# Japanese white paper for INVEST, Bremen

## Japan Drilling Earth Science Consortium (J-DESC)

IODP
INTEGRATED OCEAN DRILLING PROGRAM

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# Contents

# Executive Summary

This is an executive summary of a reports from Japanese domestic workshop for INVEST meeting. The workshop has been taken care of by J-DESC (Japan Drilling Earth Science Consortium), which has made an effort to sum up opinions for current status of IODP, potential future directions and perspective of IODP, and expected drilling technology and strategies. Our workshop has 5 discussion boards: 1) Deep subseafloor biosphere, 2) Earth's Interior, 3) Geohazard, 4) Paleoenvironment and 5) Technology development. Each community has its own small meeting and/or workshops a few times. Then domestic INVEST steering committee in J-DESC held general meetings at Tokyo twice and has promoted the discussion for 2$^{nd}$ phase of IODP. The following is the main summary of each discussion board.

## Life and Ecosystem in Deep Biosphere and Subseafloor Aquifers

The deep subseafloor biosphere is substantially associated with fluid flow regime and biogeochemical elements cycle. To understand the ecological nature of the deep subseafloor biosphere, an interdisciplinary approach involving microbiology, geochemistry, hydrogeology and geology is required. We suggest five major themes that remain to be clarified in the future scientific drilling; 1) Extent of the Biosphere, 2) Ecological roles of geo-fluids and thermal energy, 3) Biogeochemical functions, fluxes and ecological roles, 4) Modern proxies for the past biosphere and ecosystem, 5) Analytical and technological development. To achieve these scientific goals, the utilization of *Chikyu* riser-drilling system and integration of other scientific communities is highly recommended.

## Earth's Interior
## -Breakthrough the Discontinuities and Paleomagnetism-

Major discontinuities within the solid Earth was established during the growth of the early Earth, and have been evolving by material and energy transfer through the discontinuities from the deep interior to the surface, and vice versa. Asthenospheric upwelling driven by heat transfer from the Earth's interior adiabatically melts to segregate magma, which moves upward through the Moho discontinuity and ultimately forms crust. The distribution of well-imaged Moho exhibiting seismological characteristics representative of sub-oceanic Moho should be indispensable to a possible drilling site. Furthermore, technological requirements may limit sites to be water depth < 4500m, with low Moho temperature (<250°C), DRF (Drilling depth below rig floor) <12 km, close to operational base (< 300 km) and stable sea current and weather conditions. Three sites in the Pacific Ocean may meet most but not all of the above criteria for the Mohole site; 1) The region around IODP-Site 1256, 2) The eastern edge of the north Hawaiian arch, and 3) The eastern Pacific plate off Mexico. Development of new technology must be required to complete the "21st Century Mohole". In addition, we also propose to accomplish a "Pre-Mohole" with existing technology including off-set drilling, then proceed to the "Full- Mohole". The further development of *Chikyu* riser-drilling system will be expected.

Along- and Across-Arc heterogeneities in geophysical structure of subducting zones are closely linked with geochemical heterogeneities of output magmas, which are most exciting subject to be studied in the forthcoming decades. Our proposal is to drill and sample incoming plate sediments and oceanic crust, forearc peridotite (whenever available), and tephra records of magmas, and back arc basin magmas and peridotites (when applicable) with greater spatial resolution in along- and across-arc. The objective arcs requires pre-drilling investigations of 3D-geophysical structure, which is closely linked to the heterogeneities in geochemical variations of magmas. Several candidate areas exist at continental margins and oceanic arcs. Carefully-designed Oceanic drilling promises successful results that can lead transformative science in the subduction zones.

Regarding paleomagnetic study, the most significant progress in the geomagnetism and paleomagnetism since the present ISP (Initial Science Plan) was written is numerical simulations of the geodynamo. Paleomagnetic observations that can strongly constrain simulations are required now. Such observations attainable by the next phase of IODP are 1) global data for construction of a continuous paleomagnetic field model, 2) paleointensity data to understand relationship between reversal frequency and the strength of the field, in particular paleointensity during the Cretaceous Normal Superchron, and 3) data from high latitudes to clarify similarities and differences of geomagnetic field variations inside and outside the tangent cylinder.

## Building a Scientific Understanding of Geohazards

'Geohazards' has been clearly identified as a theme for the next stage of IODP. In order to contribute to geohazard mitigation along subduction plate boundaries, megathrust earthquakes and mega-volcanic eruptions that have repeatedly caused devastating damages to the human society must be the targets. Ocean drilling provides vital information on the past events in sedimentary record, and then we can scientifically evaluate the forthcoming events and quantitatively map accompanying phenomena, by updating simulation models and physical parameters.

Contribution of ocean drilling to Geohazard issue can be classified into five: 1) Ocean drilling will provide clues to understanding what was the greatest earthquake ever happened and what is the recurrence interval by revealing size and spatial distribution of characteristic deposits triggered by earthquakes. 2) Monitoring of fault motion and intraplate deformation in response to relative plate motion requires stable and sensitive network of seismic, geodetic and hydrological sensors. The networks can only be realized by the sensors installed into sub-seafloor boreholes distributed over entire seismogenic zone. The results of long-term monitoring provide us with precise spatial variation of frictional properties. Sampling materials and measuring in-situ physico-chemical parameters at seismogenic faults will be also required to clarify causes of the spatial variation. 3) 'Gigantic caldera-forming eruptions' that have repeatedly caused devastating damages to human society must be a target in the next phase of IODP, in order to contribute to geohazard mitigation along subduction plate boundaries. Particularly, very little is known on what happened during caldera-forming eruptions in the sea although not small numbers of such historic and pre-historic eruptions have been recorded. 4) Submarine landslide is also important issue for Geohazard science. It is possibly due to methane hydrate decomposition, sedimentation loading, erosion processes and so on. 5) We are interested in an active experiment to trigger a moderate earthquake in order to understand the initiation of large earthquakes by inducing seismic events on a shallow fault with water injection.

## Paleoenvironment - Climatic Crisis Survival: What and Why? -

Earth's environments have received much human attention and interest recently because human activities have dramatically and rapidly increased and have affected ecosystem on the earth last century. In the next phase of the IODP we will propose the series of the scientific research issues on paleoenvironment and paleoceanography in order to deeply understand the processes and integrated system of earth's surface environments, which can be synthesized as a proposal entitled "Climatic Crisis Survival"

The title of "Climatic Crisis Survival" means that the human beings are in the face of a perceived unprecedented crisis by a combination of natural system and anthropogenic activity such as global warming. In order to survive the climatic crisis, we must learn a lesson from the past for the future. IODP will provide an unique and invaluable opportunity to have much knowledge for our survival. The followings are important scientific issues to be solved in future and selected for 2$^{nd}$ phase of IODP: 1) Changing Earth – (Bio, Geo, Chemical Earth Evolution (Co-evolution of ocean chemistry and ecosystem) , Hydrosphere- cryosphere dynamics, Western Pacific Warm Pool (WPWP) (Throughflow, tropical marine lake), Cenozoic bipolar cryospheric evolution (Linkage of

Atlantic/Arctic/ Pacific, Antarctic), Sea-level change (Change in ice volume, stability of ice sheet), Fluctuation of primary production in deep biosphere (living or dead community ?) , 2) Future Earth ~Human Impact~ (Acidification (Difficulty of calcification), Ultra Greenhouse (Cretaceous, Paleogene, LIPs), Environmental impact of catastrophic volcanic event (Big submarine eruption), High resolution analysis of Holocene deposits)

## Technology Development for 2nd Phase of IODP

Technology developments will be expected by world-wide drilling science communities. Especially in order to make a big progress in Geohazard, Earth's Interior, Paleoenvironment and Deep Biosphere and Sub-seafloor Aquifer require the development of the following technology: 1) Ultra deep drilling technology (Earth's Interior and Geohazard), 2) Coring technology (For all the themes), 3) Monitoring and Observatory technology for the next generation (Geohazard, Geochemistry and Microbiology) and 4) Site Survey technology.

## Strategy: Toward the new frontier of ocean drilling projects

Three different types of drilling platforms are now available: riser/non-riser Chikyu, reformed JOIDES Resolution (non-riser), and Mission Specific Platform(s). For the continuing effort to maximize the scientific achievements and for the success of future IODP, utilization of capability of each drilling platform in a manner to maximize outcome is necessary. Especially, maximum utilization of riser drilling capability of Chikyu would be a key aspect to extend the frontier toward the deep oceanic crusts. Furthermore, future development of Chikyu riser capability at greater water depths would extend potential drilling targets to wider areas of the ocean. Nevertheless, we, Japanese IODP community, found some difficulties in developing riser drilling proposals in the current system. We suggest following four issues to be considered: 1) Chikyu is essentially built for ultra-deep drilling, 2) enhanced planning/support system, 3) needs of revised proposal evaluation/nuturing processes, and 4) let's do it together.

# I. Life and Ecosystem in Deep Biosphere and Subseafloor Aquifers

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## 1. Introduction

One of the key challenges of the future scientific drilling is to comprehend the geosphere-biosphere interaction in the modern earth's system and the past and future co-evolution of life and planet. Previous studies demonstrate that subseafloor populations and activities depend mainly on the supply of nutrients and energy substrates from the overlying surface world (i.e., land and ocean) and/or the underlying lithosphere (i.e. earth's crust and mantle). Hence, fluid flow regimes and geophysical conditions must play significant roles in nutrient and energy transport, affecting habitability and ecosystem existence. The subseafloor microbial community is generally composed of phylogenetically diverse Archaea and Bacteria, which genetic and physiological characteristics are largely unknown, and hence the ecological and biogeochemical roles and functions remain largely elusive. Future expeditions of the Integrated Ocean Drilling Program (IODP) will provide unprecedented opportunities for addressing these fundamentally important scientific objectives concerning deep subseafloor life and the biosphere, and the explorations are thus capable of expanding our knowledge of the co-evolution of life and planet.

## 2. Important themes of deep-biosphere research

In the IODP Initial Science Plan (ISP: 2002), "The Deep-biosphere and Subseafloor Ocean" is described as an important scientific target that should be addressed within the current phase of IODP expeditions. Although our knowledge concerning this environment has greatly expanded since publication of this ISP in 2002, newly posed or unsolved fundamental questions have yet to be addressed. Here, resulting from discussions during the domestic deep subseafloor biosphere workshop in Japan, we report on five major scientific themes of deep-biosphere research that should be directly addressed during the next phase of the IODP beyond 2013.

### 2.1. Extent of the Biosphere

The marine subsurface environment is currently considered to be the largest part of the biosphere, probably harboring one-tenth of the living biota on Earth. The ubiquitous microbial community there represents the energetic and geophysical constraints to habitability and the dispersal of microbes. Scientific ocean drilling using the Chikyu and other drilling platforms in the deep subsurface realm will provide unique opportunities for defining the transition between habitable and uninhabitable zones, or biotic and abiotic processes. The physiological states that microbes can adopt (i.e., alive, dormant, or dead) are crucial for determining their survival of the fittest in constant or transient nutrient and energy supplies to deep subseafloor habitats. It is important to determine the indigenous locations of metabolically active microbial habitats associated with ideal geophysical and geochemical settings in the deep biosphere, where microbial cell abundance generally decreases with increasing depth. Through deep drilling ventures using Chikyu, valuable sampling opportunities will allow biomass measurements and characterization of both the physiological state of subseafloor life and habitable conditions in diverse oceanographic and tectonic settings. These studies will provide new insights into the nature and extent of the earth's biosphere.

**Potential drilling sites:** various ocean seafloors with various oceanographic settings, deep continental margin sediments, deep lithosphere drilling sites (e.g., mohole project)

2.2. Ecological roles of geo-fluids and thermal energy

In the dark subseafloor biosphere, geologically produced nutrient and energy substrates may support some naturally occurring microbial populations. The substrates production and transportation are closely related to tectonic movement and thermal energy, which provide the primary driving force of regional fluid flow systems. Furthermore, the depth-pressured dehydration process that occurs in deep sedimentary realms of convergent plate boundaries provides essential water for dehydrated deep subseafloor microbial life. This so-called "geo-fluid" or "geo-pressured fluid" flow is sometimes observed in active faults and fractures in an accretionary wedge as well as in diapiric intrusion of high-buoyancy mud or salt-captured aquifers. Thermal energy from the earth's mantle directly affects widespread fluid circulation in ridge flank and back-arc hydrothermal systems. The supply of mantle-derived and/or thermogenically produced nutrients and energy via geo-fluid circulation potentially controls deep subseafloor microbial activity, population sizes, and community compositions, and plays an important role in biogeochemical cycles. This important issue is highly relevant to the geosphere-biosphere connectivity, and thus should be addressed with multidisciplinary studies in the future IODP.

**Potential drilling sites:** deep subduction zone including geological and goehydological complexities, and mud or serpentine diapir (e.g., Nankai Trough, Lau Basin, Mariana Forearc), ridge crustal system (e.g., Indian Ocean, Mid Atlantic Ridge), back-arc hydrothermal system (e.g., Okinawa Trough, Rau Basin)

2.3. Biogeochemical functions, fluxes and ecological roles

The activities of subseafloor microbes presumably play significant roles in the earth's biogeochemical cycles in geologic time. Long-term accumulation of extremely low metabolic products affects the circulation of carbon, nitrogen, oxygen, sulfur and other elements in the subseafloor environment. Complex metabolic networks are most likely responsible for connecting this food/chemical web in energy-starved microbial ecosystems. However, it is currently unknown what kinds of microbes play major roles in particular biogeochemical reactions in the food/chemical chains; it is also not known how they metabolize intermediates from buried recalcitrant organic materials or other abiogenic substrates in the final feeding processes in the ecosystem. Biogeochemical fluxes are regionally diverse relative to differences in oceanographic, hydrogeologic, and tectonic settings: for example, to primary organic production and redox status in the overlying water columns, sedimentation rates, and fluid flow regimes. However, our knowledge of the metabolic function, fluxes, and ecological roles of each biogeochemical process's key player is very limited. This must be clarified during the future IODP.

**Potential drilling sites:** hydrocarbon systems of the continental margin, including methane hydrates and free gas zones (e.g., northwestern Pacific off the Shimokita Peninsula of Japan, Nankai Trough, Gulf of Mexico), various oceanographic settings

2.4. Modern proxies for the past biosphere and ecosystem

During the evolution of life over the past 3.5 billion years or some more, ancient environments hosted primordial microbial life under anoxic and high-temperature conditions. These physical and chemical constraints spurred the adaptation and evolution of life forms during the earth's history (e.g., oxygen mass-production via photosynthesis). Previous scientific ocean drilling program has successfully revealed paleoenvironmental records related to drastic climate changes and geologic events during the earth's history. However, it is currently unknown how subseafloor life and the biosphere accommodate environmental changes via adaptive evolution and how they occupy ecological niches. Conducting scientific drilling to find modern proxies for the past biosphere and ecosystem, it is highly recommended for the future IODP. To discriminate modern (living or surviving) and past (dead or fossilized) biological signatures from extant core materials, method development is in high demand, because genomic and proteomic progresses may provide decipherable records of evolutionary history. Moreover, the expanding knowledge in this sphere and simulation analysis promote the understanding of both habitability and possible evolution of life forms on virtual or real other planets. This is an entirely new concept that has not been described in previous ISPs and is hence one of the challenges of the future IODP.

**Potential drilling sites:** hydrothermal fields, polar subseafloor, anoxic water column subsurface, sapropels, estuaries

## 3. Analytical and technological development

To promote the achievement of the major scientific objectives described above, analytical and technological development of onboard and shore-based experiments are very much required. These techniques can then be subsequently applied to drilled cores and fluids in case studies. In this regard, bio-archived core samples and their storage (i.e., frozen cores, fixed slurries for microscopic analyses, anaerobic sediment samples) are very important, because they provide opportunities to repeatedly study previously cored sites of interest with newly developed analytical techniques.

As for onboard studies, we must make every effort to generate additional data while aboard the research vessels. For example, a newly developed non-destructive scanning tool for the biological signatures using deep UV wavelengths may be applicable to the half-cut core surface. Cell enumeration should be performed using a high-throughput computer image analysis with high depth-resolution. The most important onboard work is proper preparation of frozen, fixed, or anaerobic samples for promising shore-based experiments. In shore-based laboratories, molecular and isotopic analyses at the single cell level are rapidly progressing with nanotechnology development. ‘Omics’ studies to approach gene and protein directly have been poorly represented in deep-biosphere research, including statistical and simulation analyses of pooled molecular and geochemical data.

One of microbiological ultimate goals is to cultivate dominant microbial components and isolate them for growth and metabolic characterizations. High-pressure incubation or flow-through reactor cultivation experiments may improve culture of slowly growing subseafloor microbes in laboratory conditions. We should consider not only the components of archaea and bacteria but also viruses and eukaryotes, including their relics and gene transfer, in terms of their ecological roles and functions.

Organic geochemicals and trace elements are crucial targets to investigate biogeochemical process and microbial physiology of deep biosphere. A series of state-of–art analytical techniques, e.g. X-ray microscopy and spectroscopy, enable to distinguish micro- heterogeneity in small spot. We should consider how such advanced techniques apply to drilled core samples.

Subseafloor life forms and biogeochemical process in basaltic aquifers has been poorly explored in ocean drilling projects because of the difficulty of sampling the rubble crusts and aquifer. The borehole observatory using CORK-like system and the installed sensors is expected to provide excellent opportunities for studying microbiology, biogeochemistry, and hydrogeology in previously inaccessible subseafloor aquifers within the basaltic lithosphere or deep sediment layers. Borehole utilization has great potential for developing a new in situ research system for harvesting actively growing subseafloor microbes, trace elements, and intermediate chemicals in biogeochemical process.

Lastly, the deep riser-drilling system of Chikyu will provide excellent opportunities to address the limit and extent of subseafloor life. The riser-drilling system using blowout preventer (BOP) will enable us to study high-pressure hydrocarbon systems in shallow to deep continental margin sediments. We should consider how X-ray CT scan could be used for onboard sampling and characterization of microbiology and biogeochemistry. The high pressure-coring technology including the X-ray monitoring sample transfer system without depressurization is highly recommended to deploy on the riser-drilling system of Chikyu.

## 4. Projects for Deep Biosphere presented in the Japanese workshop

- IODP proposal #601: The Deep Hot Biosphere Drilling: Exploration of Subseafloor Microbial Ecosystem Associated with Physical, Geochemical and Hydrogeologic Variations in a Mid Okinawa Trough Hydrothermal System
  Proponent: Ken Takai, JAMSTEC
- Project TAIGA: Trans-crustal Advection and In-situ biogeochemical processes of Global sub-seafloor Aquifer
  Tetsuro Urabe & Michinari Sunamura, University of Tokyo
  URL: <http://www-gbs.eps.s.u-tokyo.ac.jp/~taiga/>
- Drilling through gas hydrae stability down to deep biosphere

Hitoshi Tomaru, Kitami Institute of Technology
Keywords: methane, gas hydrate, biogeochemical process, long-term monitoring

- Gas Hydrtes and Deep Biosphere
  Ryo Matsumoto, University of Tokyo
  Keywords: gas hydrate, carbon sink, geohazard, methane flux
- Geopressured fluids-its distribution and formation mechanism
  Akira Ueda, Kyoto University
  Keywords: geopressured fluid,
- Integration of borehole observations for geophysical/geochemical/biological
  Yasuyuki Kano, Kyoto University
  Keywords: CORK, fluid flow, earthquake processes
- Significance of hydrological and Hydrogeological study on coastal zone from both inland side and sea side.
  Takeshi Hayashi, Akita University
  Keywords: hydrogeology, groundwater environments, coastal zone, water resources, sustainable management
- Direct evidence of living metabolism in deep-biosphere: a proposal for in-situ tracer method
  Yoshinori Takano, JAMSTEC
  Keywords: 13C tracer, GDGTs, Archaea
- Organic geochemical perspective for the second stage of IODP
  Hikaru Yabuta, Osaka University
  Keywords: XANES, STXM, micro-FTIR, micro-Raman spectroscopy, biofilms
- Dependence of solid-water distributions of trace elements on the redox condition within the sediment column based on their speciation by X-ray absorption spectroscopy
  Yoshio Takahashi, Hiroshima University
  Keywords: redox-sensitive elements, microbial metabolisms, XAFS
- A missing biomass inferred from chemosynthetic crabs in a cold seep field
  Tomohiro Toki, University of the Ryukyus
  Keywords: sulfur cycle, AOM, Formosa site
- Proposal for the domestic INVEST Deep Biosphere & Aquifer Workshop
  Toshiro Yamanaka, Okayama University
  Keywords: volatiles such as hydrogen, hydrogen sulfide, methane, VOCs
- Geochemical and hydrological studies of submarine caldera subseafloor
  Jun-ichiro Ishibashi, Kyushu University
  Keywords: hydrothermal fluid circulation system, Wakmiko submarine caldera
- Variation of bacterial activity in deep biosphere inferred from lipid biomarkers
  Masanori Kaneko, Kyushu University
  Keywords: GDGTs, compound-specific carbon and hydrogen isotope analysis,
- Astrobiological context in the future IODP
  Kosei E. Yamaguchi, Toho University
  Keywords: astrobiology, impact creating process, K/T boundary
- Geochemical and ecological contribution of viruses in the deep biosphere
  Katsunori Yanagawa, University of Tokyo
  Keywords: virus, regulation factor
- Single cell-level analysis of subseafloor microorganisms – towards exploration of

ecology of subseafloor life –
Yuki Morono, JAMSTEC
Keywords: genomic, isotopic, compositional analyses

- Recommendation for the domestic INVEST Deep Biosphere & Aquifer Workshop
  Takuro Nunoura, JAMSTEC
  Keywords: STP, onboard system, contamination issue, CORKs

