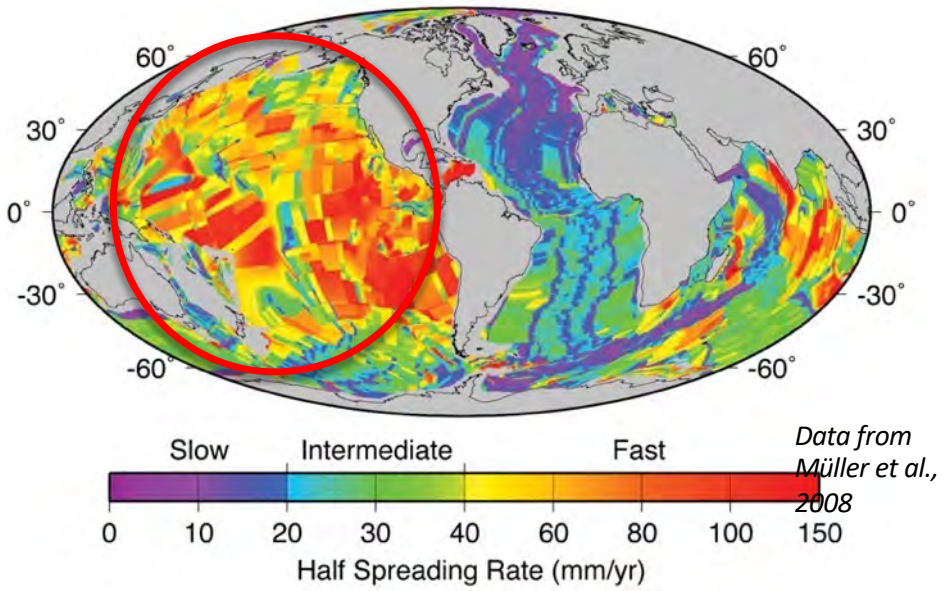
- What processes control exchanges ?
- Impact on global bio-geochemical cycles ?
- Limits (and controlling factors) of deep biosphere ?



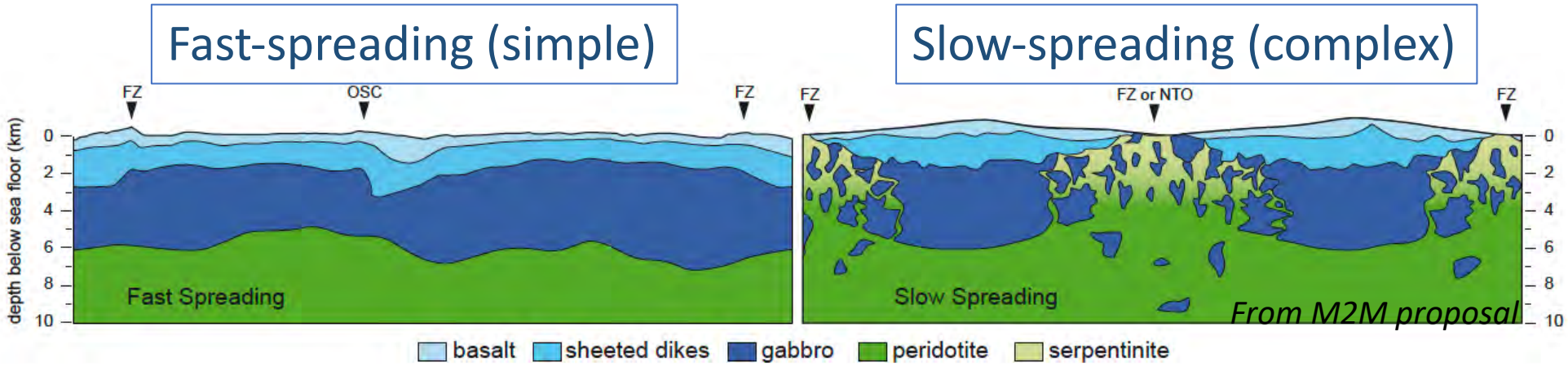
Ludwig et al. (2006) GCA

Where?

*1st MoHole : **fast-spread plate*** (Typical oceanic plate)



- *Majority of crust recycled into mantle in past 200 Ma*
- *~20% of modern ridges*
  ~50% of present ocean floor
  ~30% of Earth's surface
- *Relatively continuous and uniform*
- *Most of subduction slabs are the fast-spreading lithosphere*



Schematic along-axis cross-sections of fast and slow spreading crust at the mid-ocean ridges.