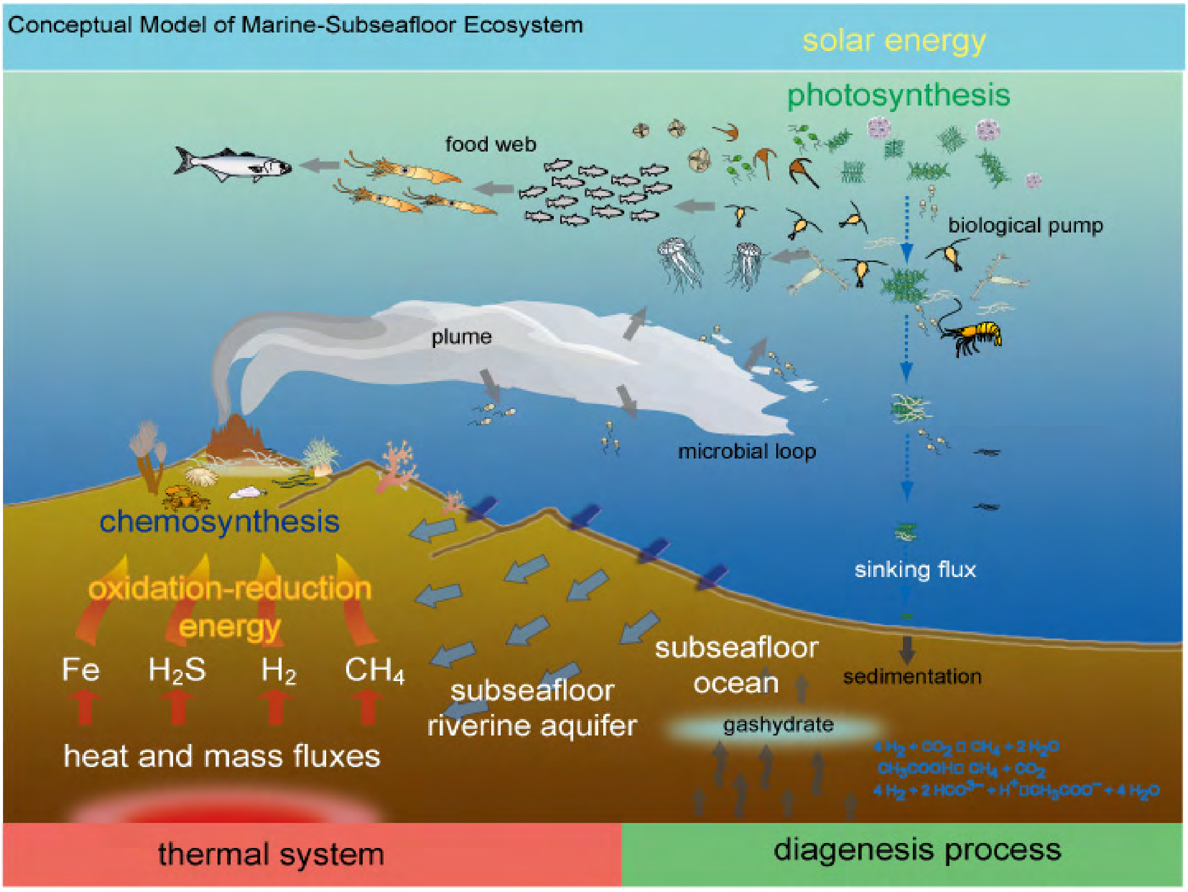


**Fig I-1.** Schematic diagram of marine-subseafloor ecosystems.

The finding of a diverse and active subseafloor microbial community in deep subseafloor sediments has changed the concept of life's habitat. However, the extent of biosphere and the nature of subsurface life remain largely unknown. Subseafloor ocean and riverine aquifer are also largely unknown, although these environments are highly relevant to the fluid flow and biogeochemical cycling as well as the subseafloor life. Photosynthesis-based heterotrophy is predominant in upper sedimentary environments while chemosynthesis may predominantly occur in deep and/or rocky aquifers near the ridge systems. Linkages between past- and modern-earth's environments, and interactions between seafloor and subseafloor ecosystems are of significant scientific themes that should be addressed during the future IODP expeditions.

# II. Earth's Interior

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**Abstract**

Major discontinuities within the solid Earth was established during the growth of the early Earth, and have been evolving by material and energy transfer through the discontinuities from the deep interior to the surface, and vice versa. Asthenospheric upwelling driven by heat transfer from the Earth's interior adiabatically melts to segregate magma, which moves upward through the Moho discontinuity and ultimately forms crust. Beneath the fast-spreading ridges, the ascending magma and the mantle on its pathway interact to form the Moho Transition Zone as the final reaction zone, that make up the Moho discontinuity. On the contrary, deep seawater invasion beneath the slow-spread oceanic crust may control the depth of the Moho discontinuity through serpentinization of the uppermost mantle. Formation of andesitic continental crust from primary basaltic arc magma is done by differentiation of the basalt magma into andesitic melt becoming the arc crust and ultramafic cumulates which then turn into the uppermost mantle. Meanwhile, subducting oceanic crust transforms into cold dense slabs and megalith falls penetrating through the upper-lower mantle boundary onto the core-mantle discontinuity, which disturbs the D" boundary layer and cools the surface of the outer core, promoting degassing and latent heat release from the core into the lowermost mantle through the discontinuity. This may trigger vigorous convection in the outer core and the generation of superplume that penetrate through the upper and lower mantle boundary and transport a mass of heat and volatiles to the surface, impacting the global environment and evolution of life. Perturbed thermal flux from the core could affect the geodynamo, which may lead variations in reversal frequency of the geomagnetic field exemplified as the Cretaceous superchron.

Understanding the processes of material and energy exchange through the discontinuities that govern the dynamics of the mantle and core will be major breakthroughs in the drilling science. For this purpose, we will pursue the following themes as the next Science Plan of IODP.

1. Breakthrough the Discontinuity: 21-Century Mohole
2. Arc crust and mantle evolution: The origin of along- and across-arc heterogeneities
3. Paleomagnetism

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# i. Breakthrough the Discontinuity: 21st Century Mohole

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**Abstract**

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

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## 1. Introduction

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

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

## 2. Nature of Moho

### 2.1. What is the Moho and how does it look like?

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

### 2.2. What operates in the Moho?

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

### 3. Architecture and compositions of the oceanic crust

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

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

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

### 4. Alteration processes and the frontiers of deep biosphere

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

## 5. Criteria for site selection and description of potential sites

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

(1) Fast-spread oceanic lithosphere with normal crustal thickness (~6 km)
(2) The presence of well-imaged Moho by seismic explorations

with technological limitations of

(3) Water depth < 4500m
(4) Moho temperature (~250°C)
(5) DRF (Drilling depth below rig floor) <12 km
(6) Close to operational base (< 300 km)
(7) Stable sea current and weather condition

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

The candidate sites are listed below:

<u>1) Around Site 1256</u>

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

<u>2) The east of north Hawaiian arch</u>

- great water depth (4100-4300 m)
- lowest-T (*~150°C*)*
- nearby a large port
- Effect of the arch magmatism should be avoided

<u>3) The eastern Pacific plate off Mexico</u>

- water depth (<4500 m)
- Modest Moho-T (*~250°C*)*
- few data available
- no large port around

* Inferred temperatures

## 6. Technology and strategy

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

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

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

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

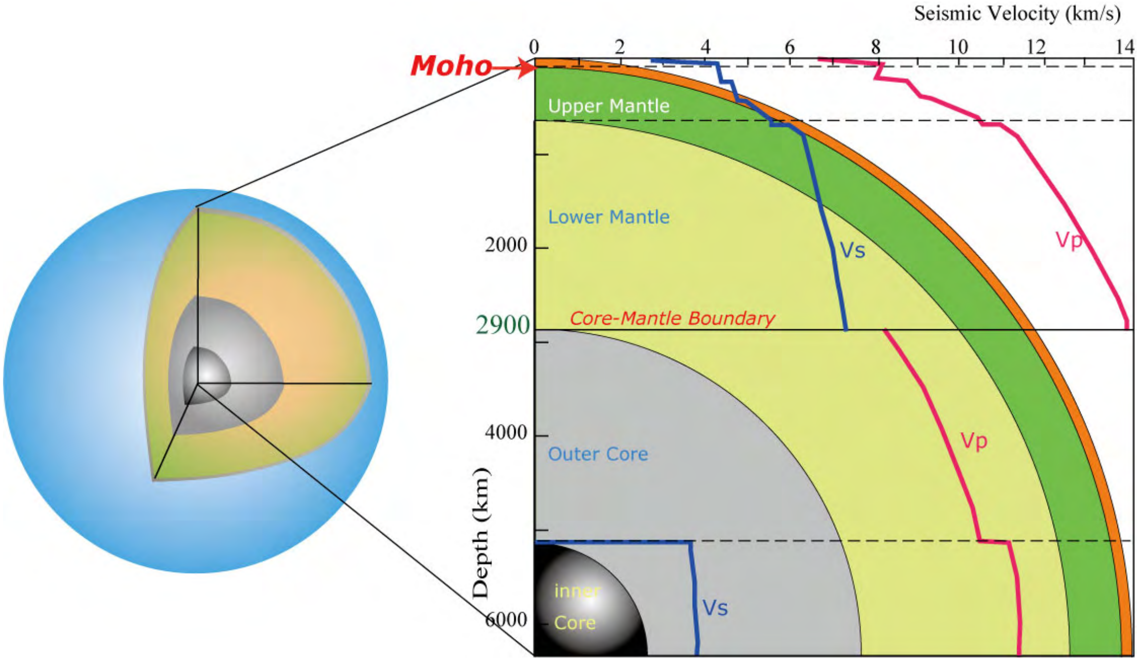


**Fig. II-1**. Velocity-depth curves for P- and S-waves, and the interior structure of Earth.

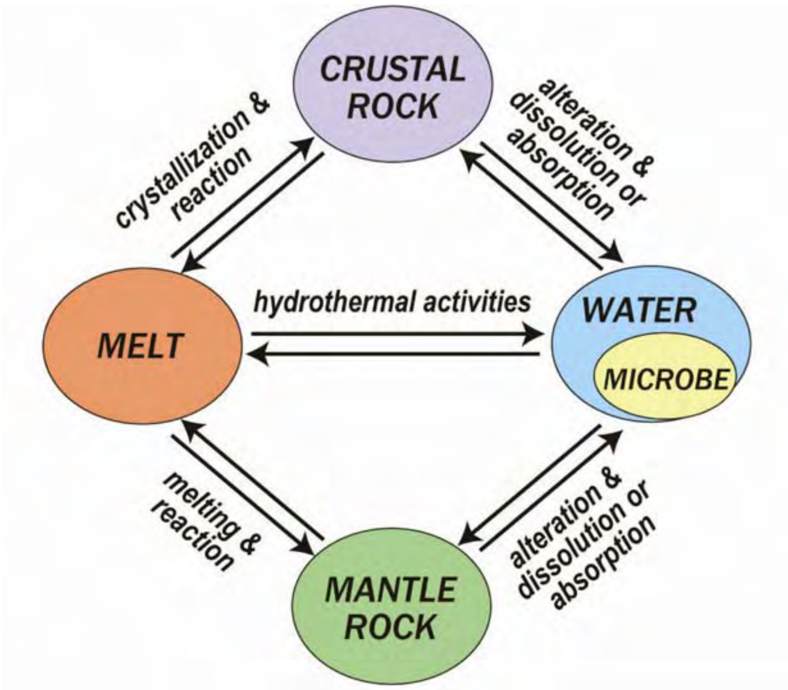


**Fig. II-2**. “Moho system” –Exchange materials and energy.

## ii. Arc crust and mantle evolution: The origin of along- and across-arc heterogeneities

Yoshihiko Tamura*[4], Jun-Ichi Kimura (JAMSTEC)

**Abstract**

Along- and Across-Arc (AAA) variations are widespread in subduction zones, either in the geophysical structure of the subducting slab, mantle wedge, and arc crust or in the geochemistry of the incoming plate, wedge mantle peridotite, and arc magmas. The geophysical heterogeneities have been investigated in arc scale geophysical expeditions, which have led to key developments in subduction zone studies. Geochemical heterogeneities in output magmas have been investigated by analyzing oceanic sediments and crust, supra-subduction zone peridotites in forearc ophiolites, and serpentine seamounts, as well as examining magmatic records. Samples from inputs and outputs of the subduction zone collected during the Ocean Drilling Project (ODP) have contributed to the recognition of geochemical variations in many subduction zones. The geophysical heterogeneities can be anything from hemispheric, through arc segment, to intra-arc in scale. Recent geochemical studies suggest that the geophysical heterogeneities have a close spatial link to the geochemical variations. Discovering the cause of this link will thus be the most exciting area of research in this field in the coming decades. To support arc mass balance, numerical geochemical models have also been proposed based on developments in theoretical and experimental petrology. However, AAA variations revealed by the geochemical investigations using ODP samples have nowhere near the spatial resolution of those obtained in the geophysical studies. Our proposal is to drill and sample incoming plate sediments and oceanic crust, forearc peridotite (whenever available), tephra records of magmas, and back arc basin magmas and peridotites (when applicable) with greater spatial resolution than before along and across arc. The arcs that this project targets are those where geophysical 3D investigations have been completed and a close link between the geophysical and geochemical heterogeneities has been revealed. There are several candidate areas, both at continental margins and oceanic arcs. Carefully designed oceanic drilling promises successful results that can lead to transformative science in subduction zones.

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## 1. Origin of 3-dimentional variation in the arc, mantle and crust

### 1.1. Introduction

Subduction zone processes are often discussed in terms of two-dimensional model cross-sections across convergent margins. Recent geophysical and geochemical studies on island arcs, however, have revealed non-uniform geophysical and geochemical features in the subduction zone slab, mantle wedge, arc crust, and arc magmas (Kodaira *et al.* 2002; Nakajima & Hasegawa 2003; Nakajima & Hasegawa 2007; Nakajima *et al.* 2005). Such along- and across-arc（AAA）heterogeneities are observed in velocity structure and b-values in the downgoing slab (Kodaira *et al.* 2002; Miura *et al.* 2005; Tsuru *et al.* 2002; Wiemer & Beniot 1996; Wyss *et al.* 2001), seismic wave structure, Poisson ratios, attenuations, Q-values, anisotropy of the mantle wedge (Hasegawa & Nakajima 2004; Nakajima & Hasegawa 2003; Nakajima *et al.* 2005; Rychert *et al.* 2008; Tono *et al.* 2009), thickness of arc crust and magnetic anomaly (Kodaira *et al.* 2008), and magma compositions (Carr *et al.* 2007; Jicha *et al.* 2004; Kimura & Yoshida 2006; Tamura *et al.* 2009). Thus, it is vital to develop a three-dimensional model of convergent margins.

The geophysical and geochemical observations often have unexpected spatial correlations that to be understood require collaborations between geophysicists, geologists, petrologists and geochemists. For example, along arc geochemical variations in magmas relate to differences in the material being subducted (Carr *et al.* 2007; Ishizuka *et al.* 2003) or fracture zone subduction (Jicha *et al.* 2004). Seismicity of the subducting slab also differs when an aseismic ridge or fracture zone is subducted. In response to differences in slab inputs, the mantle wedge structure also differs in terms of Q values and S-wave velocity (Hasegawa & Nakajima 2004). Slab tear structures may also induce along arc mantle flow in addition to the normal convection in the mantle wedge, resulting in a disturbed anisotropic mantle structure (Abt *et al.* 2009). Variations in mantle convection patterns or slab fluid inputs can also change the mantle wedge temperature and melting structures, all of which will influence magma production rate and magma chemistry (Hasegawa & Nakajima 2004; Iwamori 2000; Kimura & Stern 2009; Tamura *et al.* 2002). In response to changes in magma production rate and magma chemistry, arc crust production rate and geochemical properties of the arc crust will also differ (Hasegawa & Nakajima 2004). Fractionation of magmas, both at the arc MOHO and within the arc crust, also enhances seismic and geochemical heterogeneities in the arc mantle-crust vertical section (Tamura *et al.* 2009; Tatsumi *et al.* 2008). Thus, over the entire history of the arc, the crust grows heterogeneously, both in terms of its geophysical and geochemical properties.

### 1.2. Key scientific questions

The key scientific questions to be addressed are (1) what governs the along- and across-arc (AAA) variations in magmas, arc crust, and the mantle wedge and thus the three-dimensional evolution of convergent margins, and (2) how do subduction inputs control the variation?

These key questions can be divided further;

- How are the different slab inputs (e.g., volatiles and solid earth elements) reflected in the chemistry of arc magmas and melt production?
- How do mantle wedge dynamics affect the slab derived material fluxed in arc

magma genesis?

- What causes variations in arc crustal thickness?
- How do arc magmas evolve at the MOHO and in the middle crust?
- How is arc crust generation related to the origin of the continental crust?

### 1.3. Key observations

One of the key observations is determining the wavelength of AAA variations. Firstly, there is the wavelength of the regular occurrence of volcanoes or volcano groups on the scale of several 10s to 100 km along the arc (ref.). Recently, progress in the geophysical and geochemical observations have enabled mantle heterogeneities, on the scale of several-hundred-kilometers, to be identified (Fig. II-3; Isse *et al.*, 2009). Furthermore, arc crustal thickness has been found to vary on wavelengths of 80-100 km (Fig. II-4, Kodaira *et al.,* 2008). Geochemical variations in the magma seem to be related to all these physical variations (Fig. II-5, Kodaira *et al.*, 2007; Tamura *et al.*, 2009). Moreover, a striking characteristic of orogenic andesites and associated rocks within many volcanic arcs of modest width is the consistent increase of their incompatible element concentrations, notably K2O, away from the arc front (Gill, 1981). To explain the different wavelengths of these variations a three-dimensional model is required. This must answer the key questions above. Important geological objectives to study are (1) oceanic crust on the incoming plate, (2) stratified forearc supra-subduction ophiolites including abyssal peridotites, (3) arc magmatic products ranging from basalt to rhyolite or plutonic equivalents, and (4) back arc basin (BAB) abyssal peridotites and magmas, all of which must be sampled systematically along- and across-arc.

Geophysical and geochemical surveys must have already been undertaken in the arcs targeted for study and ideally the arcs should also have been the subject of submersible geological surveys and previous drilling.

### 1.4. 3-D arc project (AAA variations): Using arc inputs and outputs

Our proposal is building upon recent developments that have occurred in marine geophysics, geochemistry and geology, which suggest that along- and across-arc (AAA) variations in magmas, arc crust, and mantle wedge are related to the inputs into subduction zones. These are very intriguing and further breakthroughs will be achieved if scientific drilling is utilized to further address the issue.

Essentially we propose to systematically sample subduction zone input and output materials along and across the arcs (Fig. II-6). The inputs include oceanic sediments and altered oceanic crust materials. Abyssal peridotites found in fore arcs or back arc basins will also be systematically sampled in order to look at residues after modification by subduction processes such as slab-flux addition and magma extraction. Erupted AAA magmas will be sampled in tephra and by drilling important geological segments to collect lava flows, volcaniclastic rocks and dykes. This will allow AAA variations in input materials, processed materials, and output materials to be collectively investigated in order to elucidate the three-dimensional evolution of subduction zones.

A key issue is to determine how these AAA magma variations are generated. Geochemical studies allow the intensive/extensive variables (e.g., pressure, temperature, degree of melting, magma production rate) that form magmas and mass balance (e.g., extent of contribution of slab materials and mantle, the identity type of slab flux such as melt/fluid) (Kelemen *et al.* 2003; Kimura *et al.* 2009) of the heterogeneous arc segments to be defined.

Intermediate to felsic magmas are also used to study fractionation at the MOHO and in the arc crust in order to understand the origin of vertical stratification in arc mantle-crust sections.

Slab input materials and abyssal peridotites are also used to constrain source materials that generate heterogeneous AAA magma.

To be able to elucidate arc heterogeneities in three dimensions, we propose to conduct deep ocean drilling on:

- Incoming oceanic plate slab, with the drill sites aligned along arc in order to sample oceanic sediments and altered oceanic crust. Any along arc variations including subducting aseismic ridges or seamount chains will also be targeted.
- Forearc ophiolite sequences aligned along arc in order to sample modified/unmodified mantle peridotite or pre-existing oceanic crust.
- Forearc basin sediments that record tephra sequences aligned along arc.
- Volcaniclastic rocks and basement rocks between volcanoes to determine how arc volcanoes and the stability of volcano spacing and hot fingers evolved.
- Rear arc basin sediments that preserve tephra sequence, in order to elucidate across arc variations.
- BAB spreading ridges along arc in order to sample BAB abyssal peridotite and BAB magmas.

Candidate areas do not have to satisfy all the components, but clear AAA magmatic variations should have already been documented. Moreover, tephra records can provide temporal growth of the magmas and thus would contribute to deciphering the four dimensional evolution of the arc, but only if recovery was sufficient.

There are several previous studies that have attempted to answer similar questions, but the spatial resolution of the marine records is always insufficient to resolve the real arc inputs and outputs. Only with systematic drilling can more realistic constraints be placed on recycling systems in subduction factories worldwide.

**2. Expected new outcomes and capabilities**

We propose to use ocean drilling to sample the scale of AAA variations in materials entering, being processed by, and leaving the subduction system. This will provide insights into the mass balance in arcs and the petrological manufacture of new crust. Existing geochemical and petrological models can be developed further using such multidisciplinary endeavors involving geophysics and marine science, which will result in many new discoveries concerning the three-dimensional structure of the arc crust and mantle wedge.

**3. Path to achieving the goals**

Arc heterogeneities range from arc-scale (few thousand kilometers), through segment scale (few hundred kilometers) to the local scale (few tens of kilometers). The geology, geochemistry of volcanic rocks, and seismology of the target area should already have been studied in detail and spatial correlation of heterogeneities should have been observed in at least two different phenomena. Proposed drilling sites will have to be sufficiently dense and cover a wide enough area to be able to resolve the heterogeneity of the along- and across- arc systems. Techniques to sample tephras in sediment cores, and volcanic rocks and peridotites in drill cores have become well established in non-riser drilling projects, so that choosing the sampling site should be the only crucial issue for the success of this project. Developments of realistic models to explain magma genesis and arc evolution are another key factor to elucidate geochemical mass balance in the arc. Additional geophysical expeditions should also be conducted before target areas are finally selected for drilling. Such background investigations will increase the likelihood of success in determining and explaining AAA variations.

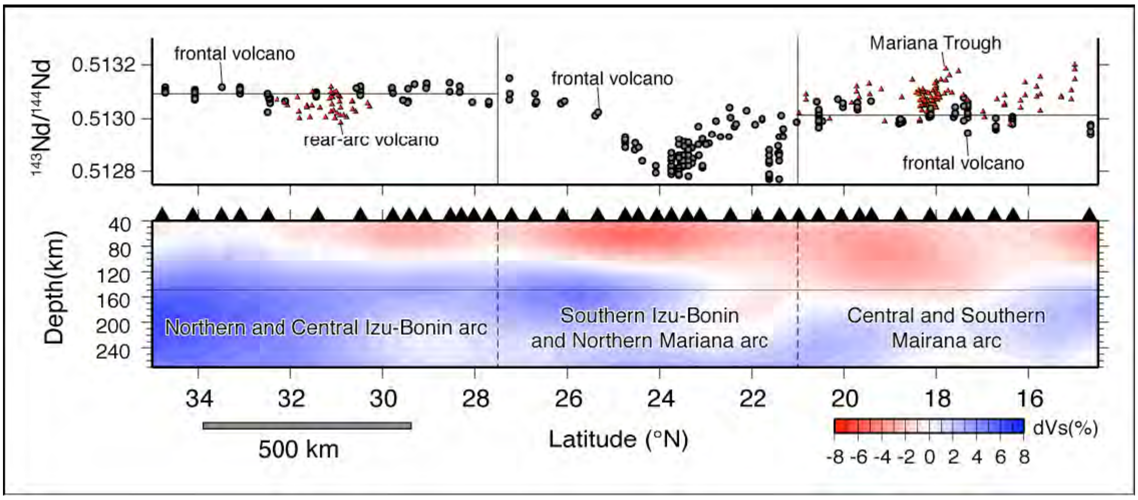


**Fig. II-3**. (a: upper diagram) Along-arc variation of 143Nd/144Nd values in frontal arc volcanoes and rear arc volcanoes of northern Izu and the Mariana Trough. (b: lower diagram) Along-volcanic front cross-section of shear wave speed perturbations (in percent) (after Isse et al., 2009).

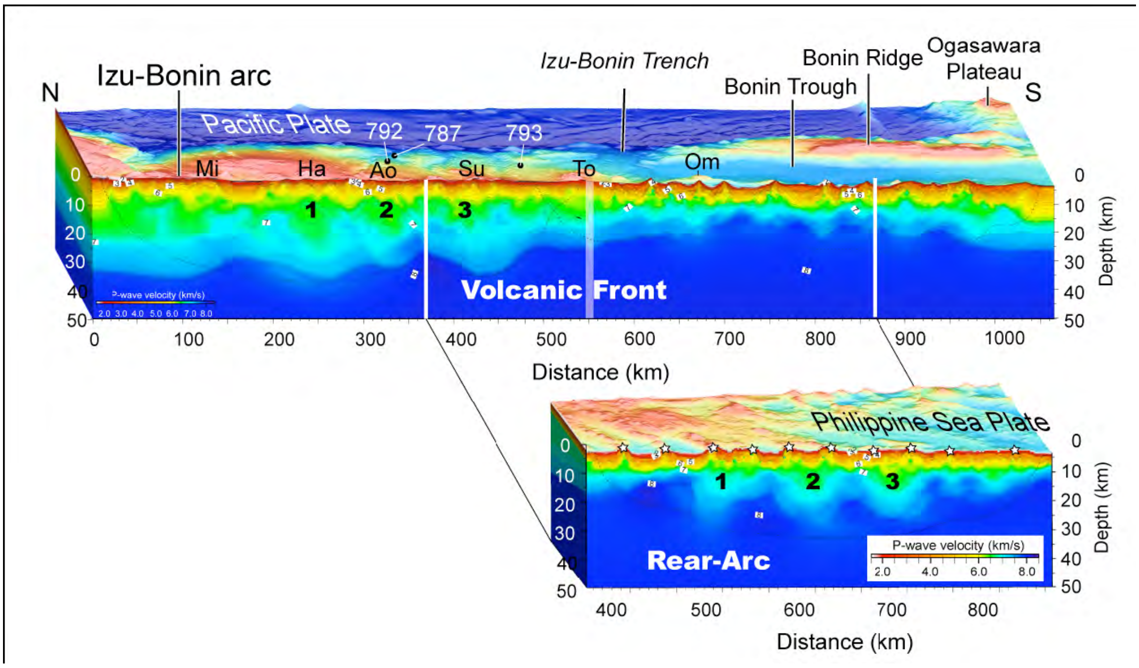


**Fig. II-4**. Three-dimensional block diagram with seismic images of both the volcanic front and the rear arcalong the Izu-Bonin arc ~150 km west of the volcanic front (after Kodaira et al., 2008). Numbered circlesindicate sites drilled on the Philippine Sea Plate in the Izu-Bonin region during ODP Legs 125 and 126, whichrecovered Oligocene and Neogene turbidites. Abbreviations show basalt-dominant Quaternary volcanoes (Mi, Miyake; Ha, Hachijo; Ao, Aogashima; Su, Sumisu; To, Torishima) on the volcanic front and the andesitic Oligocene volcano (Om, Omachi seamount) east of the front. The stars on the rear-arc profile indicate Mio-Pliocene volcanoes. Three discrete thick crustal segments (20–25 km thick) in the rear-arc and their possible counterparts below the volcanic front (Kodaira et al., 2008) are numbered from 1 to 3.

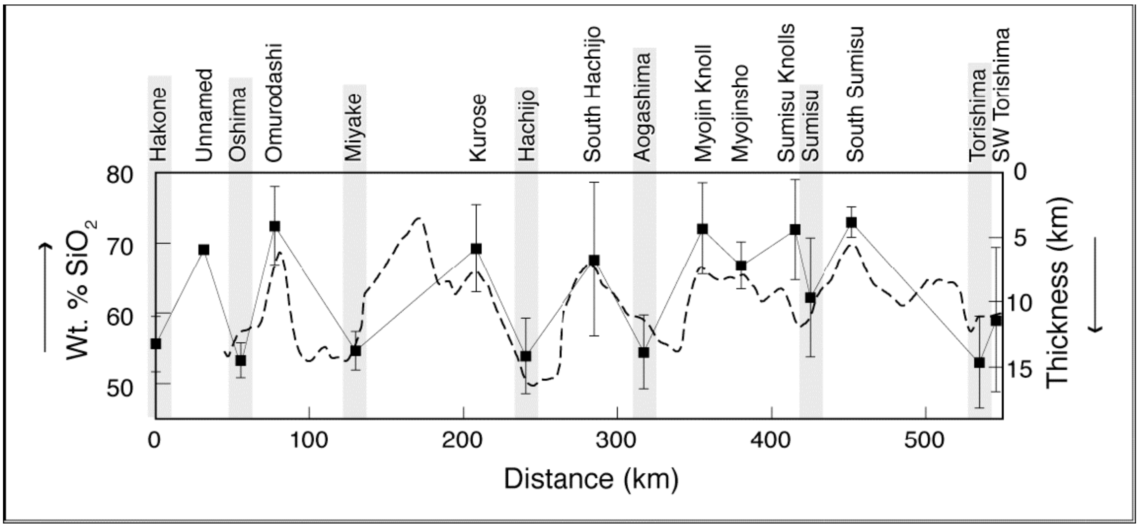


**Fig. II-5.** Along-arc crustal structure (dotted line; thickness of middle crust with Vp of 6.0-6.8 kms-1 at depths between 5 and 20 km) and average wt. % SiO2 of volcanic rocks (solid squares) sampled and dredged from the 16 Quaternary volcanoes of the Izu-Bonin arc (after Tamura et al., 2009).

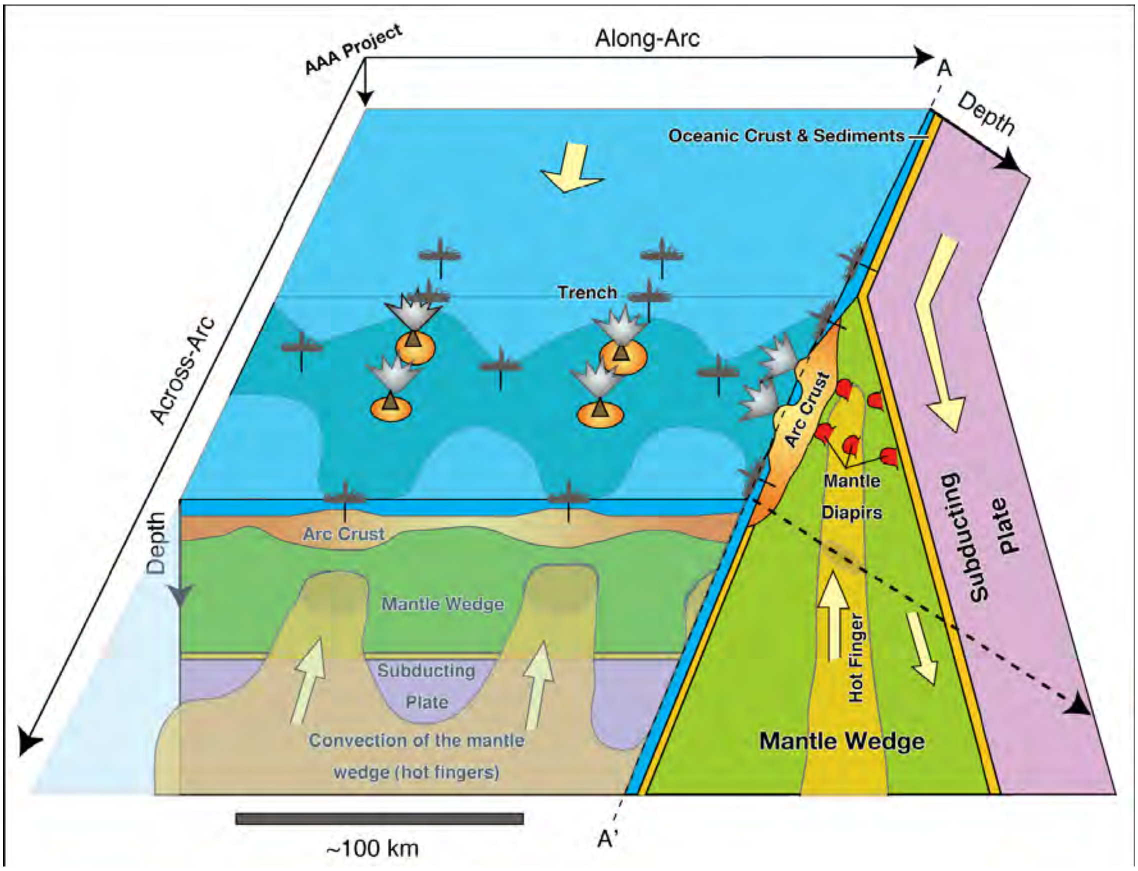


**Fig. II-6**. 3-D arc project (AAA variations): using arc inputs and outputs (see text for the details). Photocopy this figure and fold along A-A' to see the 3-D subduction zone.

# iii. Paleomagnetic problems to be solved by IODP beyond 2013

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Yusuke Suganuma (Polar Research Institute), Yasushi Harada (Tokai University),
Hirokuni Oda(AIST), and Noriko Kawamura (Japan Coast Guard Academy)

**Abstract**

The most significant progress in the geomagnetism and paleomagnetism since the present ISP was written is numerical simulations of the geodynamo. Paleomagnetic observations that can strongly constrain simulations are required now. Such observations attainable by the next phase of IODP are (1) global data for construction of a continuous paleomagnetic field model, (2) paleointensity data to understand relationship between reversal frequency and the strength of the field, in particular paleointensity during the Cretaceous Normal Superchron, and (3) data from high latitudes to clarify similarities and differences of geomagnetic field variations inside and outside the tangent cylinder. Other important issues that should be addressed by IODP are a possibility for the orbital modulation of the geomagnetic field, a possible link between climate and the geomagnetic field, and hotspot motion vs. True Polar Wander.

Proposals of paleomagnetism often request to occupy widely distributed sites for global data coverage, which does not fit the conventional ODP-style expeditions. The next-phase IODP should have more flexibility of implementation. Improvement of drilling technology is necessary for maximizing scientific output. Cores (APC, XCB, and RCB) without drilling induced magnetic overprint are strongly required for paleomagnetism. Also accurate orientation of cores is desired.

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## 1. Introduction

In the present Initial Science Plan (ISP), the importance of the paleomagnetism is recognized as the statement that “a more complete understanding of the variability of Earth’s magnetic field through time, in both magnitude and direction, is an important component of drilling studies of the Earth system”, although no paleomagnetic theme is included in the eight initiatives. The two specific paleomagnetic problems, source of marine magnetic anomalies and a possible relationship between the frequency of change in the polarity of Earth’s magnetic field and major geodynamic events including that of the Cretaceous normal superchron and superplume, are pointed out in the ISP. These problems have not yet been settled, and will continue to be the issues to be solved beyond 2013.

The most significant progress in the geomagnetism and paleomagnetism since the ISP was written is numerical simulations of the geodynamo. The first result that succeeded to make a geomagnetic polarity reversal was published in 1995 by Glatzmaier and Roberts. At that time, however, parameters used for the simulation were far from the conditions in the core of the real Earth. Since then, simulations have become closer to the Earth in accordance with the development of super-computers like the Earth Simulator. In 2005, Takahashi et al. attained a simulation in a quasi-Taylor state, the Earth-like dynamo. When considering new and revised strategies for paleomagnetism beyond 2013, it is important to aim for merging observations and simulations. By IODP drilling, paleomagnetic data that give strong constraints to simulations can be obtained. The present ISP lacks this viewpoint.

## 2. Paleomagnetic problems to be solved

### 2.1. Constraining geodynamo models

From the modern geodynamo simulations, the following observations are in particular important for further progresses. First, it is required to construct a continuous paleomagnetic field model that includes non-dipole components for the last few million years, like the CALS7K model for the last seven thousand years (Korte and Constable, 2005). From the model, we can examine, for example, whether the high-latitude flux patches that are known to have persisted at least for the last 400 years from historical observations are stable on longer timescale. Such information is necessary for understanding spatial stability of core convection and its dynamics. For constructing the model, global data coverage is essential, and thus paleomagnetic data from the southern oceans are in particular desired.

Second, it is necessary to understand the strength of the geomagnetic field in the past (paleointensity), which is an indicator of dynamo activity. A relationship between reversal frequency and the strength of the field has been suggested. Paleointensity during the Cretaceous Normal Superchron (CNS) is particularly important as an extreme case of a stable polarity, but paleointensity data obtained so far are controversial. A possible approach to the problem is to combine marine magnetic anomaly observations using deep-towed magnetometer and paleointensity determination of basalts drilled at closely-spaced several sites along a deep-tow survey line within CNS.

Third, it is important to examine similarities and differences of geomagnetic field variations inside and outside the tangent cylinder (a virtual cylinder aligned with the rotation axis in touch with the inner core at the equator). Numerical dynamo models tell us that convection and dynamo action occur differently inside and outside the tangent cylinder (e.g., Kono and Roberts, 2002). The Arctic Sea and Ross Sea are the target areas to take sediment cores for this purpose.

### 2.2. Possibility for orbital modulation of the geomagnetic field, and a link with paleoclimate

Understanding geomagnetic field variations within context of the whole Earth system is an important viewpoint. The possibility of orbital modulation of the geomagnetic field has been a matter of debate for ten years or more (e.g., Yokoyama and Yamazaki, 2000; Yamazaki and Oda, 2002; Fuller 2006; Xuan and Channell, 2009). If this is true, it has fundamental implications for the geomagnetism because it means that an energy source of the geodynamo resides outside the core. The current points of the arguments include a possibility of lithological contamination to paleointensity records and statistical significance. To settle the problem, it is required to obtain high quality paleomagnetic records, both paleointensity and direction, during the last ca. 10 m.y. with global site distribution, which can be a target for the next phase of IODP.

Another interesting topic is a possible connection between paleoclimate and geomagnetic field, which also has a long history of debate. Recently, a possible connection between influx of galactic cosmic rays and climate has been argued (e.g., Svensmark, 1997). If so, the geomagnetic field might affect climate because the strength and shape of the geomagnetic field control influx of galactic cosmic rays. It is expected for IODP to take a suite of sediment cores suitable for studying cosmogenic nuclides and paleomagnetism.

### 2.3. Hotspot motion and true polar wander

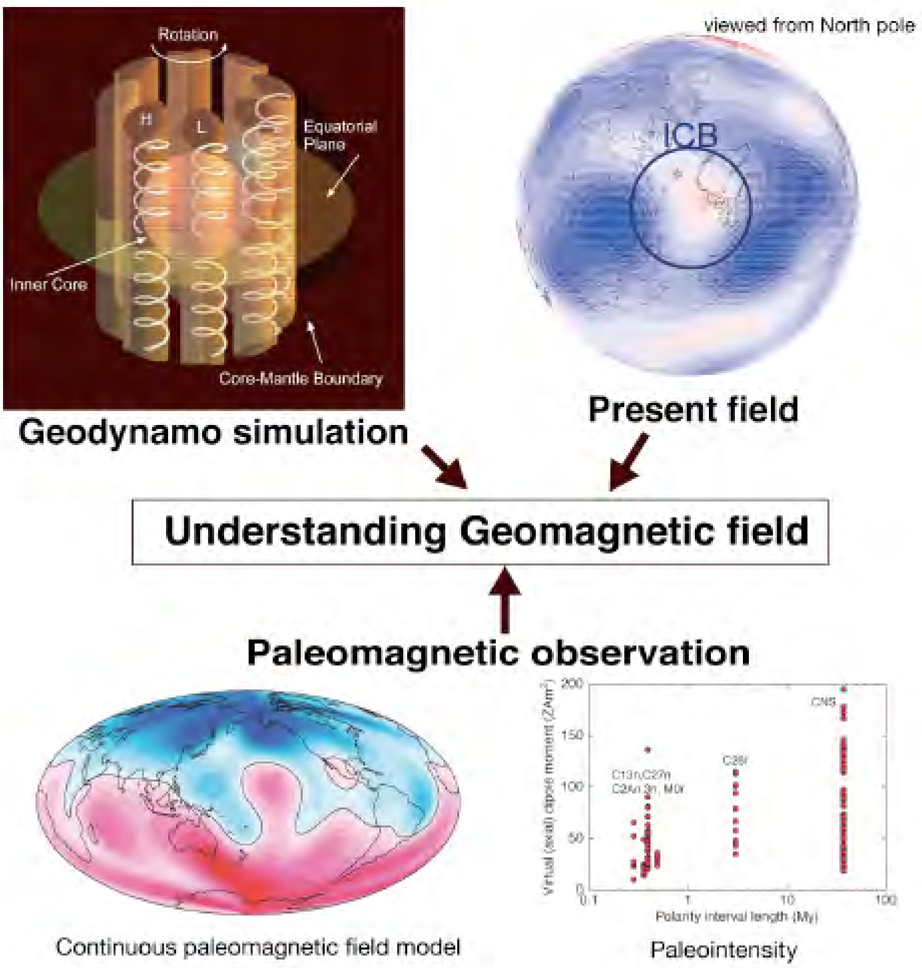
Arguments for the fixity of hotspots and the True Polar Wander (TPW) are a fundamental issue of the geodynamics, and paleomagnetism can provide essential data to settle the problem. The drilling of the Hawaii-Emperor seamount chain suggested southward migration of the Hawaii hotspot (Tarduno et al., 2003). Alternatively it could be explained by TPW. Implementation of the IODP drilling proposal of the Louisville seamount chain (636-Full3), which is currently at the OTF and waiting for being scheduled, will be the first step. It is necessary to drill several hotspot tracks to solve the problem. In particular, the location of the Tristan hotspot track is favorable for distinguishing the hotspot motion and TWP models. This may not be completed before 2013, and be carried over to the next phase of IODP.

## 3. Implementation strategy

Paleomagnetic themes often require global data coverage, and hence many paleomagnetic IODP proposals request to occupy widely distributed sites. These do not fit the conventional ODP-style expeditions: about two months for one proposal. We paleomagnetists request that the next-phase IODP has more flexibility of implementation. Occupation of widely distributed sites should be organized under a long-term program, and implemented as a piggy-back style; a few days are devoted to a paleomagnetic proposal when nearby sites are drilled for other objectives.

## 4. Technology to be developed

Improvement of drilling technology is important for paleomagnetic objectives. Drilling induced remanent magnetization has often been annoyed paleomagnetists. Coring with APC sometimes produces artificial remanent magnetization that cannot be removed by alternating-field (AF) demagnetization (e.g., ODP Leg 154). Such cores are nfortunately useless for paleomagnetism. The artificial remanent magnetization is probably acquired by deformation of sediments in a strong magnetic field of drilling strings: core-barrel, cutting shoe, and so on. A non-magnetic core-barrel reduces the problem, but far from perfect yet. Coring hard rocks with RCB also often induces secondary remanent magnetization. This can usually be erased by AF demagnetization, but for understanding sources of marine magnetic anomalies, recovering in situ magnetization before partial demagnetization is essential. Improvement of drilling technology for avoiding drilling induced magnetization should be seriously considered in the next phase of IODP for maximizing scientific output. A demand of fully oriented cores is not only for paleomagnetism but also for other fields including structural geology. Orientation of APC cores with the FLEXIT tool (a magnetic compass) available at present is not satisfactory; it can be used for judging the magnetic polarities, normal or reversed, but not enough for studying secular variations of declination partly due to a magnetic field produced by a drill-string and twisting of a core liner. Introduction of up-to-date technology will enable accurate orientation of cores including RCB.



Rotation
H
L
Equatorial Plane
Inner Core
Core-Mantle Boundary
Geodynamo simulation
viewed from North pole
ICB
Present field
Understanding Geomagnetic field
Paleomagnetic observation
CNS
C29r
C13n,C27n
C2An.3n, M0r
Polarity interval length (My)
Continuous paleomagnetic field model
Paleointensity


**Fig. II-7**.

# III. Building a Scientific Understanding of Geohazards

Japanese planning group*[6] for Geohazard mitigation science in the next ISP of IODP

**Abstract**

Geohazard is an inevitable issue for the next stage of IODP. In order to contribute to Geohazard mitigation along subduction plate boundaries, megathrust earthquakes and mega-volcanic eruptions that have repeatedly caused devastating damages to the human society must be the targets. Ocean drilling provides vital information on the past events in sedimentary records, and then we can scientifically evaluate the forthcoming events and quantitatively map accompanying phenomena, by updating simulation models and physical parameters.