Where? (In the pacific)

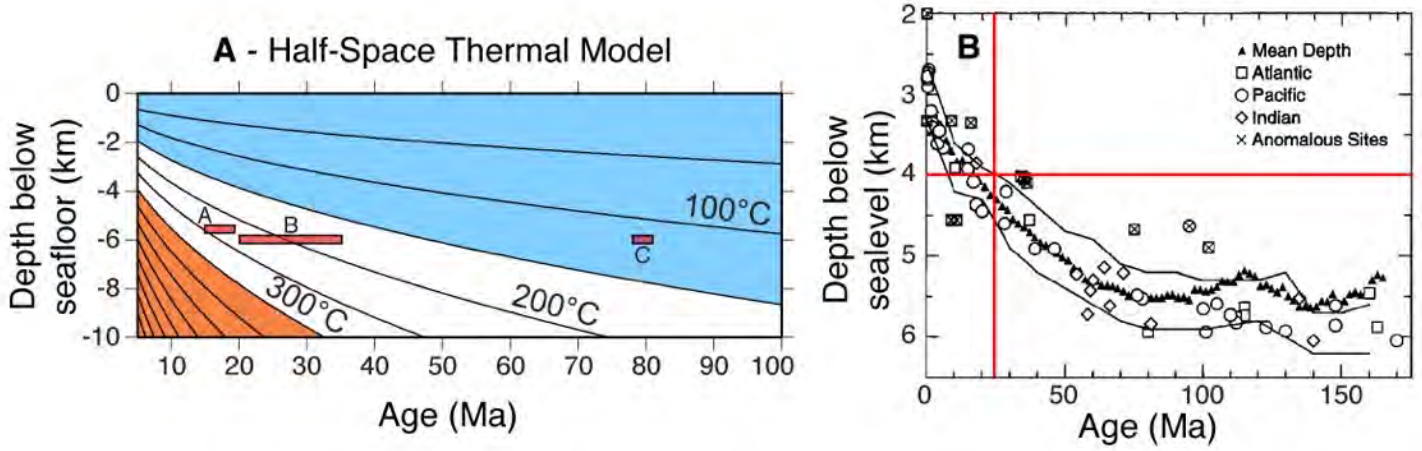
Criteria to meet scientific objectives

- Simple tectonic setting
- Normal crust (~6.0 km thickness)
- Clear Moho discontinuity (reflector)

Technical constraints

- Water depth >~ 4000 m
- Total length < 12km (<7 kmbsf)
- Cool Moho temperature (<250° C)

A. Thermal model of the oceanic plate (Half-Space).
B. Actual measurement of the water depth vs crustl Age



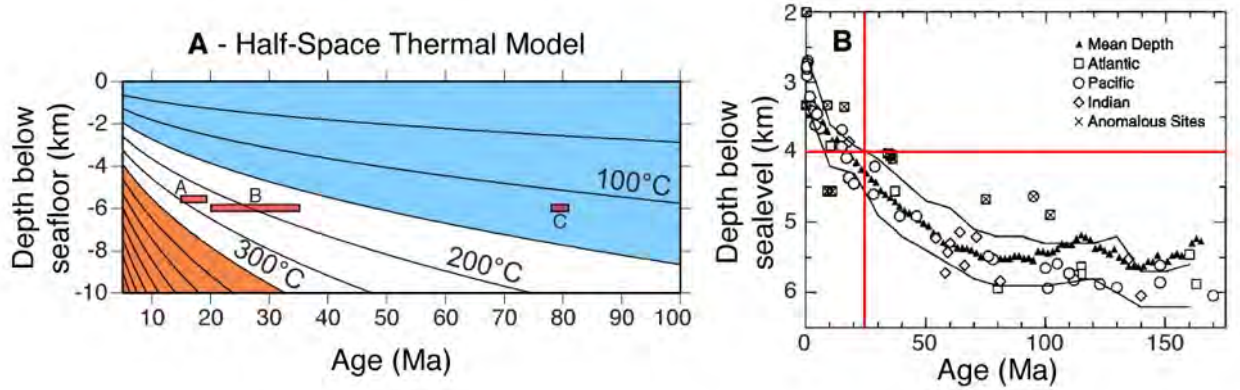
Logistics and housekeeping
- Near heliport
- Close to main port
- Stable sea condition
- Blue ocean or member country's EEZ

M2M proposal (after Carlson & Johnson, 1994)

Technological constraints: <~250° C in the mantle & ≤4000-4500 meters of water

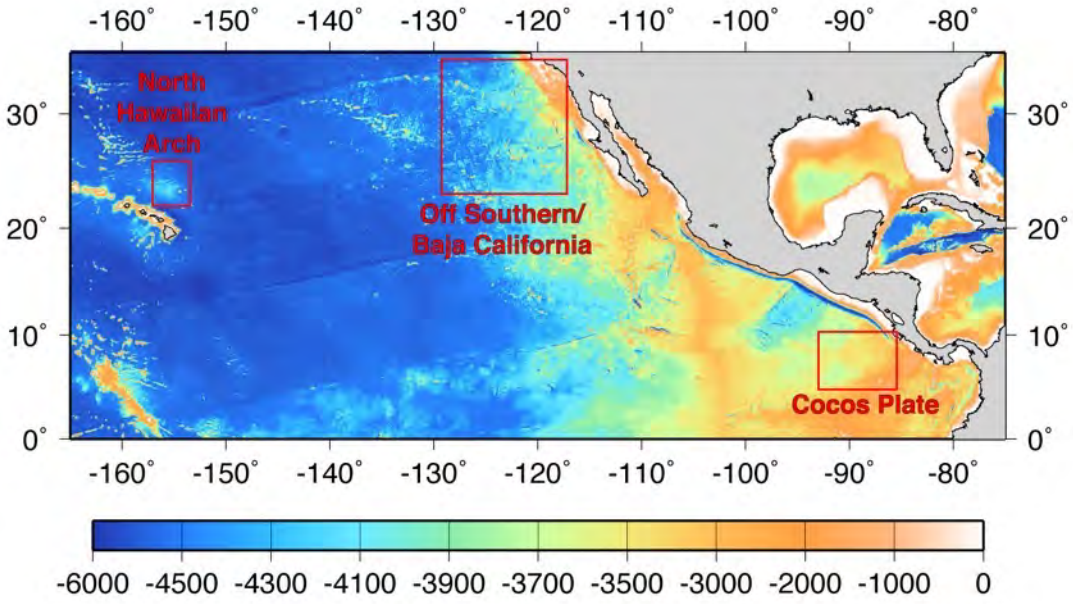
Where?