Contribution of ocean drilling to Geohazard issue can be classified into four: First of all, we have to learn the past earthquakes from sedimentary records to understand the size and recurrence of the events with a combination of 3D acoustic survey and systematic shallow drilling. Second subject is to build downhole observatories in the area of events are expected to happen. For example, understanding of deformation process in earthquake cycles requires stable, sensitive and long-term monitoring network of seismic and geodetic sensors as well as other geophysical/geochemical sensors to reveal spatial variation of frictional properties that produces the variety of interplate slip events. In the third, actual fault materials provided by deep drilling into the seismogenic zone must reveals spatial variation of micro structures and physical properties, enable us to construct quantitative models on behaviors of seismogenic faults in various time scales. Finally, ocean drilling provides fundamental knowledge on size and recurrence as well as regional and global effects of such unprecedented Geohazard because only little has known about gigantic caldera-forming eruptions to date.

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and 32 participants of the Geohazard domestic workshop in December, 2008.
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# i. Exploration into catastrophic earthquakes

*#1: Approaches from shallow geological record*

Japanese planning group for Geohazard science*[7]

**Abstract**

'Geohazards' has been clearly identified as a theme for the next stage of IODP. Among the various natural hazards on Earth, megathrust earthquakes at subduction zones, represent one of the greatest dangers, with hundreds of millions of people at risk in seismically active regions. A better understanding of these great earthquakes that had repeatedly devastating effects on our societies in the past, and will continue in the future, is an important target for the future program.

Ocean drilling will provide clues to understanding what was the greatest earthquake ever happened and what is the recurrence interval by revealing size and spacial distribution of characteristic deposits triggered by earthquakes. Contribution of ocean drilling at shallow sediments to Earthquake Geohazard can be summarized as:

1) The past earthquake events identified in the sedimentary record providing vital information on the size and recurrence of the events, with systematic shallow drilling and a combination of 3D acoustic survey.
2) Distribution of the characteristic (earthquake-triggered) sediments and their spatial variety corresponding to lateral variation in the seismic types.

Technical needs to implement this science include complete (100%) coring technology, X-ray CT technology to detect subtle event deposits from core, precise dating of the event deposits, 3D acoustic survey for spatial distribution of the event deposits.

*[7]Names and affiliations of group members are shown in Appendix.

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## 1. Introduction

Mankind has experienced many historic disasters in the past, but catastrophic events, which we do not even aware of, may happen in the future because of the shortage of human history comparing to the geologic time scale. The "earthquake cycle" concept has been proposed to express the recurrence history of megathrust earthquakes rupturing the same segment (asperity) on the plate boundary fault, and to evaluate earthquake and tsunami hazards in the future. However, a gigantic (M>9) earthquake is considered to be an earthquake that ruptured multiple adjacent asperities at the same time, which is beyond the sight of the traditional earthquake cycle concept. An example of such gigantic earthquakes is the 2004 Sumatra-Andaman earthquake (Mw9.1-9.3) that demonstrated how gigantic interplate earthquake causes catastrophic impact to the human societies on a global scale. Increasing numbers of paleoseismological studies suggest that the earthquakes involving multiple segments rupture have occurred in many subduction zones [e.g. Satake and Atwater, 2007] and force us to acknowledge the existence of the gigantic earthquakes in future projection of earthquake/tsunami hazards.

To evaluate pre-historical earthquakes, we need to extract data on magnitude and distribution of crustal movement and tsunami by analyzing geomorphological and geological traces, that provide rupture extent of such earthquakes. When rupture area was located at coastal regions, crustal movement can be easily assessed from relative sea level change (abrupt uplift and subsidence) that has been recorded in marine terraces. However, most of the rupture area of interplate earthquake along subduction zone is located off coast, and ocean drilling is the only method to recover sedimentary record to extract data on the crustal motion.

Earthquakes and tsunami geohazards at subduction margins require two different approaches: science on shallow sediments and deep seismogenic fault drilling. From shallow sediments, event deposits formed by earthquakes need to be extracted to analyze the planar distribution of single event deposit and their recurrence based on dating technologies. The planar distribution suggests source region of the triggering earthquake thus can be used to assess the earthquakes coupling in several adjacent segments. Combination of on-land and submarine topography may bring coupling evaluation, recurrence interval and dating of earthquake events in different scales. This topic requires collaboration between researchers in different background including geomorphology, engineering geology and geology.

This white paper describes how shallow ocean drilling realistically contributes to build scientific understanding of earthquake hazard through revealing past events along the plate boundary, which is critical to understand size and recurrence of the past gigantic earthquakes involving multiple segments rupture.

## 2. Geologic signatures of the past earthquakes

Three types of geologic signatures of ancient earthquake and tsunamis have been observed in major seismic regions, and many studies have attempted to estimate the area, age and magnitude of individual event.

First, the seismically induced deformation structure within strata, for example an intrusion of fluidized sediment to the surrounding strata, sand dyke and sills, are well observed at liquefied sandy layer under low permeable cap rock (e.g. Obermeier et al., 2002). The vein structure (Ogawa, 1980), an array of sigmoidal shaped fine grain-fill veins formed with seismic shaking induced layer parallel shear (Hanamura and Ogawa, 1993; Brothers et al., 1996; Ohsumi and Ogawa, 2008), and they are found in diatomaceous silt layer. The occurrence of these deformation structures used to be controlled by lithologic feature, and they often experiences a multiple events. The seismic history must be assumed from overlapped structure based on crosscutting relationship.

Secondly, seismically induced gravity flow at submarine slope, turbidite and debris flow are well observed at large earthquake, and its deposits are interleaved between interseismic horizontal strata. High energy gravity flow sometimes causes erosion of old basal deposit, and discontinuous history is preserved. The distribution and thickness of gravity flow deposit depends upon not only seismic magnitude but also submarine topography and provenance basin conditions. Systematic patterns of surface failures along each slope can recently be clarified by analogue models (Yamada et al., in press) and need to be applied to real event deposits.

Chaotic sedimentary bodies formed in combination with earthquake-induced liquefaction and slumping are valuable marker of paleoseismic events. Since materials produced by surface slumping and liquefaction are erupted to the ocean floor, the age of the event can be precisely determined from the coherent layers just above the chaotic body. Main merits to use liquefied sandy materials are their wide distribution and frequent occurrence. Fossil example of large-scale chaotic sedimentary body within Late Pliocene to Pleistocene trench-slope cover sediments of the Chikura Group, Central Japan, can be traced E–W over a distance of 5 km (Yamamoto et al., 2007). Possibility of large-scale submarine slides to generate large tsunamis would be discussed by separate white paper on submarine landslides and mass movements.

Thirdly, a stirred of abyssal sediment arises from seismic and tsunami induced force. This is not accompanied with transportation unlike gravity flow. It has been discussed that the passing tsunami induced a pulse of water pressure and orbital motion of water particles will reach to sea bottom (Ward, 2002). However, the earthquake tsunami is considered insufficient to stir and transport abyssal sediment (Dawson et al., 2007). The earthquake faulting makes regional ocean floor movement, though the vertical displacement does not exceed 10 m. The kinetic energy of slope failure and bolide impacts concentrates at small area, and its assumed tsunami waves are from several times to hundred times higher than an earthquake tsunami (Dawson et al., 2007).

## 3. New approaches

Strong seismic ground motion also disturbs surface soft sediment, and such sediment suspensions have been observed after large earthquakes in the Cariaco Basin (Thunell et al., 1999), in 1994 Sanriku–Oki earthquake offshore Japan (Itou et al., 2000) and in the 26 Dec 2004 Mw9.1-9.3 rupture offshore Aceh, northern Sumatra (Seeber et al., 2007). The deposit derived from suspension will be distributed around the epicenter and the displaced fault immediately after the event. Where the ground motion did not trigger large slope failure and distant transportation of sediment, the record of age, location and magnitude of the event will be preserved. Such event deposits may be difficult to identify because of the similar material with surroundings. To detect such subtle difference in sediments, the X-ray computed tomography (X-CT), that has been well established through medical research and applied for geologic sample recently, can be applied with functions to visualize chemical composition and density of the target material. The X-CT observation may detect ground motion induced sediment disturbance. Detailed isotope dating and large amount of coring around fault zone have potential to reveal recurrent history and distribution of seismic ground motion. Inversion model will simulate asperity from surface ground motion distribution. The result of paleo-asperity history will combine with other seismologic projects. Record of historical behavior of asperity constrains fault simulation model. Fault characterization from view point of paleo-asperity contributes for geologic understanding of fault material in deep drilling.

## 3. Answers to the 8 questions at INVEST

**What are the major hypotheses and unanswered questions in your topic? Describe the global relevance of those questions.**

[Hypotheses]

A gigantic earthquake (M~9) is sporadically but repeatedly occurred in a subduction seismogenic zone by widely simultaneous failure of neighboring asperities.

[Global relevance]

Several paleo-seismological evidences suggesting a magnitude-9 class unusually large earthquake has been reported in subduction zones around the Pacific as well as the Indian Ocean, for example, the Chile, Cascadia, Kuril and Nankai subduction zones. The 2004 Sumatra-Andaman earthquake is one of the striking examples of those events. Although most of those are suggested to be occurred by simultaneous failure of neighboring magnitude-8 class asperities, a process to nucleate such a gigantic earthquake is still unknown.

[Unanswered questions]

Have gigantic earthquakes repeatedly occurred?

If so, what is the pattern of simultaneous rupture of neighboring segments?

**Which of these represent the highest research priorities that can realistically be achieved in the next decade?**

The answers of these two questions above can be realistically achieved by shallow drillings in the next decade, by examining sedimentary records.

**What drilling, sampling, experimental and site characterization strategies are required to achieve your goals?**

1. Site characterization: 3D MCS is vital to visualize 3D geometry of characteristic event deposits triggered by earthquakes. The survey is focused on shallow deposits and does not need to image deep ‘seismogenic zones’ thus acquisition and processing should be tuned to this purpose. The data extract the size and recurrence of each event, then determine the drill sites for shallow sequences.

2. Drilling: In order to correlate the 3D geophysical data with surface geology and to determine precise locations of subsequent drill sites, dense piston cores (~30m) need to be recovered in every few hundred meters, followed by systematic drilling (~1000m) in every few (tens of?) kilometers along subduction margins.

3. Sampling: Sampling in sedimentary sections to reveal timing, recurrence cycles and sizes of gigantic earthquakes.

**What are your platform and technological needs?**

Shallow drillings themselves can be done by a non-riser vessel.
Technology to recover 100% cores from soft surface deposits is vital.
X-ray CT technology is vital to detect subtle event deposits in the cores.
Technological constrains of the piston coring to limit applicable areas and recoverable length need to be solved.

**What mix of long-term projects and single expeditions will best answer these questions?**

A series of single expeditions for shallow sedimentary sequences reveal earthquake cycles, size and along-strike variations. This drilling campaign should be the first to visualize the lateral variation of failure patterns. Then candidates of the deep targets can be determined.

**How can the future drilling program interact with other science programs and with industry to achieve your goals?**

It has to be noted that IODP activity has to share its product with other scientific programs to achieve earthquake/tsunami hazard mitigation. For example, there are several Japanese geohazards related project in the Nankai seismogenic zone. The most related project to IODP geohazrds study is "Research concerning Interaction Between the Tokai, Tonankai and Nankai Earthquakes" which is funded by MEXT. The main aim of this project is a hazard mitigation of a possible gigantic earthquake in the Nankai seismogeinic zone by means of cable-connected real-time seafloor observatory, high-resolution deep seismic imaging and numerical simulation for earthquake cycle. A long-term monitoring system by the NantroSeize is planned to be connected to this network. Since paleoseismological approach in this project is conducted in only on-shore area, ocean shallow drilling to obtain off-shore paleoseismological data is necessary to reveal precise rupture history along the Nankai seismogenic zone.

**What hot topics can be highlighted to be used for outreach and raising the public's interest?**

'Gigantic earthquakes in the past'. Maximum earthquake ever happened at subduction zones can be revealed from sedimentary records, and is surely one of the most serious concerns of human society.

**How are your science goals relevant to society?**

The size of the maximum earthquake happened in the past and its recurrence are used for disaster mitigation by local governments. The mechanical models of gigantic earthquakes should be improved by this knowledge, and by understanding development process of segmentation (asperity) from temporal and spatial distribution of the earthquake-triggered sediments.

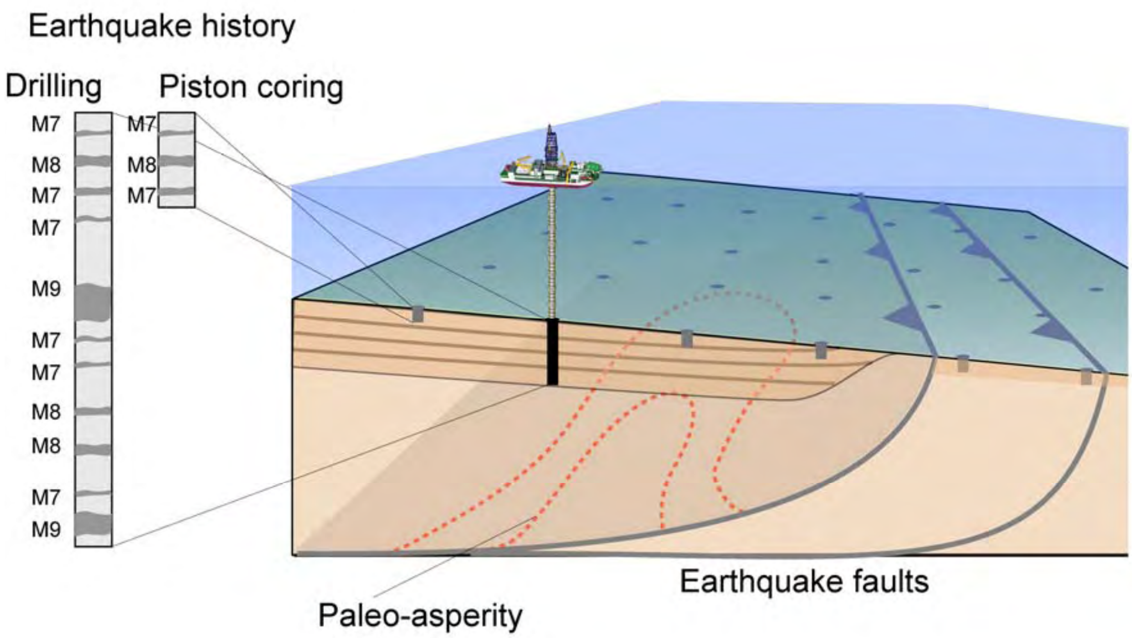


**Fig. III-1**. Conceptual view of systematic shallow drillings for IODP seismic Geohazards.

Appendix. List of member of planning group (*in alphabetical order*)

| | |
|---|---|
| Ryo Anma | University of Tsukuba |
| Ryota Hino | Tohoku University |
| Takehiro Hirose | JAMSTEC |
| Ken Ikehara | Geological Survey of Japan, AIST |
| Satoshi Ide | University of Tokyo |
| Hisao Ito | JAMSTEC |
| Yoshihiro Ito | Tohoku University |
| Masao Iwai | Kochi University |
| Koichiro Obana | JAMSTEC |
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| Shuichi Kodaira | JAMSTEC |
| Weiren Lin | JAMSTEC |
| Fukashi Maeno | University of Tokyo |
| Yuta Mitsui | Kyoto University |
| Ayumu Miyakawa | Kyoto University |
| Kimihiro Mochizuki | University of Tokyo |
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# ii. Exploration into catastrophic earthquakes

*#2: Approaches from integration of drilling, monitoring, and numerical modeling*

Japanese planning group for Geohazard science*[8]

**Abstract**

'Geohazards' has been clearly identified as a theme for the next stage of IODP. Among the various natural hazards on Earth, megathrust earthquakes at subduction zones, represent one of the greatest dangers, with hundreds of millions of people at risk in seismically active regions. A better understanding of these great earthquakes that have repeatedly had devastating effects on our societies in the past, and will continue in the future, is an important target for the future program.

Ocean drilling will provide clues to understanding what defines frictional properties along the faults by revealing deformation processes in earthquake cycle as well as the details of compositions and physical structures of fault zones. This information can then be used to quantitatively evaluate forthcoming events and numerically map accompanying phenomena, by improving the physical parameters used in simulation models.

Monitoring of fault motion and intraplate deformation in response to relative plate motion requires stable and sensitive network of seismic, geodetic and hydrological sensors. The networks can only be realized by the sensors installed into sub-seafloor boreholes distributed over entire seismogenic zone. The results of long-term monitoring provide us with precise spatial variation of frictional properties. Sampling fault materials. measuring in-situ physic-chemical parameters, and monitoring fault motions in ultra-deep (~ 10 km) holes at asperity and non-asperity will clarify how spatial variation of micro structures and physical properties are related to diversity in releasing mechanism of accumulated stress along the fault.

The scientific goal of the next decade is to understand characteristics of asperities of megathrust earthquakes and to predict how a rupture nucleates before rupturing. These can eventually lead to understanding the mechanism of multiple ruptures of asperities causing catastrophic gigantic earthquakes.

*[8]Names and affiliations of group members are shown in Appendix.
*Corresponding author: Ryota Hino < hino@aob.gp.tohoku.ac.jp >*

## 1. Introduction

The 2004 Sumatra-Andaman earthquake (M9.1) demonstrated how gigantic (M>9) interplate earthquake causes catastrophic impact to the human societies on a global scale. Mankind has experienced many historic disasters in the past, but catastrophic events, which we do not even aware of, may happen in the future because of the shortage of human history comparing to the geologic time scale. Estimation of cultural damages caused by these catastrophes cannot be accomplished without scientific evaluations, including possibility of occurrence, plausible size of forthcoming events and hazard mapping of accompanying phenomena, such as ground shaking and tsunami heights. It has become possible to simulate recurrent earthquakes [e.g. Ruina, 1983] and processes of dynamic rupture of individual earthquake events [e.g. Fukuyama et al., 2002]. The simulations are expected to help in evaluating possible hazards and any improvements in the simulation reliability directly contribute to improvements of credibility of the hazard evaluation.

The "earthquake cycle" concept has been proposed to express the recurrence history of megathrust earthquakes rupturing the same segment (asperity) on the plate boundary fault, and to evaluate earthquake and tsunami hazards in the future. However, a gigantic earthquake is considered to be an earthquake that ruptured multiple adjacent asperities at the same time, which is beyond the sight of the traditional earthquake cycle concept. Increasing numbers of paleoseismological studies suggest that the earthquakes involving multiple segments occurred in many subduction zones [e.g. Sawai et al., 2004] and force us to acknowledge the existence of the gigantic earthquakes in future projection of earthquake/tsunami hazards. Several studies have succeeded in reproducing interplate earthquake recurrence histories in which both single-piece ruptures and simultaneous multiple neighboring-segment failures have occurred (Fig. III-2) [Kodaira et al., 2006; Kato, 2008]. In their simulations, the resultant earthquake history is strongly dependent on heterogeneous distribution of frictional properties, pointing to the importance of building a realistic earth model on which numerical simulation for reliable hazard projection.

Although we expect numerical modeling to provide future behavior of the megathrust zone, the current simulations can not immediately be applicable for ‘earthquake forecasts’. The most significant issue is lack of knowledge of constitutive parameters and their distribution along the actual seismogenic fault. Reliable forecasting also requires the numerical modeling to be assimilated to the observed behavior of the faults, and thus reliable monitoring systems.

This white paper describes how deep ocean drilling contributes to build scientific understanding of earthquake hazard (Fig. III-3) through revealing frictional properties along the plate boundary, which is critical to understand characteristics of asperities causing megathrust earthquakes and to predict how a rupture nucleates before rupturing. These can eventually lead to understanding the mechanism of multiple ruptures of asperities causing catastrophic huge earthquakes, such as the recurrence intervals and possible range of magnitudes, and factors controlling simultaneous failure or separated failure of neighboring asperities.

## 2. Ocean drilling for understanding of deformation process in earthquake cycles

Development of stable and sensitive network of seismic and geodetic sensors plays key roles in building a realistic earth model applied for the simulation. The spatial distribution of asperities, the most fundamental information, has become to be revealed by geodetic observations [e.g. Hashimoto et al., 2009]. On the other hand, diverse kinds of episodic slow slips (ESS) without radiating short-period seismic energy have been detected [e.g. Obara, 2002; Ito and Obara, 2006; Ito et al., 2007]. The variety of the ESSs is interpreted as the manifestation of the variation of frictional properties along the plate interface [e.g. Schwartz and Rokosky, 2007] and some frictional parameters at the source region can be estimated from rupture process of the ESSs [e.g. Miyazaki et al., 2004, Fukuda et al., 2009]. Since these previous studies are base on the observations at onshore sites, remote from the asperities and the ESS sources, their results need to be improved in spatial resolution by offshore data.

To realize stable and sensitive observation in offshore area, downhole monitoring systems are required, but deep holes reaching to source faults are not necessary for all of the observatories. These systems have to be integrated with on- and off-shore observatories to form a broad and dense network covering the seismogenic zone entirely. Well-heads of drilled sites will provide seafloor geodetic measurements with stable benchmarks. Fault motion can also be detected by sub-bottom pore pressure and temperature transients [e.g. Davis et al., 2006] because fluids are expected to be redistributed by the fault motions.

Nevertheless, ultra-deep (~ 10 km) observatories are indispensable, even if the number is limited, because they enable direct monitoring of loading process and fault response to it. Simultaneous monitoring at an asperity and at a boundary of adjacent asperities is required to understand complete behavior of the fault. Realization of in-situ measurements of fault motions will bring tremendous breakthrough to seismology, where faulting dynamics has been studied base only on remote sensing. Measuring deformation of the boreholes will provide continuous profiles of displacement within fault zones as well as vertical arrays of geodetic instruments. The migration of fluid accompanied with various physic-chemical processes can also be monitored by gas/fluid analyzers, electromagnetic antennas, and scintillation detectors for natural radiations installed deep into the seismogenic zone. Repeating loggings and active monitoring can also trace the temporal changes along the faults.