The trade-off between water depth and temperature



Carlson & Johnson, 1994

Technological constraints: <~250 ° C in the mantle & ≤4000-4500 meters of water

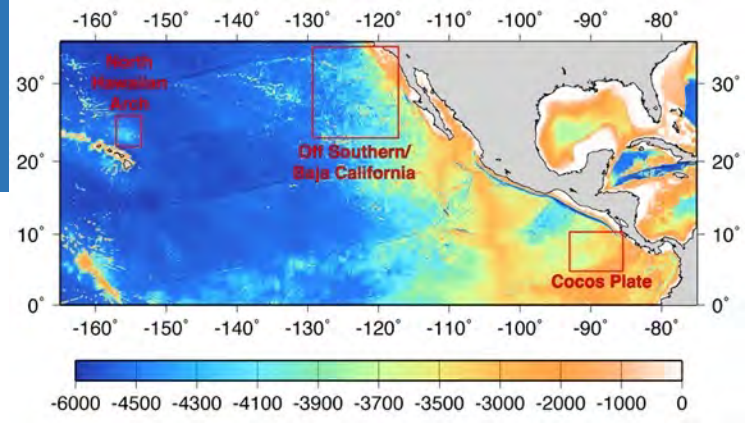


3 site candidates

- Cocos Plate (Site 1256D)
- Off Baja California
- Off Hawaii

Conditions of the three candidates

Site Candidate	Half spreading rate (mm/yr)	Crustal Age (Ma)	Water Depth (km)	Crustal thickness(km)	Total penetration (km)	Inferred Moho-T(°C)	Sediment Thickness (m)	Crustal thickness(km)	Distance from main port (km)	Pros	Cons
Cocos Plate	110	15-19	3.4 – 3.6	5 - 5.5	~10	> 250	250 - 300	5 - 5.5	~600	Shallow water depth and total length, near deep hole	High-T
Baja California	45 - 60	20 - 30	4.3	~ 6	10 - 11	200 - 250	80 - 130	~ 6	800-1000	Moderate T	Few site survey data, off-ridge volcanism?
Off Hawaii	40 - 45	75-81	4.1 – 4.5	~ 6.25	> 11	~150	~200	~ 6.25	~400	Low Moho-T, close to main port	Total depth, near hotspot



Each site has Pros & Cons

Feasibility studies

FINAL REPORT

Implementation Plan for the BEAM" – "Borehole into the Earth's Mantle" Program

Prepared For:

Yoshi Kawamura
Integrated Ocean Drilling Program – Management International

Nobu Eguchi
Japan Agency for Marine Earth Science and Technology

Purpose:
Develop an implementation plan for the BEAM Project that moves the project from its current feasibility phase towards a project execution phase that could be used by the various project stakeholders as the basis for internal operational planning and decision making.

Version:	Date:
001	14 July 2013

Project Number:
IOD-I212-003
JAM-I213-001

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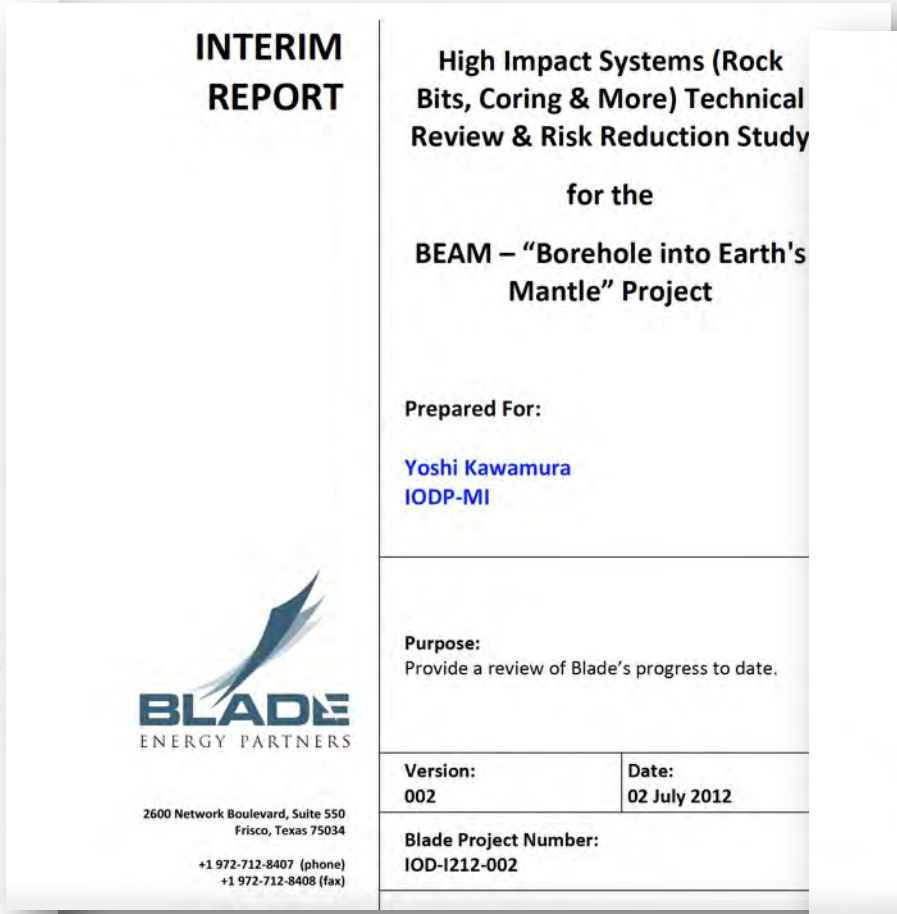

INTERIM REPORT

High Impact Systems (Rock Bits, Coring & More) Technical Review & Risk Reduction Study

for the

BEAM – "Borehole into Earth's Mantle" Project

Prepared For:

Yoshi Kawamura
IODP-MI

Purpose:
Provide a review of Blade's progress to date.

Version:	Date:
002	02 July 2012

Blade Project Number:
IOD-I212-002

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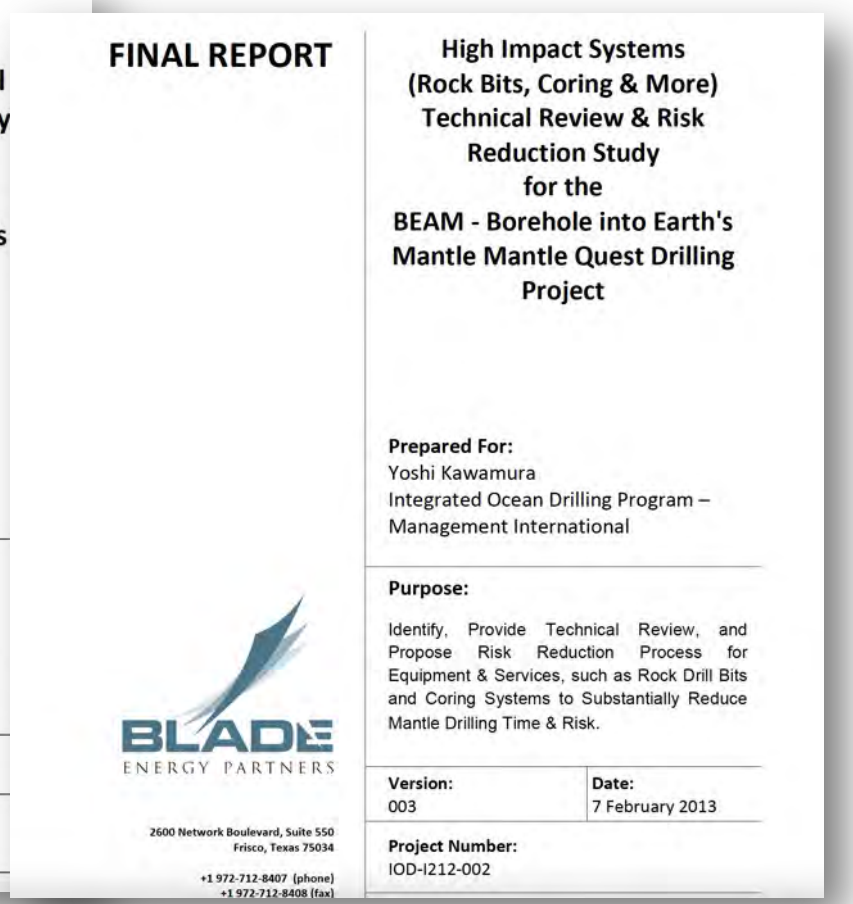

FINAL REPORT

High Impact Systems (Rock Bits, Coring & More) Technical Review & Risk Reduction Study for the BEAM - Borehole into Earth's Mantle Mantle Quest Drilling Project

Prepared For:
Yoshi Kawamura
Integrated Ocean Drilling Program – Management International

Purpose:

Identify, Provide Technical Review, and Propose Risk Reduction Process for Equipment & Services, such as Rock Drill Bits and Coring Systems to Substantially Reduce Mantle Drilling Time & Risk.

Version:	Date:
003	7 February 2013

Project Number:
IOD-I212-002

BLADE ENERGY PARTNERS

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Plus, JAMSTEC conducted the feasibility study in 2021.