These monitoring data, especially from ultra-deep downhole measurements, are sensitive to fault motions and could be possible to detect small events expected to be induced by nucleation process of large earthquakes [e.g. Kato and Hirasawa, 1999; Matsumoto et al., 2007], which have never been observed. The detection of precursory events will not only shed light on faulting dynamics of megathrust but also would provide a chance of successful short-term forecasting of earthquake occurrence. Therefore, it is strongly desirable to collect these data in real time by connecting to seafloor cabled communication network.

## 3. Ocean drilling for clarifying composition and structure of seismogenic faults

In the first approximation, the stability of frictional slip is primarily controlled by environmental parameters, such as pressure and temperature [Scholtz, 2002]. The normal earthquakes and ESSs, however, sometimes occur almost side-by-side at the same depth along the plate boundary [e.g. Yagi et al., 2001, 2003], thus there must be unknown factors that control interplate slip behavior. Possible factors controlling frictional properties, other than PT conditions, include thickness and structure [Marone and Kilgore, 1993; Chester et al., 1993] and/or composition of fault zones [Moore and Saffer, 2001; Moore and Lockner, 2004]. Therefore, we need to define them both in asperities and those of non-asperities (sources of ESSs, boundary between asperities, etc.) from core samples and logging data. Since seismogenic faults expected to be record past coseismic slip events, the dynamic weakening mechanisms of faults during an earthquake will be identified through detailed microstructural analyses and laboratory experiments using core samples [Otsuki et al., 2003; Ma et al., 2006] by integrating with the in-situ monitoring fault motions. The weakening mechanisms revealed from core samples and logging data will be incorporated into the analysis of earthquake initiation and rupture processes.

The detailed descriptions of fault core samples that are possibly collected by side-wall sampling and the rheology of these samples determined by laboratory experiments, are necessary to reveal the characteristics of asperities and non-asperities. Fault plane heterogeneity generated by deformation fabric and/or mineral precipitation may explain the variety of seismic types. Directional drilling along a fault plane and branch holes are required to recover lateral variation in the core samples. Technology to detect deep fault planes approaching the drill bit is essential.

Another important issue is the different spatial scaling studied, from microscopic fabrics in drill holes, through 3D geophysical dataset that cover hundreds of meters to kilometers, and up to the entire subduction system, which extends over hundreds of kilometers. We need to be able to combine information over these different scale lengths to establish a realistic earth model for reliable simulation. Active source experiments using deep drilling holes (e.g. VSP, cross-hole tomography) in collaboration with active and passive surveys will provide us multi-scale structure around target faults and help to extrapolate physical properties at the drill sites to spatial distributions of constitutive parameters. Key factors that control the frictional behavior and elementary physico-chemical processes in the subduction fault zone must include distribution and mobility of fluid along and across faults [e.g. Sibson, 1992]. Fluid distribution in and around the fault zones estimated by seismic and other geophysical explorations should give a foundation for integration of local characteristics defined by core-log data and regional structure.

It is often assumed that geometrical irregularities of plate boundaries define asperity distribution [e.g. Kodaira et al., 2000; Mochizuki et al., 2008]. Drilling at subducting seamounts or their peripheries must provide answers how and why such irregularities affect interplate rupturing.

## 4. Integration into comprehensive earthquake faulting model

Since it is difficult to construct an earth model for the earthquake simulation by extrapolating the information obtained by a small number of drill sites, it would be better to make a regional model. The model has to contain at least a whole segment of a megathrust earthquake and preferably encompasses multiple segments and can be built based on spatial distribution of frictional properties and also on mapping of rupture zones of past earthquakes. The former will be provided by the monitoring systems proposed in this white paper and the latter by paleoseismological studies presented in the separated paper [Japanese planning group for Geohazard science, 2009].

Through comparison of observed and calculated spatio-temporal variations of fault motion, the earthquake cycle simulation should be assessed and simulation model would be improved. A chronology of megathrust earthquakes revealed by paleoseismological studies has to be reproduced in the modeled earthquake cycle. The ESS activity occurred in the seismic-aseimsic transition zone is another important constraint. Some of ESSs have short recurrence time such as a few years [e.g. Ozawa et al., 2003]. The monitoring systems are expected to reveal entire processes composing a cycle of the ESS activity, which help in constructing a physical model governing the EES cycle. The model could be enhanced to that of ordinary earthquakes, provided that differences between ESSs and ordinary earthquakes are merely in frictional properties. The ESSs with short recurrence periods could be a target of experimental forecasting based on the numerical simulation with data assimilation.

Detailed characteristics of fault zones will contribute to validate the physical model on which the numerical simulation are founded. The core-log data obtained by ultra-deep drilling reaching to the megathrusts provide unique opportunity to correlate frictional parameters in core-log scale and those required to explain the fault behavior estimated by remote observations. In situ measurements of pore pressure and stress constrain the range of uncertainty of both physical and earth models. Improving assumed frictional parameters at asperities, it is possible to build a source model for reliable estimation of strong ground motion caused by future great earthquakes. Dynamic processes in rupture propagation recorded in the cores will also be another constraint on the source model.

**5. Implementation**

Since all the processes involving earthquake generation in any spatial and temporal scale are subjected to heterogeneity along faults, they cannot be described and predicted without comprehensive understanding of seismogenic fault structure. This means that our goal cannot be achieved by a single expedition of an ultra-deep boreholes but require a suit of drill sites at locations with different frictional behavior (Fig. III-3). Therefore, the sites to be drilled have to be well characterized in terms of frictional properties prior to drilling. This requires not only conventional site survey efforts by geophysical (mostly seismic) explorations but also mapping of fault activities, earthquakes and ESSs. Ultra-deep (up to 10 km beneath sea level) drilling and drilling through unstable formation in the fault zones required in this white paper cannot be achieved without a riser platform, such as *Chikyu*.

It has to be noted that IODP activity has to share its product with other scientific programs to achieve earthquake/tsunami hazard mitigation. For example, there is a national project aiming hazard mitigation of a possible gigantic earthquake in the Nankai seismogeinic zone in Japan. This project will provide cable-connected real-time seafloor observatories, high-resolution deep seismic imaging and numerical simulation for earthquake cycle, all these subjects are supposed to be performed under tight cooperation with the NanTroSeize project.

Mitigation of earthquake and tsunami hazards, to which IODP Geohazard contributes, is surely one of the most serious concerns of human society. Reproduction of past earthquake cycles must raise a strong public interest. Ubiquitousness of gigantic earthquakes has to gain public awareness through the IODP geohazard research.

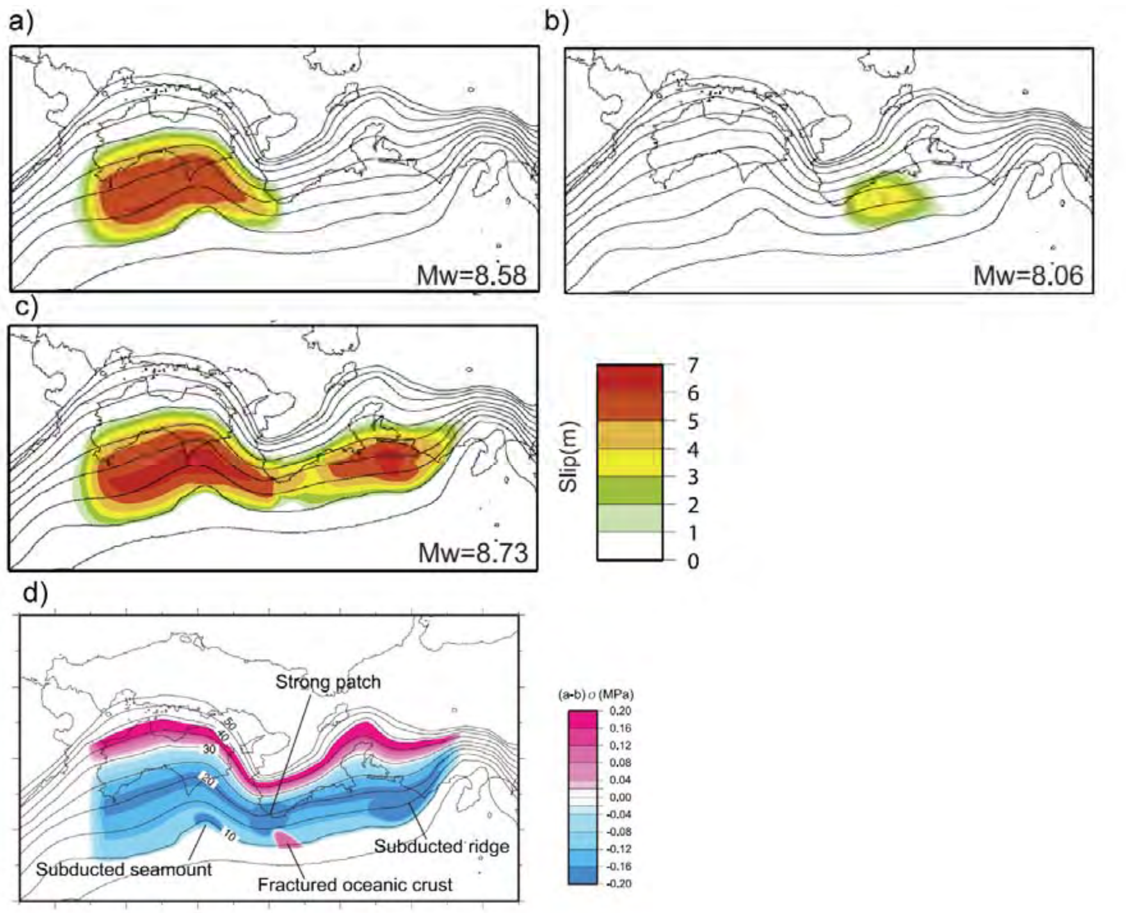


**Fig III-2**. Simulated earthquake history along the Nankai Trough, Japan [Kodaira et al., 2006. Independent ruptures of a single asperity (a and b) and simultaneous failures of asperities (c) appears in the simulated earthquake cycle. In the simulation, heterogeneous distribution of frictional parameters is given to the plate boundary (d).

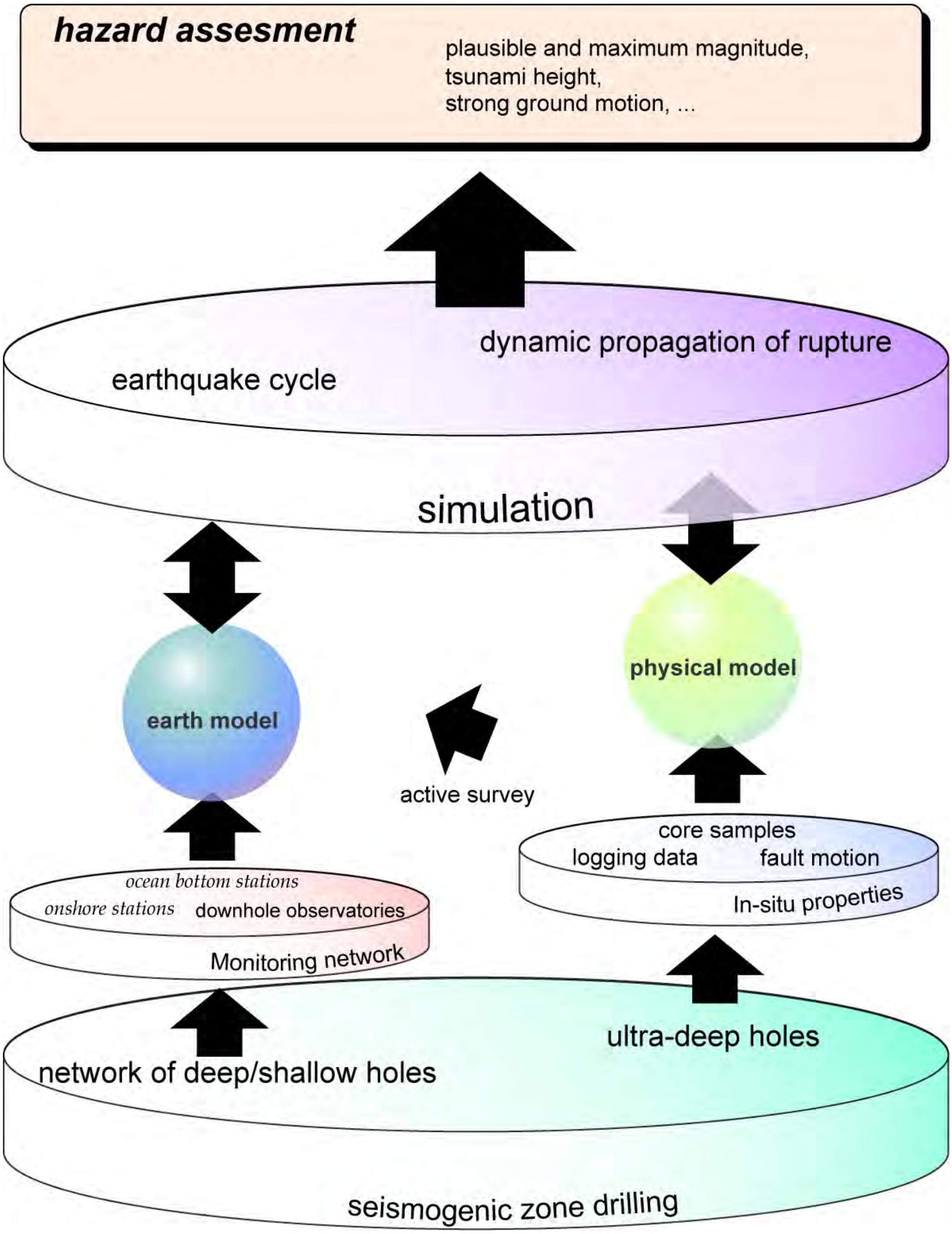


**Fig. III-3**. Strategy of IODP for scientific understanding of earthquake geohazards.

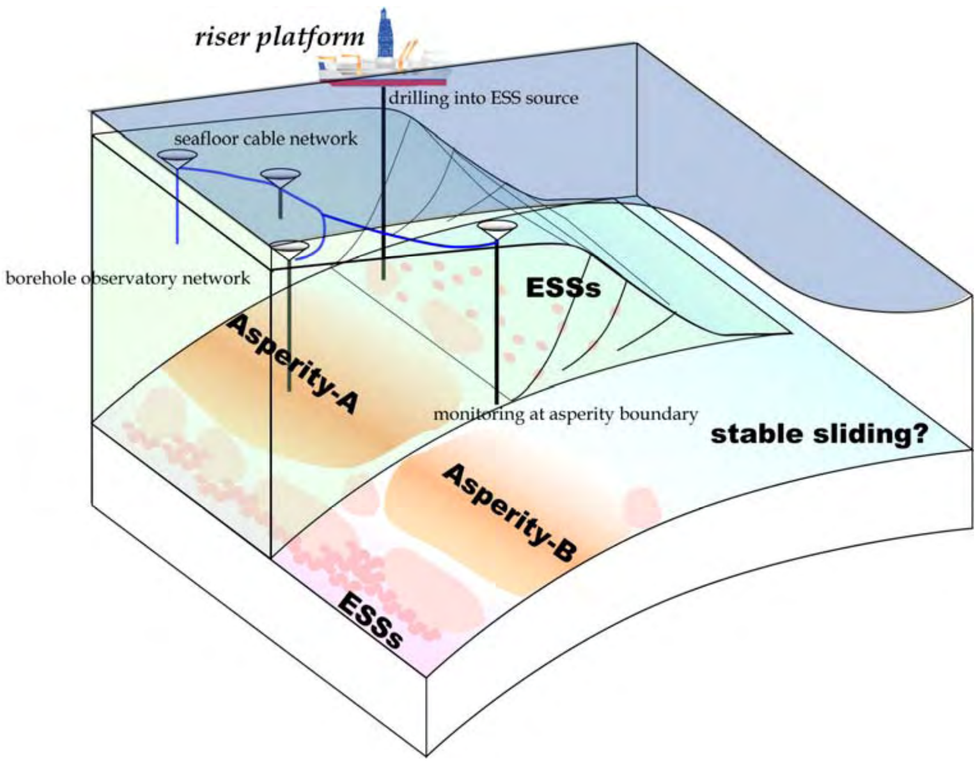


**Fig. III-4**. Conceptual view of seismogenic drilling for IODP geohazard.

Appendix. List of member of planning group (*in alphabetical order*)

| | |
|---|---|
| Ryo Anma | University of Tsukuba |
| *Ryota Hino | Tohoku University |
| Takehiro Hirose | JAMSTEC |
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| Yoshihiro Ito | Tohoku University |
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| Yukari Kido | JAMSTEC |
| Masataka Kinoshita | JAMSTEC |
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| Shuichi Kodaira | JAMSTEC |
| Weiren Lin | JAMSTEC |
| Fukashi Maeno | University of Tokyo |
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| Ayumu Miyakawa | Kyoto University |
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# iii. Ocean Transform Fault Drilling and Water Injection: An Active Experiment to Trigger a Moderate Earthquake

Jim Mori*[9], Yasuyuki Kano (Disaster Prevention Research Institute, Kyoto University), and Jeff McGuire (Woods Hole Oceanographic Institution)

**Abstract**

We propose an experiment to understand the initiation of large earthquakes by inducing seismic events on a shallow fault with water injection. Increasing the fluid pressure near an active fault will reduce normal pressure on a fault and bring it closer to failure, according to the classic Coulomb failure criterion. A study to monitor the water pressure and subsequent triggered earthquakes can help answer some fundamental questions in seismology about the stress levels that cause earthquakes and the physical conditions that are necessary for a large earthquake to occur. This is an effort to repeat the famous Rangely, Colorado experiment that induced earthquakes with water pumping during 1969 to 1973. That experiment influenced much of the early optimism for earthquake prediction and earthquake control in the 1970's, although it has never been repeated.

An appropriate location for such an experiment are mid-ocean transform faults, where there are high levels of seismic activity and moderate (M5 to M6) sized earthquakes that regularly occur at intervals of 5 to 15 years. If we can trigger a moderate seismic event a few years earlier than its expected recurrence time, we can directly observe the physical processes and conditions associated with the initiation of the earthquake.

This experiment represents a new utilization of the drilling platforms for active experiments. These kinds of projects can provide new research directions for IODP.

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## 1. Introduction

From the time of the famous Rangely, Colorado example 30 years ago (Raleigh et al., 1967), it has widely been observed that increasing fluid pressure in the vicinity of faults can induce earthquakes. The results from Rangely were one of the main reasons for the optimism in earthquake prediction in the 1970's, although that experiment has never been repeated. More recently very small earthquakes have been induced in the aftershock region of the Kobe earthquake with water injections (Tadokoro et al., 2000). Also, there has been a great interest in the oil industry for inducing tiny seismic events with fluid pumping in wells to recover hydrocarbons in old wells. Finally, filling of water reservoirs often produces small earthquakes, and was apparently responsible for causing the 1967 Koyna, India (M6.5) and 1975 Oroville, California (M5.7) earthquakes. So there are a variety of experiences for triggering earthquakes with fluid pressures, both controlled and uncontrolled.

There has been considerable recent information on the static and dynamic triggering of small earthquakes, although very little is known about the stress levels that trigger larger damaging earthquakes. Is there a difference in the stress levels and physical processes of initiation between small earthquakes that often occur and the rare large earthquake ? If we can actually trigger a moderate size earthquake, we can learn about the initiation process of earthquakes and possibilities for earthquake prediction.

## 2. Scientific Motivation

The standard explanation for fluid induced earthquakes, is that increases in pore pressure reduce normal stress on a fault and bring cracks closer to failure, in terms of the Coulomb Failure Criterion. This provides a framework for understanding changes in water pressures in terms of the stress levels associated with earthquakes. Producing local changes in the pore pressure and observing changes in the earthquake occurrence can provide answers to question such as,

*What is the level of stress needed to initiate (or trigger) an earthquake ?*

In a simple model of earthquakes, an event occurs when the accumulating stress reaches the breaking strength of the fault. However, anticipating this level of stress when the earthquake happens is very difficult

*How is the time dependence of increasing stress related to causing earthquakes ?*

For large tectonic earthquakes, the stress that causes the event builds up over years to millennia. It is very difficult to say at what point in this process the earthquake occurs. The mid-ocean transforms are one of the places in the world where this stress accumulation and earthquake occurrence is most regular (McGuire et al., 2008).

*Are there differences in the initiation of small and large earthquakes ?*

*What conditions are necessary to initiate a moderate to large size earthquake ?*

Small earthquakes are common and occur almost continuously in seismic areas, but very little is known about that rare initiation that grows into a large damaging earthquake. The most interesting observations would be if a relatively large (M5 to M6) event could be induced. With data from this experiment we can begin to understand how large earthquakes are different from small earthquakes.

These are all fundamental questions about earthquakes that have been pondered for decades by seismologists. An project to trigger both small and moderate size earthquakes has the potential for making major advances in understanding the source process of earthquakes and ways that they may (or may not) be predicted.

**3. Possible Location for Experiment**

Appropriate sites for such an experiment would be transform faults near mid-ocean ridges, such as Blanco on the Juan de Fuca Ridge and Quebrada, Gofar, or Discovery on the East Pacific Rise. In such settings, shallow moderate (M5 to M6) earthquakes occur at repeating intervals of 5 to 15 years (McGuire et al., 2005). The source faults and hypocenters of these strike-slip earthquakes are shallower than for onshore faults because of the high thermal greadient and thus are more easily accessible by drilling to depths of a few kilometers.

An interesting experiment would be to carry out a water injection experiment at one of these sites a few years before the expected earthquakes recurrence, to try to trigger an early occurrence of the event. In addition, earthquakes in this region are often preceded by foreshock sequences. Triggering foreshocks would also provide important information on earthquake initiation processes.

**4. Technical Considerations**

A 2 to 3 km deep borehole would be drilled to be close (within a kilometer) to the hypocentral region of a moderate earthquake. Earthquakes along along the transforms occur at shallow depth above the 600 $^{o}$C isotherm at depths of about 2 to 5 km (Behn et al., 2007). Fluid pumping can probably increase pore pressure over a fairly large region, so the drilling does not have to be exactly at the (unknown) earthquake hypocenter. The hole needs to be cased and open near the bottom. Water pressurized at various pressures from about 0.001 MPa (about 0.1 psi) to higher values, (possibly 1 MPa, 140 psi) would be pumped into the borehole in order to raise pore pressure in the region of the hypocenter. The upper value for the pumping pressure approach the values of the static stress drops of the earthquakes. This could be an interesting utilization of riser drilling.