Eguchi&Sawada, (2022) Chikyu Monthly written in Japanese

Feasibility studies

Coring (sampling) strategy

BLADE Final report (2013)

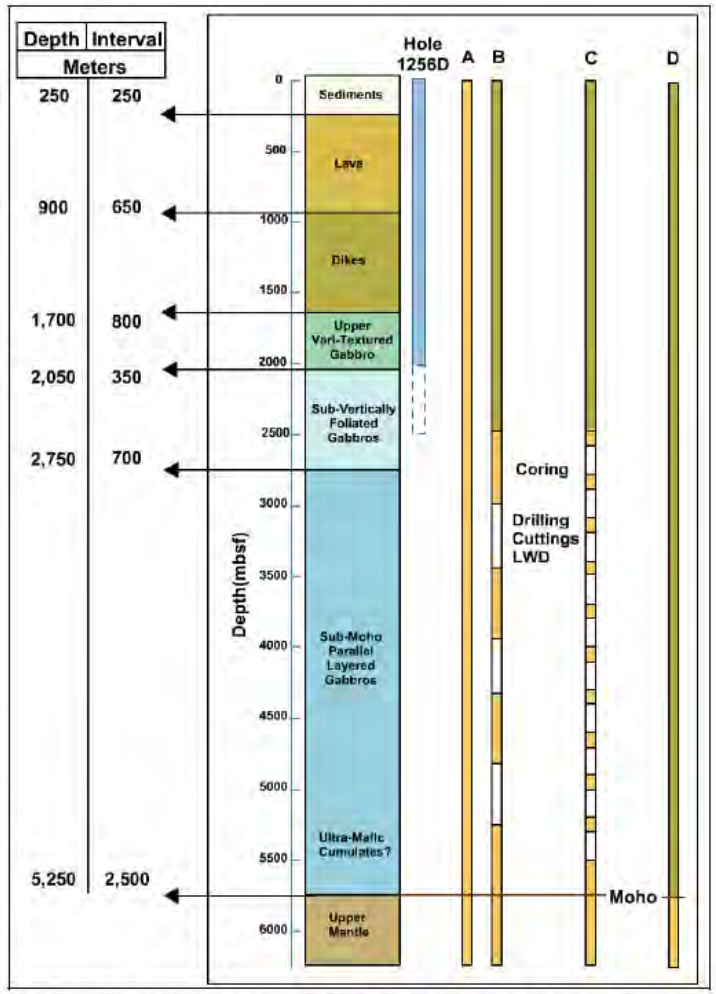
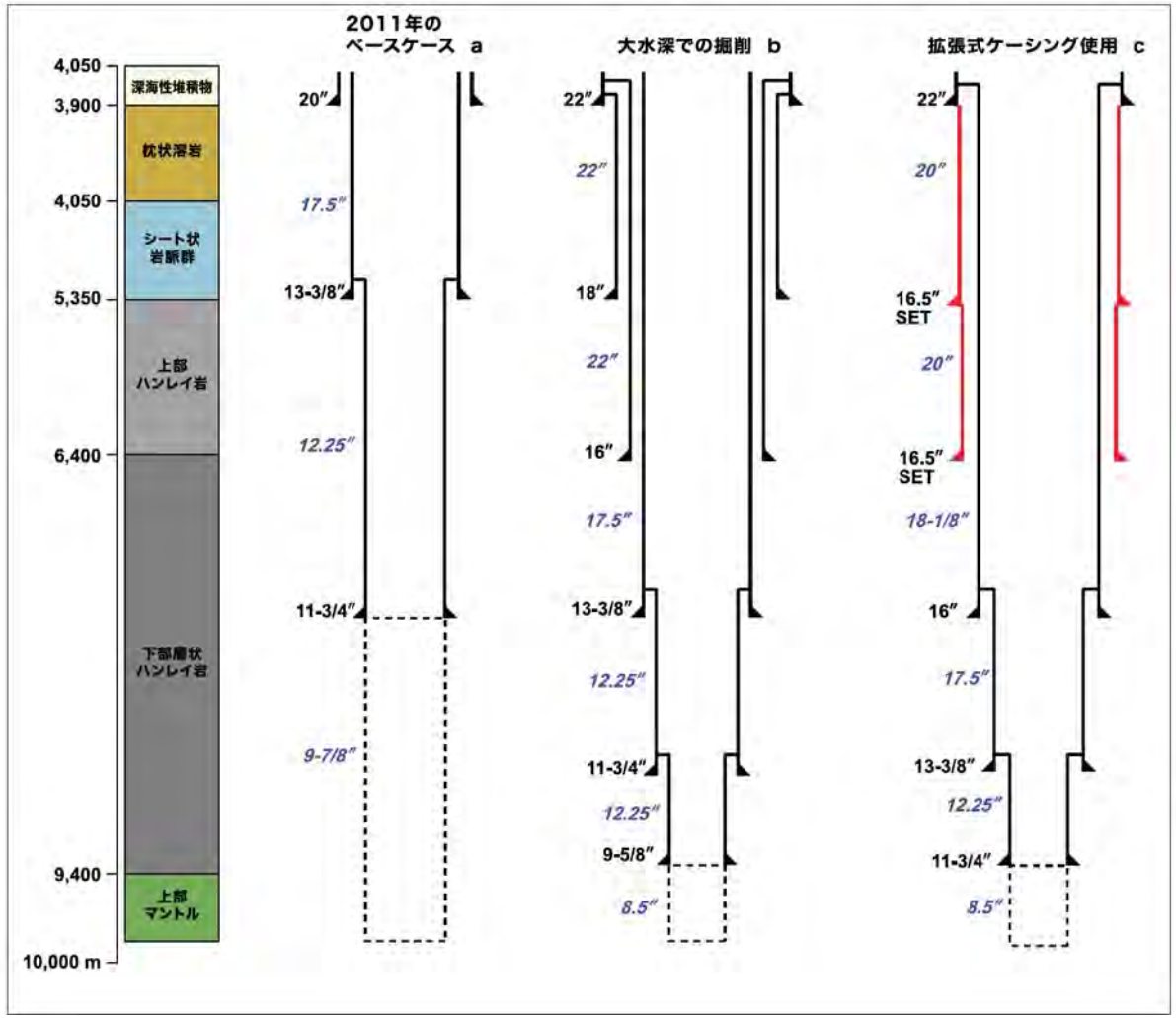


Figure 6. Assumed General Stratigraphy for the 3 Well Locations

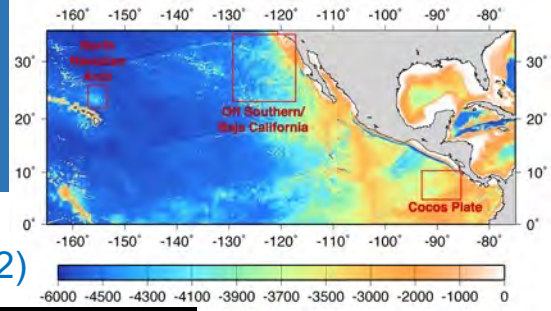
Casing strategy

Eguchi & Sawada (2022)



Conditions of the three candidates

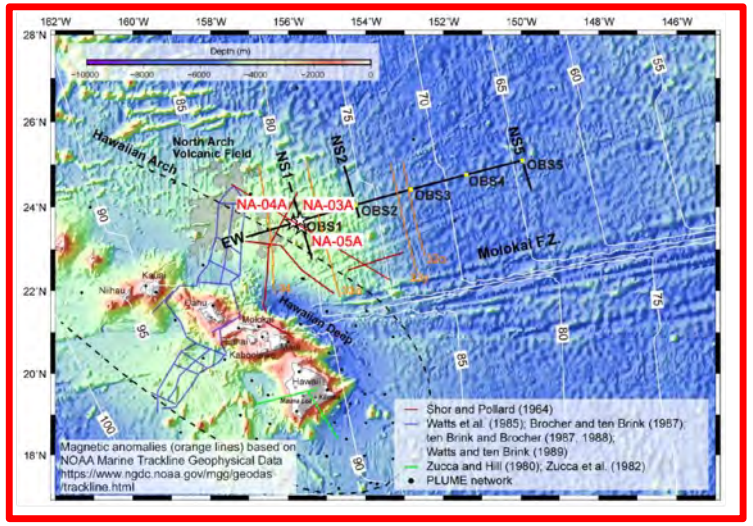
Estimated number of days for drilling

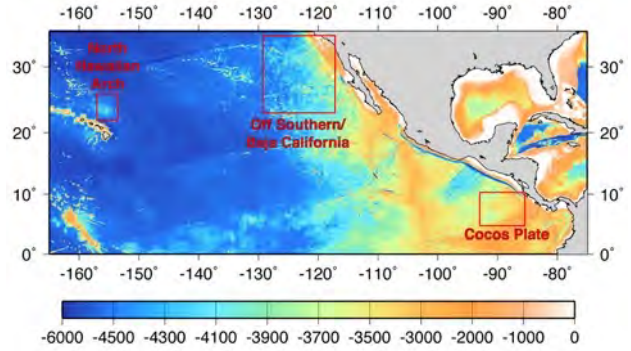


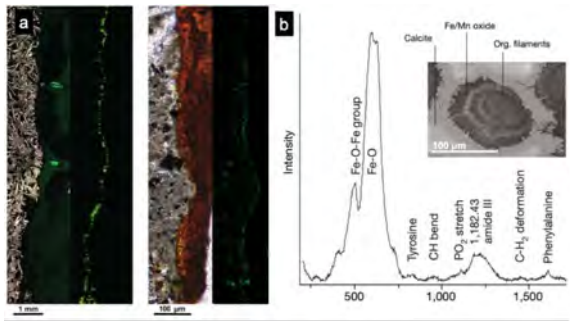
After Eguchi & Sawada (2022)