An appropriate site in water depths of about 2500 meters can likely be found. However, if the technical capabilities allowed drilling at depths of 3500 to 3800 meters, a much better location could be chosen (Fig. III-6).

In most cases, induced earthquakes do not occur immediately after pumping, so there will likely be a several day delay to any induced seismic events.

A complete explanation of the earthquake activity needs understanding of the local fluid, thermal and stress distributions. Depending on the scale of the planned project, several near-fault boreholes to install seismometers along with fluid and strain monitoring instrumentation will also be considered. Also, there would obviously be important information on the physical structure of the fault zone from the borehole cores.

## 5. Related Activities

The main objective of this program is to record any changes in the local earthquake activity, so deployment of an array of ocean bottom seismometers (OBS) is an important aspect. There will be needed coordination with US and/or Japan OBS programs, such as NOAA and JAMSTEC. The monitoring program would last from several months before to several months after the water pumping experiment.

## 6. Societal Relevance

The results of this experiment can lead to important advances in understanding earthquake prediction and possibly earthquake control. Success in this field has obvious societal relevance for the hundreds of millions of people that live in regions that are prone to large earthquakes. Earthquake prediction has long been an unreached goal in seismology. Understanding the process of triggering and inducing earthquakes is one of few promising paths toward prediction.

Using current technology to actually cause a moderate sized earthquake to happen, should catch the interest of people. This project could be a highlight in outreach activities to the public.

In addition, there would likely be public concern that this type of experiment could produce a large earthquake or tsunami that causes damage. This is the main reason that prohibits this type of experiment on land. A remote mid-ocean ridge site is an ideal location, since even large earthquakes (M7) do not cause any damage when they occur in the mid-ocean ridge region. Also, strike-slip transform faults would minimize the possibility of a tsunami.

## 7. Active Experiments

This proposal presents a new use of the drilling capabilities of the IODP platforms that can potentially produce exciting new science results. The mode of ‘Active Experiments’ is a new area of emphasis for IODP expeditions. There have been other proposed active experiments in the IODP programs (e.g. fluid pumping on the Juan de Fuca Ridge), however the present program has predominantly involved collecting cores and physical properties measurements, and more recently some emphasis on (passive) geophysical observatories. Designing and carrying out active experiments for targeted in situ geologic or biological environments, can lead to a variety of innovative directions for IODP.

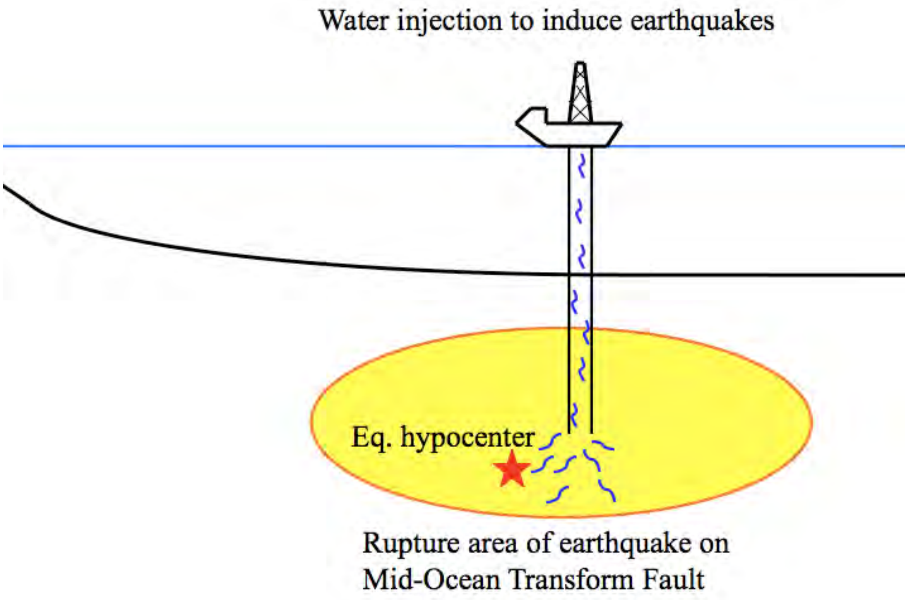


**Fig. III-5**. Schematic of water injection experiment to induce earthquakes.

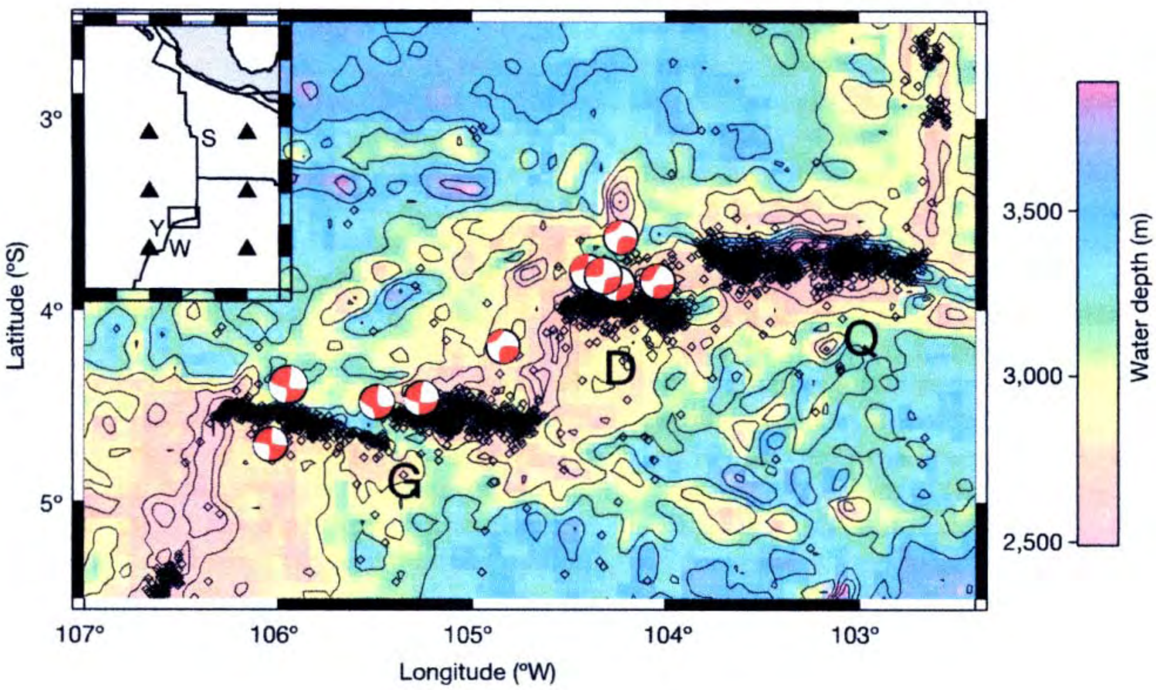


**Fig. III-6**. Seismicity near the on transform faults of the East Pacific Rise. (McGuire et al., 2005).

# iv. Exploration into unprecedented volcanic catastrophes in the ocean: *unveiling impact of gigantic caldera-forming eruption*

Japanese planning group for Geohazard science*[10]

**Abstract**

'Gigantic caldera-forming eruptions' that have repeatedly caused devastating damages to human society must be a target in the next phase of IODP, in order to contribute to geohazard mitigation along subduction plate boundaries. Particularly, very little is known on what happened during caldera-forming eruptions in the sea although not small numbers of such historic and pre-historic eruptions have been recorded. Ocean drilling will provide vital information on major controversial issues; (1) eruption sequence and variation of such catastrophic volcanic events, (2) recurrence history and predicted patterns for future events, and (3) nature of large silicic magmatic system, including physicochemical condition of magma chamber and structure of collapsed caldera. For approaching these issues, systematic/multiple drilling inside and outside caldera in the sea will be necessary by obtaining non-disturbed cores of submarine volcaniclastic deposits. Sedimentary records and inner structure of collapsed caldera detected by ocean drilling will renew our fundamental knowledge on 'volcanic catastrophe' and its origin. Condition and global impact of the past gigantic caldera-forming eruptions, which may have posed extreme environmental impacts on the earth-human system, should be unveiled and quantitatively evaluated to create mitigation and evacuation plans for future unprecedented volcanic catastrophe.

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## 1. Why 'gigantic caldera-forming eruption in the ocean'?

'Gigantic caldera-forming eruptions' are catastrophic volcanic events that pose one of the greatest natural hazards on earth. Such eruptions are the fundamental volcanic process in subduction zones, and many have occurred on deep/shallow submarine condition. Although they are infrequent events; once eruptions occurred, surrounding environment including human society will be severely damaged in both regional and global scale.

The 1883 Krakatau eruption in Indonesia is one of famous examples of gigantic caldera-forming eruptions, where a severe disaster was induced with 36,000 death tolls (Simkin and Fiske, 1983). In the 7.3 ka eruption at Kikai caldera, Japan, ancient human society was severely damaged by a pyroclastic flow and extensive ash-fall as recorded some archeological sites (Fig. III-7). Eruptions like the Krakatau and Kikai events, or much larger ones, are thought to have occurred many times in island arc volcanism. However, their eruption sequences, sizes, and impacts on oceanic environments have not been constrained due to lack of information about detail sedimentary records. Another noticeable example of catastrophic volcanic events is the 74 ka Toba eruption in Indonesia, which is the largest explosive eruption in the world during the past hundred thousand years. This eruption dispersed 2,800 $km^3$ of magma and may have caused the human population crash by widely spread volcanic ash, gases, and aerosols (e.g. Rampino and Ambrose, 2000; Oppenheimer, 2002). In general, such largest-scale eruptions are called as 'super-eruptions', in which major disruption of services and infrastructures that society depends upon can be expected for periods of months to years (e.g. Self, 2006); however, the process and impact of this type of volcanic events are still mostly problematic because on-land geological records are very limited.

Although our knowledge of gigantic caldera-forming eruptions has advanced in a past few decades, several issues remain poorly constrained. Some of them are as the followings: (1) **Sequence and variation of eruptive events** in oceanic environment, that result from transport process and timing of powerfully emitted volcanic material (ash-falls, pyroclastic flows, and noxious gases) and energy (air waves and tsunamis). They will be important for unveiling geohazard not only near source region but also in long-term global scale. (2) **Recurrence history** (frequency) of such catastrophic events and predicted patterns for future ones. (3) Nature of '**large silicic magmatic system**' beneath seafloor, including physicochemical condition of magma chamber and structure of collapsed caldera. The detail image of existing large silicic magmatic system will be essential for evaluating the evolutional history and future eruptive potential.

An important point is that eruption sequence and variation of the caldera-forming events in the ocean must be quite different from on-land ones because of involvement of *seawater* in the eruption processes. And, submarine deposits can avoid atmospheric erosion and alteration as on-land ones suffer; that is the *Ocean* plays a role in preserving original precise sedimentary records of past volcanic events. Furthermore, geophysical surveys, which are much easier than on-land by means of on board observation from the sea-surface, are great advantage in ocean researches. From these viewpoints, ocean drilling will allow to extend our knowledge on above issues, and to quantitatively evaluate the devastating volcanic impacts and hazards on human society.

Drilling targets for geohazard mitigation in the next phase of IODP should include submarine/marine calderas in the western Pacific region.

**2. Understanding sequence and variation of eruptive events**

Large-scale submarine volcanic events should be recorded as tephra layers in ocean floor sediments surrounding source calderas. Stratigraphy, components, and internal structures of submarine pyroclastic flows/fallout deposits will give constraints on transport processes and timing of powerfully emitted volcanic material and energy in near source region. They will become strong evidence for the sequence and variation of the eruption, and also become basic data to quantitatively evaluate regional geohazard near the caldera.

[*Pyroclastic flows*] Huge pyroclastic flows during explosive caldera-forming eruption would be those of the most destructive phenomena on earth. These flows emanate from collapsing eruptive columns above the volcanic vents. They are extremely hot, rapidly moving mixtures of gas and ash that hug the seafloor/sea-surface and travel even over a few hundred kilometers, laying down submarine/subaerial pyroclastic flow deposits. The nature of transport and sedimentation processes of volcanic materials, however, has remained unknown, and what happens when huge pyroclastic flows encounter seawater has been the subject to much speculation due to lack of systematic research on submarine pyroclastic flow deposits.

[*Tsunamis*] Submarine caldera-forming eruptions have potential to generate devastative tsunamis like the 1883 Krakatau eruptions. However, little has understood on their generation and propagation processes. Sedimentary records like 'homogenites' (Cita et al., 1983) derived from energetic tsunami passage and disturbance of seafloor sediments may have remained on ocean floor, which will be strong constraint for the timing and energy of tsunamis. Their sedimentary characteristics should be linked with source processes of volcanogenic tsunami and coastal hazard based on numerical simulation.

[*Explosive magma-water interaction*] In explosive submarine eruptions, fragmented magma experiences various transport media, such as volcanic gas, air, steam, and liquid seawater as well as changes in physical characteristics of magma itself during cooling. Interactions between magma and these transport media significantly affect eruption styles, and result in a number of distinguishing characteristics, including intense explosive jets, the production of anomalously fine-grained tephras, and the formation of base surges from collapsing fountains. Sedimentary characteristics of submarine deposits produced by the magma-water interaction may strongly reflect the powerful energy and material transport processes, which will be important clues for understanding evolution and dynamics of submarine gigantic caldera-forming eruptions.

For unveiling above issues, **systematic/multiple drilling** outside caldera is necessary (Fig. III-8). Three dimensional sedimentary structures of loose pumiceous deposits (volcaniclastic materials) must be extracted from '**non-disturbed**' cores. Sampling technique for such **'non-disturbed'** and **'high resolution'** cores is crucial to reconstruct detail eruption sequence. **Non-riser drilling (**in certain cases, **riser-drilling) technology** by **Chikyu** or **JOIDES Resolution** should be suitable for this research.

## 3. Unveiling recurrence history

On the basis of our present knowledge, many catastrophic caldera-forming events have occurred repeatedly from the past, and they should be recorded as tephra layers in ocean floor sediments. In order to construct predicted patterns for future events, we need to identify the 'recurrence history' from the sedimentary records.

For this purpose, discrimination and dating of each sedimentary layer by ocean drilling are crucial. Distribution and thickness of pyroclastic deposits is also important for limiting volume of erupted magma in each volcanic event. Combination of such sedimentological data with geochemical and geochronological studies (ex. biostratigraphy, paleomagnetics, and Ar-Ar or K-Ar dating techniques) will enable us to construct the predicted patterns of past to future volcanic events. 'Non-disturbed cores' obtained by systematic drilling are essential to reconstruct the precise event stratigraphy.

## 4. Challenge to get a perspective view of 'large silicic magmatic system'

'Large silicic magmatic system' existing along arc is a result from an evolutional process of subduction magmatism, and knowledge of that is essential to understand why and how gigantic caldera-forming eruptions occur there. A detail image of this system (from magma chamber to seafloor) will be a strong constraint on a caldera-forming eruption and its origin.

Firstly, the 3D structure of collapsed caldera, including developments of ring faults, dykes, intra-caldera deposits, and resurgent domes, is important to constrain eruption sequence such as burying (fall back) process during caldera formation and post volcanic activities like resurgent dome formation. Secondary, magma chamber depth and temperature gradient to seafloor is important to evaluate physical condition and pre-eruptive magmatic processes. In the case of Kikai caldera, Japan, the depth of magma chamber top is estimated to be about 3-4 km, based on mineralogical and geochemical studies (Saito et al., 2001). However, such data basically include much obscure, and no one has obtained a clear image of caldera structure and magma chamber yet.

For unveiling 'large silicic magmatic system', high resolution three dimensional caldera structures need to be imaged by **extensive acoustic and seismic surveys**. In general, it is very difficult for on-land calderas to obtain such geophysical data because installation sites of observatories and instruments are limited. In ocean researches, these geophysical surveys are much easier by means of on board observation from the sea-surface, as conducted at Sumisu caldera, Japan (Tani et al., 2008). This is a great advantage of IODP. Seismic surveys should be conducted by a series of single expeditions together with site surveys. The geophysical and geochemical data near magma chamber can be obtained by riser and **high temperature (600 - 900 °C) drilling technology** of **'Chikyu'**. Furthermore, time-series data of geochemical characteristics of samples will constrain the process of crustal magma chamber in subduction zone (Fig. III-8). This subject will be related to 'subduction zones and volcanic arc' in *Earth's Interior*.

## 5. Understanding global geohazard

Extreme explosiveness of caldera-forming eruptions is driven by a release of volcanic gases as silicic magma rises from a crustal magma chamber to the earth surface. More importantly, sulfur released into the stratosphere cause significant changes in atmospheric concentration of the gas and aerosol ($H_2SO_4$), which can be recorded in ice cores in polar region. The released sulfur during gigantic caldera-forming eruptions generates aerosol clouds of unprecedented opacity to solar radiation, which cause a long-term global geohazard called as ‘volcanic winter’.

This subject is also related to paleoenvironmental researches. Evaluation of total tephra volume by ocean drilling and geochemical constraints as changes of volatile concentration (S species, Cl, F, and Br) in erupted magma enables us to estimate the amount of volatile released during eruptions of the past. Studies with general atmospheric circulation models may be required to further evaluate the potential climatic effects and other feedbacks within global environment. The extreme global impacts have potential to be investigated under the linkage of IODP and ice-core drilling project in polar region (ex. ANDRILL and SHALDRILL).

## 6. Relevance and contribution to human society

‘Volcanic catastrophe’ is one significant cause of environmental and ecological fluctuation in the earth-human system. Detection and reconstruction of the past events will be crucial to find predicted patterns for future eruptions and consequent hazards. The results of simulation of a ‘volcanic catastrophe’, extracted from drilling data with numerical calculation, should be shown broadly to public people. Condition and global impact of such unprecedented volcanic events should be **highlighted in order to raise interest and educational outreach of the public**, as we have experienced at the Sumatran earthquake and tsunami disaster. On the basis of renewed knowledge obtained by IODP, we also should prepare mitigation and evacuation plans for a future event.

Exploring a large silicic magmatic system is economically important, in terms of tapping new resources like mineral deposits and geothermal energy. These goals and scientific results are expected to contribute human activity.

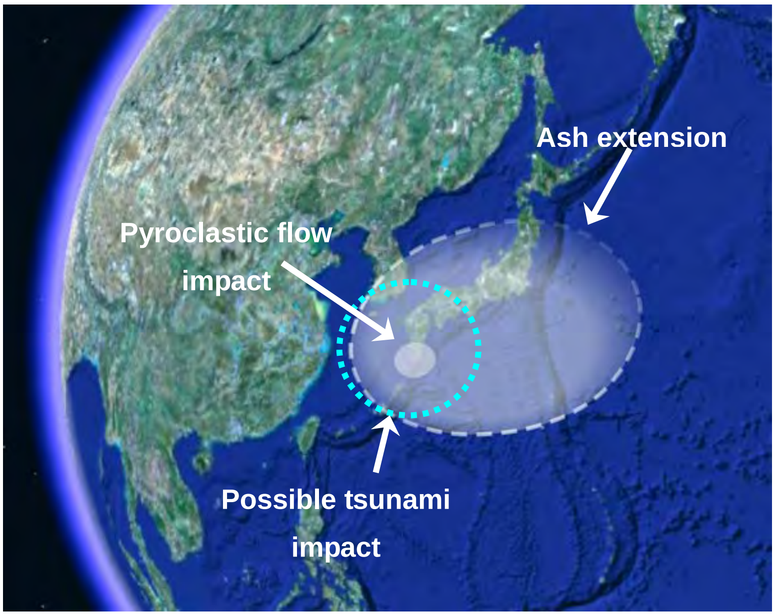


**Fig. III-7**. An example of the 'gigantic caldera-forming eruption'. This eruption occurred 7,300 years ago at Kikai caldera, Japan. Archeological records in southern Japan indicate this eruption have severely damaged to ancient human activities.

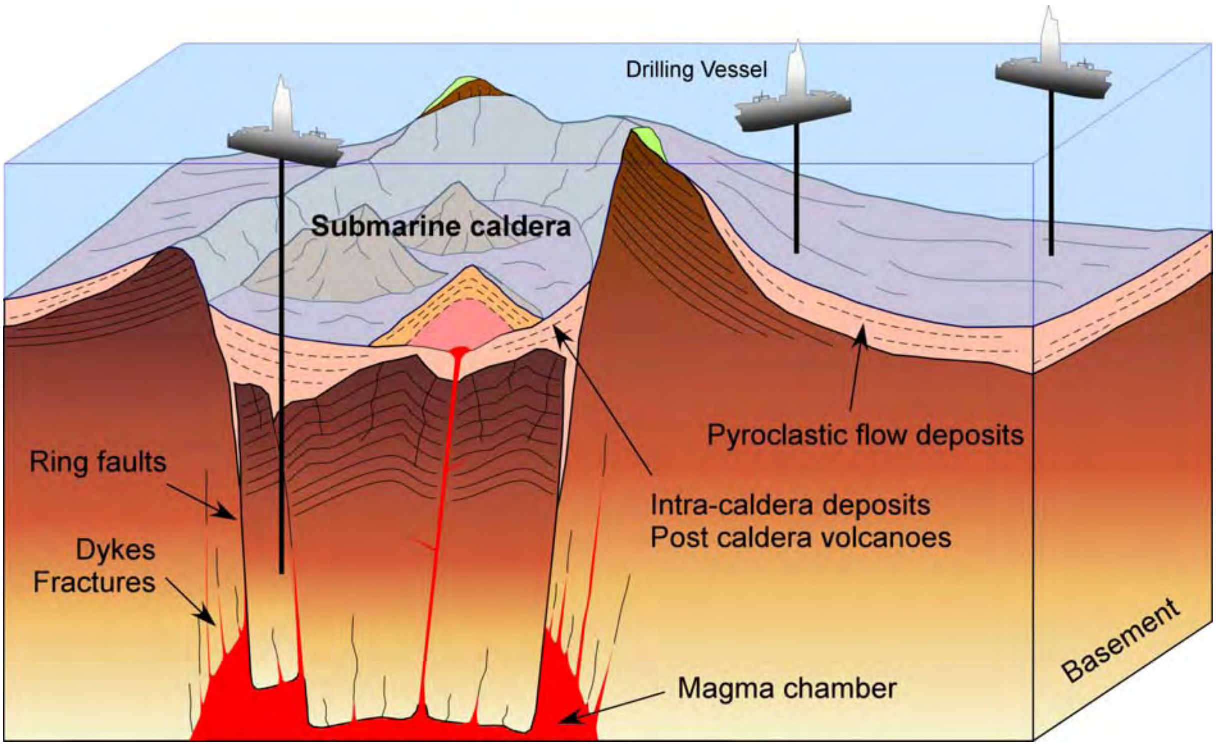


**Fig. III-8**. Idealized cross section of a large silicic magmatic system beneath ocean. Possible drilling sites are inside and outside caldera.

## v. Submarine landslides and mass movements

A submarine landslide team of The Japanese planning group
for Geohazard science at IODP*[11]

**Abstract**

The aim of this white paper is to decipher the fundamental formation processes of submarine landslides and mass movements (SLM) associated with earthquakes (and other reasons, e.g. gas hydrate melting, tectonic movements etc.). Our working hypothesis is that topography of slope, pore fluid pressure and physical properties of sediments are only three factors to generating the earthquake-related SLM. It means that all earthquake-related SLM do not need necessarily predefined weak planes before sliding. Materials of SLM before sliding include natural heterogeneity such as strata, discontinuities, and deformation structures. When the fluid pressure increases and exceeds the shear strength in sediments on account of earthquake shaking, consequently fluid migration increasing of pore fluid pressure beneath a low permeability layer, the materials slide along one of such surfaces if the slopes were just before gravitational instability. In this hypothesis, heterogeneity in sediments strongly constrains the very locality of the horizon of high fluid pressure and slip surfaces. The seismic vibration may also significantly reduce the cohesion along the surfaces and elicit weak planes as result. Topography of slope plays important roles in 1) shear force along the slip plane and 2) size of submarine landslides. This hypothesis may also be applied to additional mechanisms of submarine landslides to methane hydrate decomposition, sedimentation loading, erosion processes and so on, which are believed to be common elsewhere.

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## 1. Major hypothesis

[Pore fluid pressure, physical properties of sediments, and topography are only three factors to form submarine landslides]

Rock body that constitutes slopes includes discontinuity and heterogeneity (e.g. bedding, fracture and fault planes) without exception. If earthquakes occur, the existing discontinuity would be weakened due to liquefaction and/or redistribution of pore fluid derived from earthquake shaking. Increase of pore fluid pressure occurs decrease of frictional resistibility in the existing discontinuity. One of the existing discontinuities may be developed into a slip plane in the rock body, and consequently the rock body would slide gravitationally.

Kokusho and Takahashi (2008) proposed that if pore fluid pressure increases rapidly in the strata due to earthquakes or other triggers, pore fluid would concentrates beneath low permeability layers. In a horizon beneath the low permeability layer, the pore fluid pressure should increase drastically, and the horizon is linked each other to be a water film (Kokusho and Takahashi, 2008). The water film having high pore fluid pressure could be a slip plane of the submarine landslide. Thus, slip planes of submarine landslides are probably formed due to increase of pore fluid pressure.

The horizon of the water films is constrained by physical properties of sediments, particularly permeability of sediments. Location of low permeability layers decides the location of slip planes. Topography plays an important role in shear stress on the slip plane. Also topography is constrained size of the submarine landslides. Amount of gravitational unstable materials before sliding are dependent on strongly topography.

## 2. Major unanswered questions

What is a major trigger of submarine landslides?
What determine sizes of submarine landslides?
Where do submarine landslides occur?

These questions were discussed at the Geohazard Workshop 2007, in Oregon, but still not answered clearly.

## 3. Highest research priorities that can realistically be achieved in the next decade

A trigger (or triggering mechanism) each submarine landslide needs to be understood. Previous studies have proposed several triggering mechanisms to make submarine landslides, such as earthquakes, wave loading, tides, sedimentation, gas, loading due to glaciations, erosion and diapirs (Locat and Lee, 2002). Our hypothesis is “slip surfaces are initiated by increase in pore fluid pressure”. We want to understand how the pore fluid pressure responds to these triggering mechanisms by long-time monitoring of pore fluid pressure. We choose carefully monitoring horizons on the basis of slope stability analysis and/or computer simulation methods to seek candidates of slip planes. Weak planes in a rock body may be one of interests on monitoring. Long-time monitoring of pore fluid pressure using boreholes will bring answers to the hypothesis (see Fig. III-9).

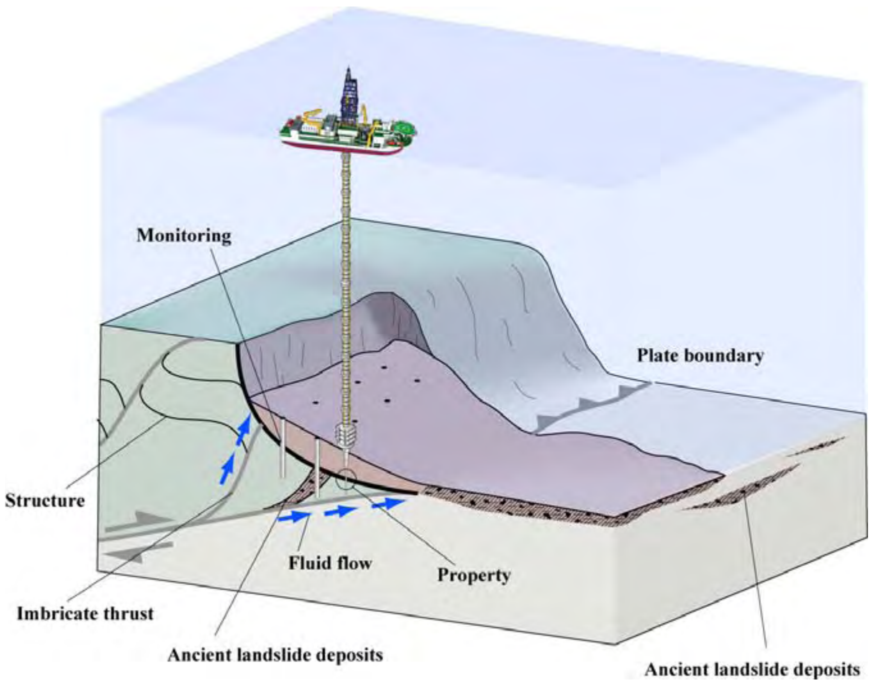


**Fig. III-9**. Deep-sea drilling and submarine landslides, at deformation front of an accretionary prism.

### 4. Drilling, sampling, experimental and site characterization strategies

In order to monitor the pore fluid pressure, we need to install sensitive pressure gauges and pressure-resistive tilt meters into boreholes. At some giant submarine landslides (Hawaii Island), target depths to set the tools may be deeper than 1000 mbsf.

Detailed site survey plays an important role in study about submarine landslides. The site survey data give us exact location of scarp of submarine landslides, depositional basin and its forms of mass movements. Since the Nankai region is the most well-studied subduction margin in the work and has finished 3-D seismic surveys, a number of single channel seismic surveys, series of drilled core studies, massive piston coring surveys, and systematic submersible surveys, this region should be the highest research priority area that can realistically be studied in the next decade. Despite the site survey is expensive and funding from the IODP and other organization is limited, we need many case studies including surrounding site survey dataset to understand mechanisms and processes of formation of submarine landslides.

Furthermore, the Nankai, Suruga, and Sagami troughs where repeats subduction great earthquakes historically, and accretionary prism is developed. Particularly Kanto region including Tokyo, metropolitan of Japan, has been attacked repeatedly by large earthquakes of M > 7.0. The balance between sediment accretion and surface landslide is important factor for accretion tectonics to keep prism shape in critical taper model (Davis, et al., 1983). Many submarine landslides are observed at toe of the Nankai and Boso accretionary prisms. If a basal fault of the landslide connect with the plate boundary fault, the landslide may happen concurrent with plate subduction earthquakes. The understanding of timing, structure and distribution of ancient landslide will contribute not only disaster evaluation but also accretion tectonics in plate subduction zone.

## 5. Platform and technological needs

In general, non riser drilling may work. In case of coastal submarine landslides, mission specific platform may be called for shallow water drilling.

## 6. Required expedition styles

A series of single expeditions in different regions is required for comparative study to understand basic mechanism of submarine landslides. Each expedition should consist of a series of drill holes at a large slide and surrounding smaller slides under the same geologic environments.

## 7. Interactions with other science programs and with industry

1) Submarine landslides play an important role in formation of tsunamis as shown in Fine et al (2005) and other studies. Around Japan, however most of the submarine landslides tend to be in small size, probably because small-scale slope failures have occurred frequently due to repeated earthquake shaking, thus tsunami may not have occurred by single submarine landslide. Submarine landslides, however, can enlarge the size of tsunami if their timing is synchronized with the ocean floor motion. Thus, we have to collaborate with research groups of tsunamigenic deposits on land and also groups of computer simulations.
2) Information between continents strongly depends on submarine cables (e.g. internet, e-mail, economic business, social security and so on) thus the cables are one of the basic infrastructures in our society. Submarine landslides have repeatedly broken submarine cable systems in several places. An earthquake of 26/Dec., 2006 in Taiwan (M =7.0 and M = 7.1) generated submarine slope failures and subsequent turbidity currents, broke submarine cable systems (Soh and Machiyama, 2007). In 1929, turbidity currents cut cables in Grand Bank, New foundland, after a slope failure triggered by a large earthquake M=7.2 (Heezen and Ewing, 1962). Protection of the submarine cable systems is of a highly demand for cable companies and governmental organizations, thus there is potential to collaborate with them.

## 8. Outreach and raising the public's interest

Answers of this question are same as the previous questions. In Japan, tsunamis caused by submarine landslides may have large impact, because our country has been damaged by large Tsunamis in the past. Nowadays we have mega cities, nuclear power plants, airports, and many structures in the coastal areas. Protection of such structures has high priority in disaster mitigation. Protection of submarine cable system is another topics of large impact. Our society significantly depends on submarine cables and conservation of benthic ecosystem is also important (see above).

## 9. Social Relevance

When we understand the basic mechanism of submarine landslides with our hypothesis, i size, timing and location of future possible submarine landslides could be assessed. These must be of high interests of the public.

We greatly appreciate Prof. Yujiro Ogawa for providing useful suggestions and comments.

# IV. Climatic Crisis Survival

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## 1. Changing Earth

### 1.1. Bio, Geo, Chemical Earth Evolution

On the basis of investigations of the primary mineralogy of ooids and early marine carbonate cements, the Phanerozoic has been divided into three time intervals of ‘aragonite seas’ and two time intervals of ‘calcite seas’ (Fig. IV-1). It was showed that these oscillations resulted from secular shifts in the Mg/Ca ratio of seawater generated by changes in the spreading rates of mid-ocean ridges. It is generally accepted that the carbonate mineralogy of marine calcifying taxa also showed secular variations during the Phanerozoic. A remarkable difference was indicated in the mode of calcification of reef builders and sediments between mid-Cretaceous platforms and Cenozoic reefs (Fig. IV-1). Cenozoic reefs abound with organisms whose calcification sites are within their bodies, such as corals, nongeniculate coralline algae and Halimeda. In contrast, mid-Cretaceous platforms contain abundant grains/sediments, such as ooids and microbialites, which were formed by chemical (?) precipitation and biotic extracellular calcification. Coccoliths of *Discoaster* species show the general trend toward less robust morphologies in the Cenozoic. Therefore, core samples from submerged shallow-water reefs/carbonate platforms as well as from deep-sea sediments are important data source to delineate secular variations and evolution of marine calcifying taxa and their causes, to clarify interrelationships between their physiology and ecology and climate changes and geologic events, and to provide good constraint on models for the global biogeochemical cycles.

### 1.2. Hydrosphere-cryosphere dynamics

#### *1.2.1. Western Pacific Warm Pool (WPWP)*

Reconstruction of the past changes of the Western Pacific Warm Pool (WPWP) is a key to understand the global climate dynamics since the region is characterized as high (> 28 degree C) annual mean sea surface temperature (SST). Distribution pattern of this water mass result from regional climate changes such as El Niño/Southern Oscillation. Indonesian Through Flow (ITF) in today's ocean is one of major components of global thromohaline circulation (Fig. IV-2). Furthermore, according to a simulation, a switch in ITF source water from the South Pacific to North Pacific waters might have led to a cooling of the Indian Ocean and then an increase in the aridity of Africa in the Pliocene around 4-5 Ma (Fig. IV-2). At the time, the North Pacific sediments were characterized by higher rate of biogenic opal precipitation due to higher nutrient availability by vigorous mixing with subsurface water. Then, the opal productivity suddenly decreased at 2.7 Ma, presumably caused by surface ocean stratification.

In order to reconstruct the paleoenvironmental history of the western equatorial Pacific, one can make use of coral and lake records. In the Republic of Palau, there are a number of meromictic marine lakes Mecherchar Jellyfish Lake (JFL). Some of these lakes are only 30-60 m deep and have been filled by seawater for at least 10,000 years, where the sedimentation rate is very high and the sediment composition changed from calcareous to siliceous components at the end of the Little Ice Age, when a drier and cooler climate was replaced by a warmer and wetter environment.

*1.2.2 Cenozoic bipolar cryospheric evolution*

For our comprehensive understanding of the climate changes during the Cenozoic Era, the roles of the Arctic Ocean should be clarified. The Atlantic/Arctic gateway situation to the Pacific must be refined for the understanding of the global climate change. Due to the proximity to the largest and coldest (during winter) continent in the world the Okhotsk Sea today produces and transports seasonal sea-ice to 44°N, the lowest latitude in the world (Fig. IV-3). The temporal variability in the formation of the North Pacific Intermediate Water (NPIW) must be understood and hence the Okhotsk Sea must be investigated. Since the presence of the Amur River in terms of supplying adequate freshwater plays a major role in the sea-ice formation we also need to investigate the land (river)-ocean linkage.

Understanding the history of ice volume variation and associated cryospheric changes during the Cenozoic is of very importance because ice-volume and distribution variations: (a) lead to changing global sea-levels, (b) affect Earth's albedo, (c) control the latitudinal gradient of the Southern Hemisphere and thus heat transport via atmospheric and oceanic circulation, and (d) influence the distribution of ice shelves and seasonal sea-ice. We recognize that efforts to understand the role of Antarctic drivers on global climate variability require a fundamental knowledge of Antarctic cryospheric evolution. The Southern Ocean drilling will enable us to delineate behavior of several major climate cycles and climate shifts such as Younger Dryas (YD)/Antarctic Cold Reversal (ACR), Dansgaard-Oeschger cycle, mid-Brunhes climate shift (~0.4Ma), late Miocene cooling, major Antarctic glaciation around the Oligocene/Miocene boundary (Mi-1 glaciation; ~24Ma), first ice sheet inception around the Eocene/Oligocene boundary (Oi-1 glaciation; ~34Ma). In particularly, we need to investigate the Antarctic cryospheric evolution in the Indian sector of the Southern Ocean which is significantly affected regions of the EAIS (East Antarctic Ice Sheet) variability.

1.3. Sea-level change

Sea-level change caused by the growth or decay of ice sheets is spatially variable because of the adjustment of the earth's surface to the time-dependent ice-water load and because of the changing gravitational potential of the earth-ocean-ice system. Observations of relative sea-level change therefore do not bear a simple relation to changes in ice volume, (or ice volume equivalent sea level) and at most localities corrections for glacio-hydro-isostasy are required. Even sea levels at ocean island sites are not immune from isostatic effects. Only in some special instances, where the separate isostatic responses to the changing water and ice loads fortuitously cancel out, will the relationship be relatively straight forward. Thus, in general, changes in ocean volume inferred from sea level data will be dependent on the models of glacio-hydro-isostasy and be functions of the spatial and temporal distribution of the ice load and on the rheological response of the Earth to surface loading. However, through an iterative approach, useful estimates of grounded and land-based ice volumes can be inferred from the sea-level data, particularly when the data is from sites that lie far from the former ice sheets so that the otherwise dominant glacio-isostatic term is relatively small (Fig. IV-4). Sites well suited for studying sea-level change during the LGM include the Arafura Sea and Timor Sea on the Australian margin. The margin is tectonically stable, as witnessed by the occurrence of Last Interglacial Shorelines (MIS; Marine Oxygen Isotope Stage -5e) near present-day sea level. Also, the continent lies far from the former ice sheets such that the isostatic corrections, due mainly to the hydro-isostatic effects, are small and not strongly dependent on the details of the ice-load geometry. Finally, there are wide and shallow shelf areas with depressions where conditions may have been favourable for the preservation of evidence for former and now submerged shoreline positions. This area will provide one of the few reliable estimates of sea level at the time of the LGM. The reconstructed sea level change can be strong constraints on the sophisticate climate models such as Atmospheric-Ocean coupled General Circulation Models.

1.4. Fluctuation of primary production in deep biosphere

During the evolution of life over the past 3.5 billion years or some more, ancient environment hosted primordial microbial life under anoxic and high-temperature conditions. These physical and chemical constraints spurred the adaptation and evolution of life forms during the earth's history (e.g., oxygen mass-production via photosynthesis). Previous scientific ocean drilling program has successfully revealed paleoenvironmental records related to drastic climate changes and geologic events during the earth's history. However, it is currently unknown how subseafloor life and the biosphere accommodate environmental changes via adaptive evolution and how they occupy ecological niches. Conducting scientific drilling to find modern proxies for past biosphere and ecosystem conditions is crucial, and hence it is highly recommended for the future IODP. To discriminate modern (living or surviving) and past (dead or fossilized) biological signatures from core materials, method development is in high demand, because genomic and proteomic progresses may provide decipherable records of evolutionary history. Moreover, the expanding knowledge in this sphere and simulation analysis promotes the understanding of both habitability and possible evolution of life forms on real other planets. This is an entirely new concept that has not been described in previous ISPs and is hence one of the challenges of the future IODP.

## 2. Future Earth ~Human Impact~

### 2.1. Ocean Acidification

Ocean acidification has become the biggest threat to calcifying marine organisms in recent years. Previous studies have reported that calcification rate of calcareous marine organisms (e.g., corals, foraminifers, coccolithophores, pteropods, mussels, and oysters) changes in response to lowering pH levels even waters oversaturated with respect to calcite. The rising level of partial pressure of carbon dioxides in seawater is making the world's oceans more acidic. The pH could drop from 8.15 at the pre-industrial 1800 through 8.06 at modern to 7.9 by the end of this century. Previous DSDP/ODP expeditions have provided lines of evidence indicating a contemporaneous carbonate dissolution event associated with sever ocean acidification across the Paleocene/Eocene boundary, which would have been triggered by massive dissociation of methane and subsequent elevation of atmospheric $pCO_2$ (Fig. IV-5). The carbonate sediments will buffer pH by dissolution of carbonate. However, deep (~>4 km) seafloor in the Pacific is covered with red clay sediments without carbonate, which is more affected by acidification, due to aragonite and/or calcite undersaturation by little chemical buffering and pressure effects. In 2nd phase of IODP, we would like to investigate the process and degree of ocean acidification in the past and buffering effect on pH by deep-sea carbonate dissolution, terrestrial weathering and others processes.

### 2.2. Ultra Greenhouse

Understanding the dynamics of Earth’s climate system during the extremely warm supergreenhouse period has been proposed as one of the major targets of the initial phase of the IODP. One of the most intriguing of the known supergreenhouse periods is the mid-Cretaceous. This kind of hot Earth can be attributed to high partial pressure of carbon dioxide in the atmosphere. During the past decades, intensive investigations of ocean drilling have revealed that the Cretaceous oceanic anoxia have prevailed over global ocean. Although the possible relationship between LIPs activities (“Forcing”) and black shale depositions and oceanic anoxia (“Response”) have been described in the initial phase of the Initial Science Plan, detail processes and causal mechanisms of these marked events have still been unanswered (Fig. IV-6). In particular, changes in the vertical profile of environmental setting in the ocean and seawater chemistry by the LIPs eruptions are largely unknown.

A typical feature of the greenhouse world is also characterized by latitudinal gradient of SST. Proxy records demonstrated that the equator-to-pole SST gradient was significantly lower during the Cretaceous than at present. Such a reduced meridional SST gradient would be attributed to the larger meridional heat transport by atmospheric and/or oceanic circulation. However, reconstructions of these circulation systems during the Cretaceous from direct evidence have been hampered by the lack of reliable proxies. It was once hypothesized that warm saline bottom water (WSBW) produced at low latitude conveyed noticeable heat from the equator to high latitudes. Although a certain amount of WSBW production in the equatorial Atlantic has been evidenced, it is widely accepted from model experiments that circulation of this WSBW would only have local effect at low latitudes and deep and/or bottom water in global ocean circulation would have been formed at high latitudes. Although most of paleoclimatic and paleoceanographic data have been obtained from the Atlantic Ocean, the record of the Pacific Ocean must provide us significant data sets for ocean-atmosphere dynamics in the greenhouse world. Because Pacific Ocean was the exclusively large and deep ocean on the Earth during the Cretaceous, it must have played major role on the formation of bottom water current and/so controlled the global oceanic circulation system. However, only a few drilling have been conducted in the Pacific compared to the Atlantic. Therefore, in the next phase of the Initial Science Plan, we should aim to reconstruct the variations of ocean-atmosphere circulation systems and clarify the detail process and causal mechanism of the environmental change in the Pacific Ocean at the interval of marked climatic transitions of the Cretaceous period in longer and/or shorter time-scales.

### 2.3. Environmental impact of catastrophic volcanic event

Gigantic caldera-forming eruptions of silicic magma on subduction zones have led to devastation of substantial regions by huge pyroclastic flows and tsunamis, as well as extensive ash-falls and injection of noxious gases into the atmosphere. While most recent work on gigantic caldera-forming eruptions is focused on on-land events, many Quaternary ones, including historical ones, have occurred in areas of shallow seas and still remain speculative and controversial, especially with respect to effects of seawater on eruption dynamics and evolution. Therefore future exploration by ocean drilling for submarine deposits of gigantic eruptions will provide superb opportunities for understanding mass of magma and gas emitted, runout properties of huge pyroclastic flows, generation mechanism of destructive tsunamis, and predicted patterns for future catastrophic eruptions.