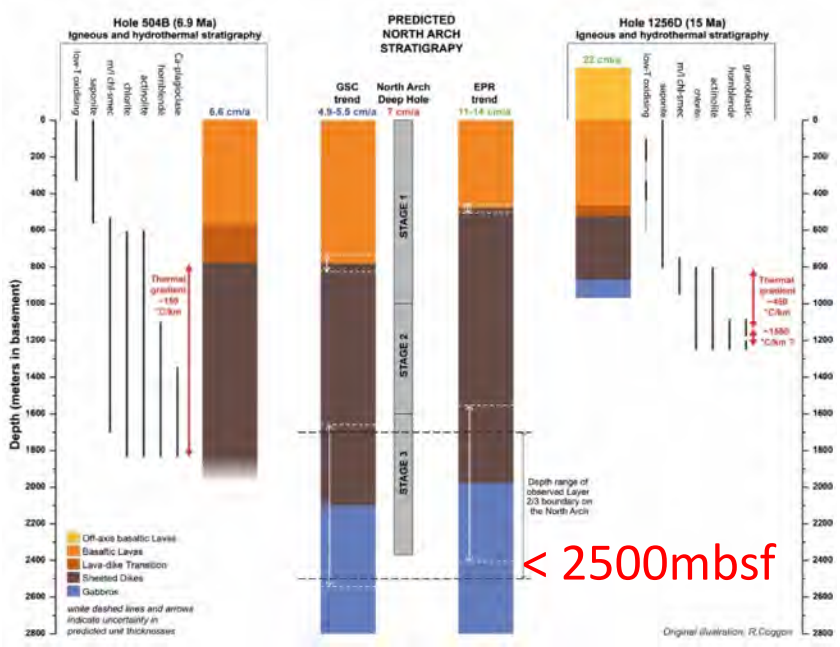
Site Candidate	Half spreading rate (mm/yr)	Crustal Age (Ma)	Water Depth (km)	Crustal thickness(km)	Total penetration (km)	Inferred Moho-T(°C)	Sediment Thickness (m)	Crustal thickness(km)	Distance from main port (km)	Pros	Cons	On site (date)	Project (date)
Cocos Plate	110	15-19	3.4 – 3.6	5 - 5.5	~10	> 250	250 - 300	5 - 5.5	~600	Shallow water depth and total length, near deep hole	High-T	202 - 289	250 - 337
Baja California	45 - 60	20 - 30	4.3	~ 6	10 - 11	200 - 250	80 - 130	~ 6	800-1000	Moderate T	Few site survey data, off-ridge volcanism?	208 – 327	244 – 363
Off Hawaii	40 - 45	75-81	4.1 – 4.5	~ 6.25	> 11	~150	~200	~ 6.25	~400	Low Moho-T, close to main port	Total depth, near hotspot	221 - 341	248 - 368

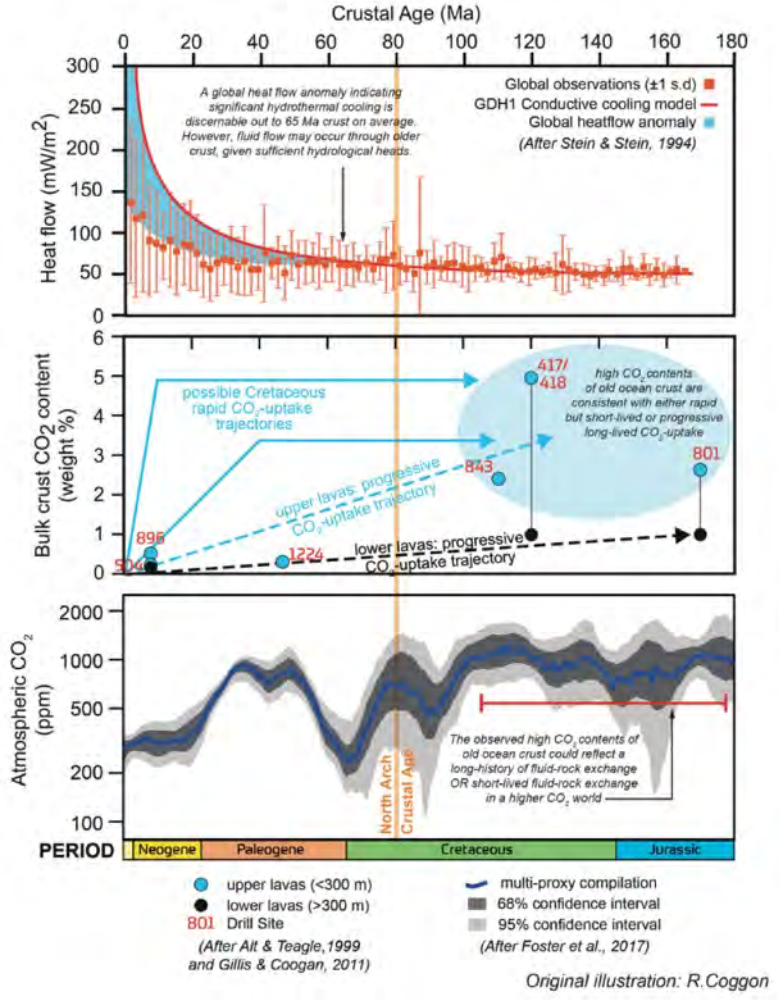
Off Hawaii mid-aged crust drilling (IODP 951-Full; Umino et al. 2020)











Umino et al. (2021)Sci.Drill.

Layer 2/3 (upper/lower crust) boundary

“What good will it do to get a single sample of the mantle?...”

Photo: Fritz Goro

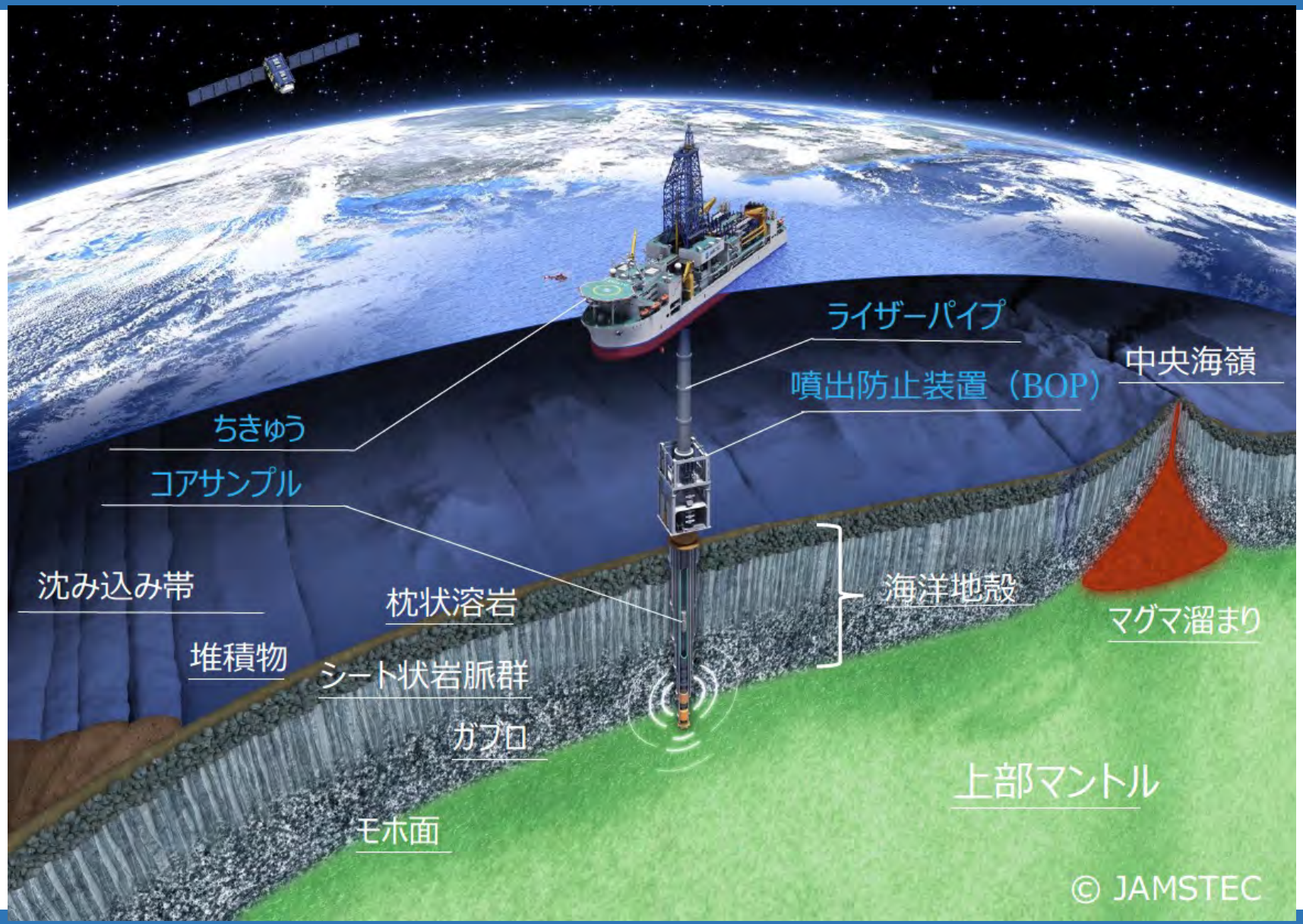
“Perhaps it is true that we won't find out as much about the earth’s interior from one hole as we hope.

To those who raise that objection, I say, If there is not a first hole, there cannot be a second or a tenth or a hundredth hole.

We must make a beginning.”

--- Harry Hess, April 1958

Thank you!


ライザーパイプ
噴出防止装置（BOP）
中央海嶺
ちきゅう
コアサンプル
沈み込み帯
枕状溶岩
堆積物
シート状岩脈群
海洋地殻
マグマ溜まり
ガブロ
上部マントル
モホ面
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Received 25 March 2012

IODP Proposal Cover Sheet

805-MDP

☒ New ☐ Revised ☐ Addendum

Please fill out information in all gray boxes

Above For Official Use Only

Please check if this is Mission proposal ☐

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

Contact Information:

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

IODP Proposal Cover Sheet

951 - Full

Hawaiian North Arch Crust

Received for: 2020-10-01

Title	Drilling Middle Aged Oceanic Crust on North Arch off Hawaii		
Proponents	Susumu Umino, Gregory Moore, Damon Teagle, Steven D'Hondt, Rosalind Coggon, Laura Crispini, Takeshi Hanyu, Nobukazu Seama, Brian Boston, Frieder Klein, Masako Tominaga, Mikiya Yamashita, Michael Garcia, Michelle Harris, Benoit Ildefonse, Ikuo Katayama, Yuki Kusano, Yohey Suzuki, Elizabeth Trembath-Reichert, Yasuhiro Yamada		
Keywords	Crustal Architecture, Hydrothermal Alteration, Habitability	Area	North Arch off Hawaii

Proponent Information

Proponent	Susumu Umino
Affiliation	Kanazawa University
Country	Japan

☑ Permission is granted to post the coversheet/site table on www.iodp.org

IODP Moho to Mantle proposal

(805-MDP: Umino et al.2012) Proponents

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