According the archeological works around Japanese island, large scale of submarine eruption about 7 kyr. ago destroyed the primitive culture and affect terrestrial and marine environments in Kyushu Island, the southernmost island in Japan. Such large submarine volcanic events could be recorded in oceanic floor sediments surrounding source calderas. Distribution and thickness of pyroclastic flows/fallouts and their recurrence can be extracted from sediments detected by drilling outside and inside caldera. Detailed surveys of stratigraphy, components, and internal structures of submarine pyroclastic deposits will limit mass and volume of erupted magma, and enable to construct past volcanic events and predicted patterns for future explosive activities. They also provide opportunities for understanding sedimentation processes and runout properties of pyroclastic flows and magma-water interaction.

### 2.4. High resolution Holocene

The Holocene is a geological epoch, which started about a 11700 years ago and characterized by Human civilization and increase in anthropogenic activities. Holocene climate has been much more stable than that during the deglaciation and glacial periods. It is supported by no evidence of millennial-scale fluctuations in $\delta^{18}O$, methane concentrations, and snow accumulation in Greenland ice cores during the Holocene, except for a brief cooling about 8.2 cal. kyr B.P. However recent evidences from

Greenland ice core [O'Brien et al., 1995] and sediments retrieved from the northern North Atlantic [Bond et al., 1997] suggested that the climate during the Holocene has been punctuated by millennial-scale events. Bond et al. [2001] inferred that solar-induced atmospheric changes might be amplified and transmitted globally through North Atlantic thermohaline overturning. On the other hand, the mid-Holocene is well known for having a warmer climate than the present as is cited as Hypsithermal period (Holocene Climatic Optimum) around 5ka. Currently, it is important to increase our understanding of modern climatic variability and its socioeconomic impacts as a function of increased concentrations of greenhouse gases. Also interestingly these climatic chage in Holocene has made an impact on the population change and civilization. In Japanese islands, the population showed a large maximum at Holocene Climatic Optimum (an increase from 20 thousand people at 10 ka to 260 thousand at 50 ka). However, the temperature suddenly decreased at 4.2 ka, when the population definitely declined to 80 thousand people. The timing of the abandonment of living right is consistent with the timing (around 4.0–4.3 cal. kyr B.P.) of the decline of civilizations in north Mesopotamia and along the Yangtze River. We think it very important that IODP will drill into thick Holocene sediments near continental margin with high sedimentation rate to evaluate naturally-induced global warming and the rise/fall of the civilizations in the world in response to climatic change.

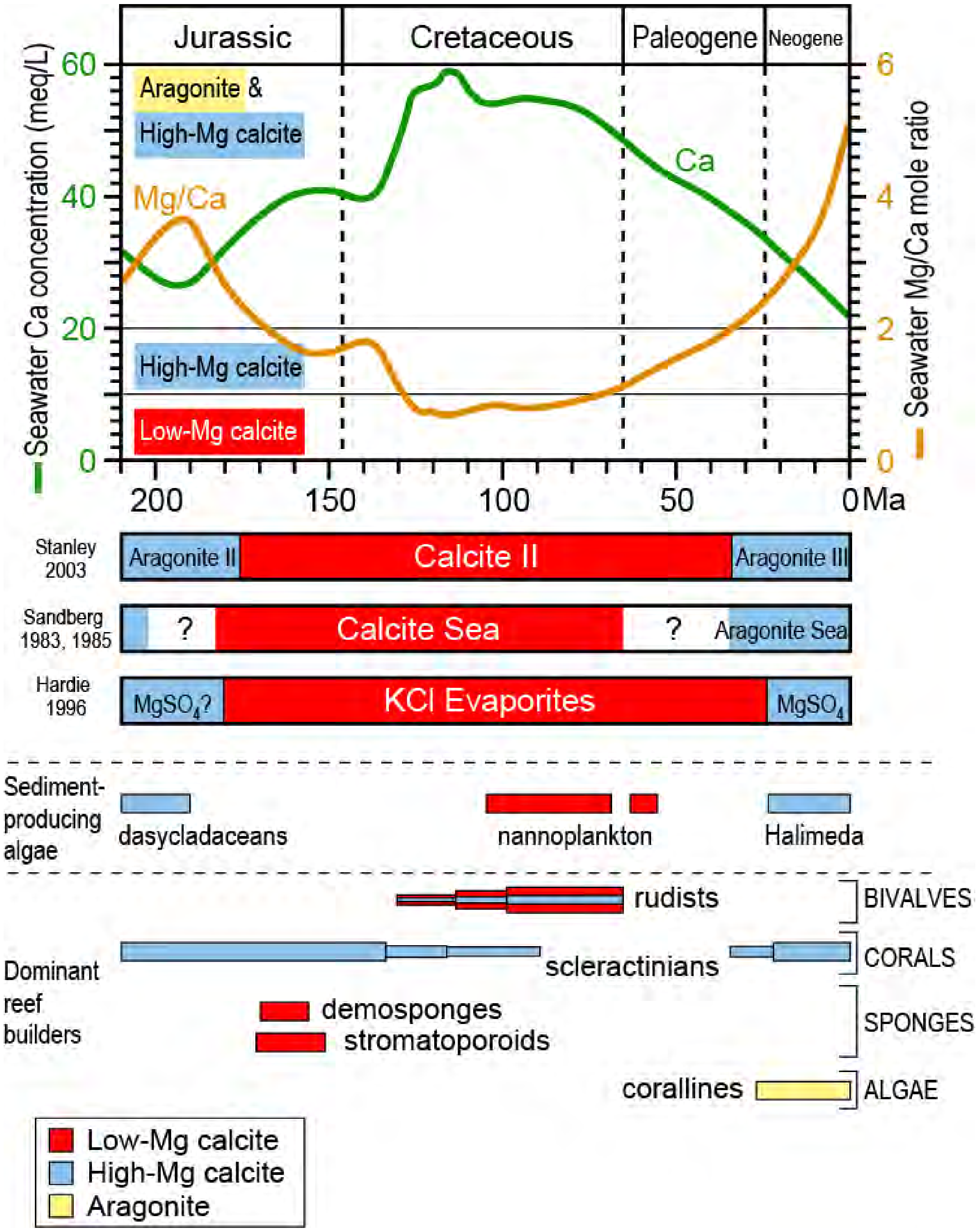


**Fig. IV-1**, Comparison of the temporal distribution of mineralogies for important hypercalcifying marine taxa and mineralogies for non-skeletal marine carbonates and evaporites. The upper diagram shows nucleation fields with respect the Mg/Ca molar ratio of seawater for low-Mg calcite, high-Mg calcite, and aragonite. Also shown are the temporal oscillations in the geologic record between calcitic and aragonitic non-skeletal carbonates and the temporal oscillations between KCl and $MgSO_4$ marine evaporites. Modified after Stanley 2006).

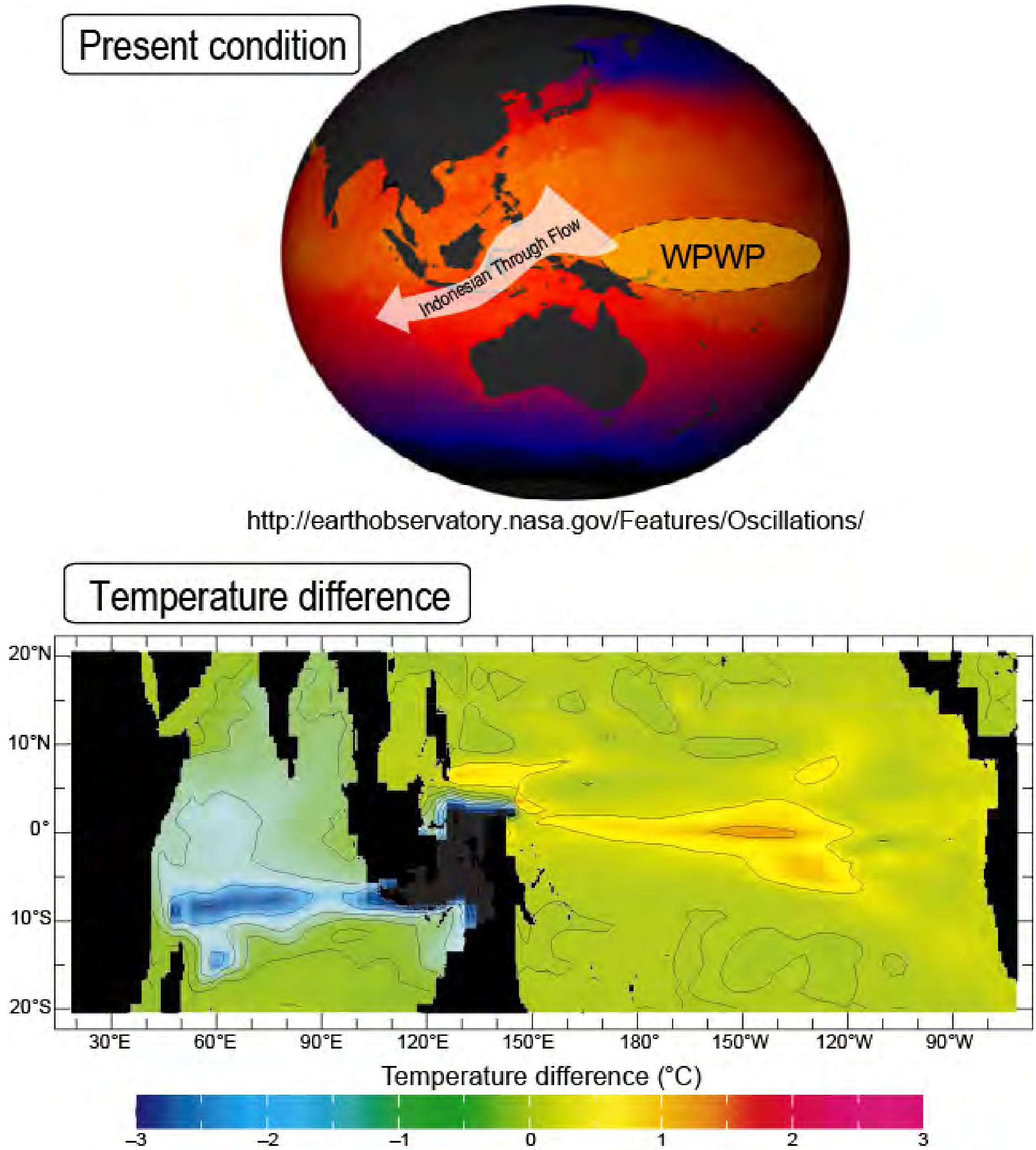


**Fig. IV-2**. Schematic image of Indonesian Through Flow and Western Pacific Warm Pool (WPWP) at the present ocean (top) and the difference in temperatures at 100 m depth between the two ocean GCM runs of Rodgers et al. (2000), which approximates the difference between that at present minus that at 4 Myr ago (after Cane and Molnar, 2001).

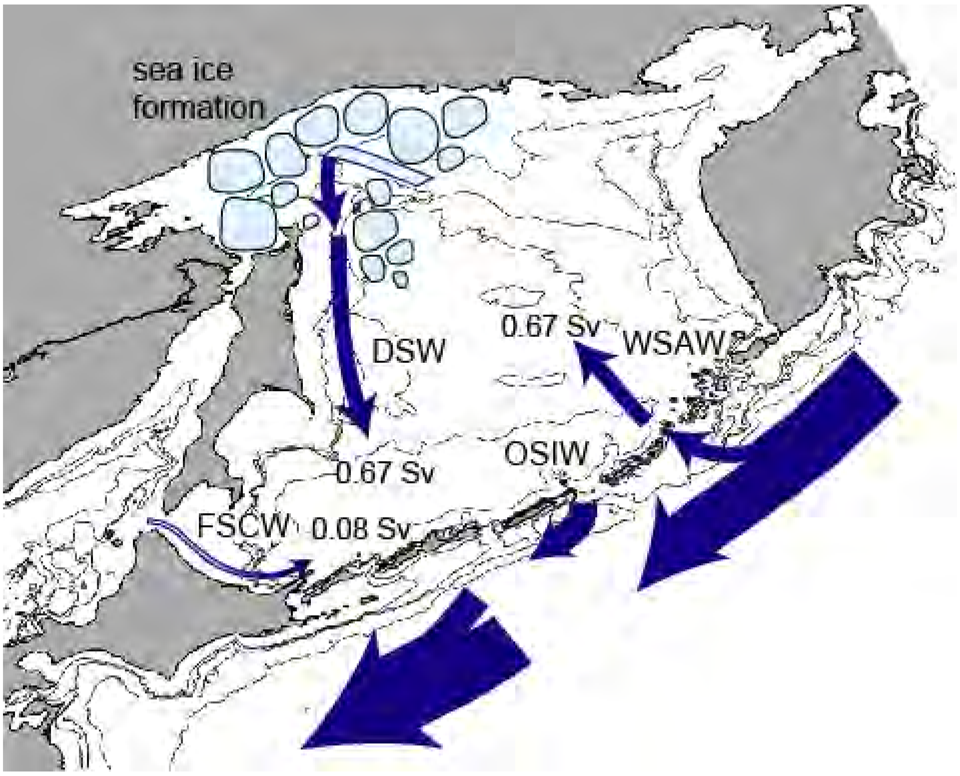


**Fig. IV-3**. Schematic illustration for the formation of Okhotsk Sea Intermediate Water (OSIW) after Itoh et al. (2003). Production rates and volume transports of Dense Shelf Water (DSW), Forerunner of Soya Warm Current Water (FSCW), Western Subarctic Water (WSAW), Okhotsk Sea Intermediate Water (OSIW), and Oyashio Intermediate Water (OYIW) are presented at densisies from 26.75 to 27.05 Sq. Line thicknesses are qualitatively related to the magnitude of the volume transports.

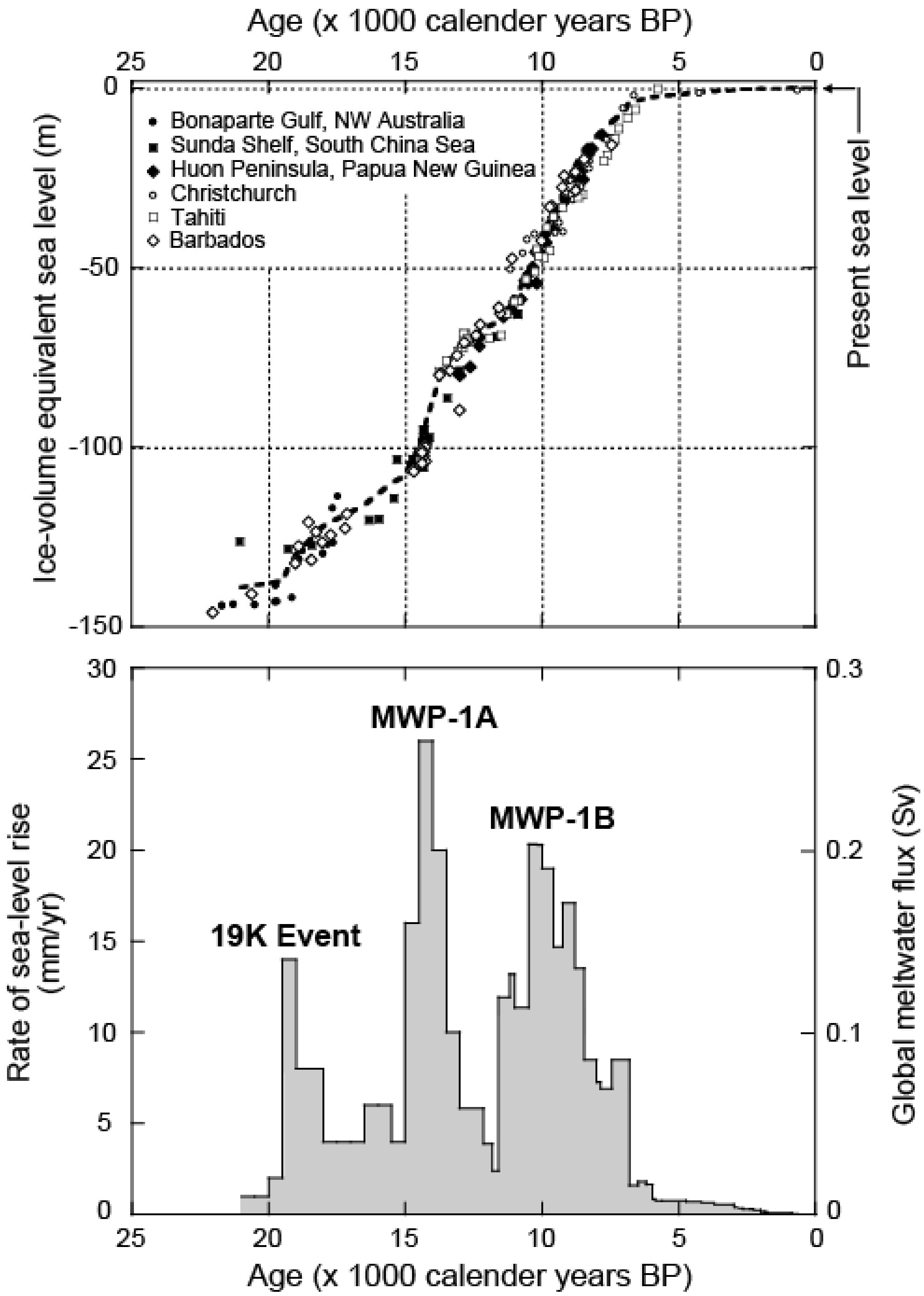


**Fig. IV-4** (top) Sea level change during the last 25,000 years. (bottom) 100-500 year averages of the rate of sea-level rise and global meltwater flux estimated based on the sea-level record. MWP, Meltwater Pulse. Modified after Ohkouchi (2008). Data are based on Fairbanks (1987), Chappell and Polach (1991), Bard et al. (1996), Yokoyama et al. (2000), Hanebuth et al. (2000).

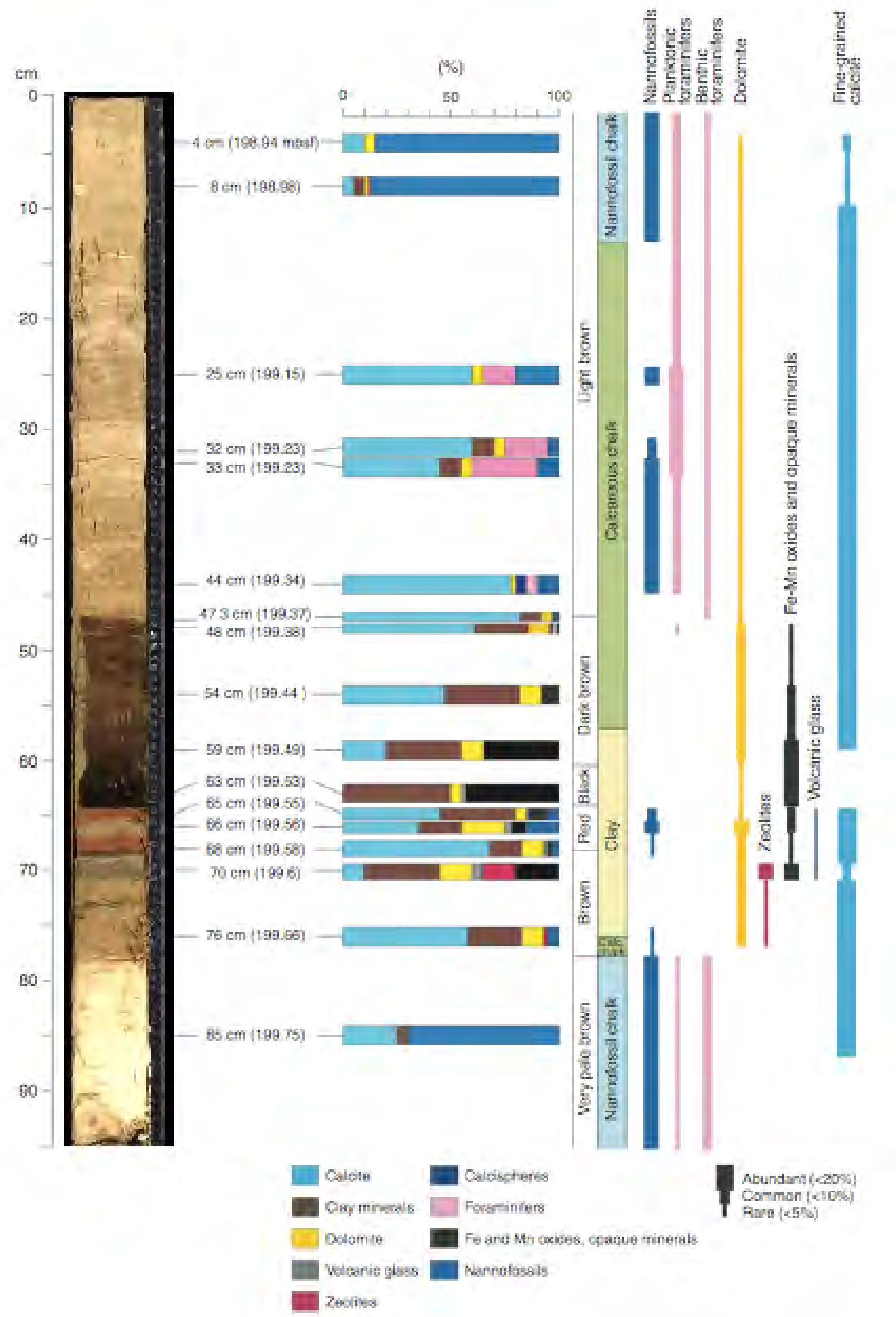

**Fig. IV-5**. Variation of sediment components (minerals and microfossils) in the Core 199-1120B-20X-2 recovered from equatorial Pacific (Leg 199). Note that the clay layer (63 cm) does not contain carbonate minerals and microfossils, suggesting ocean acidification. Shipboard Science Party (2002).

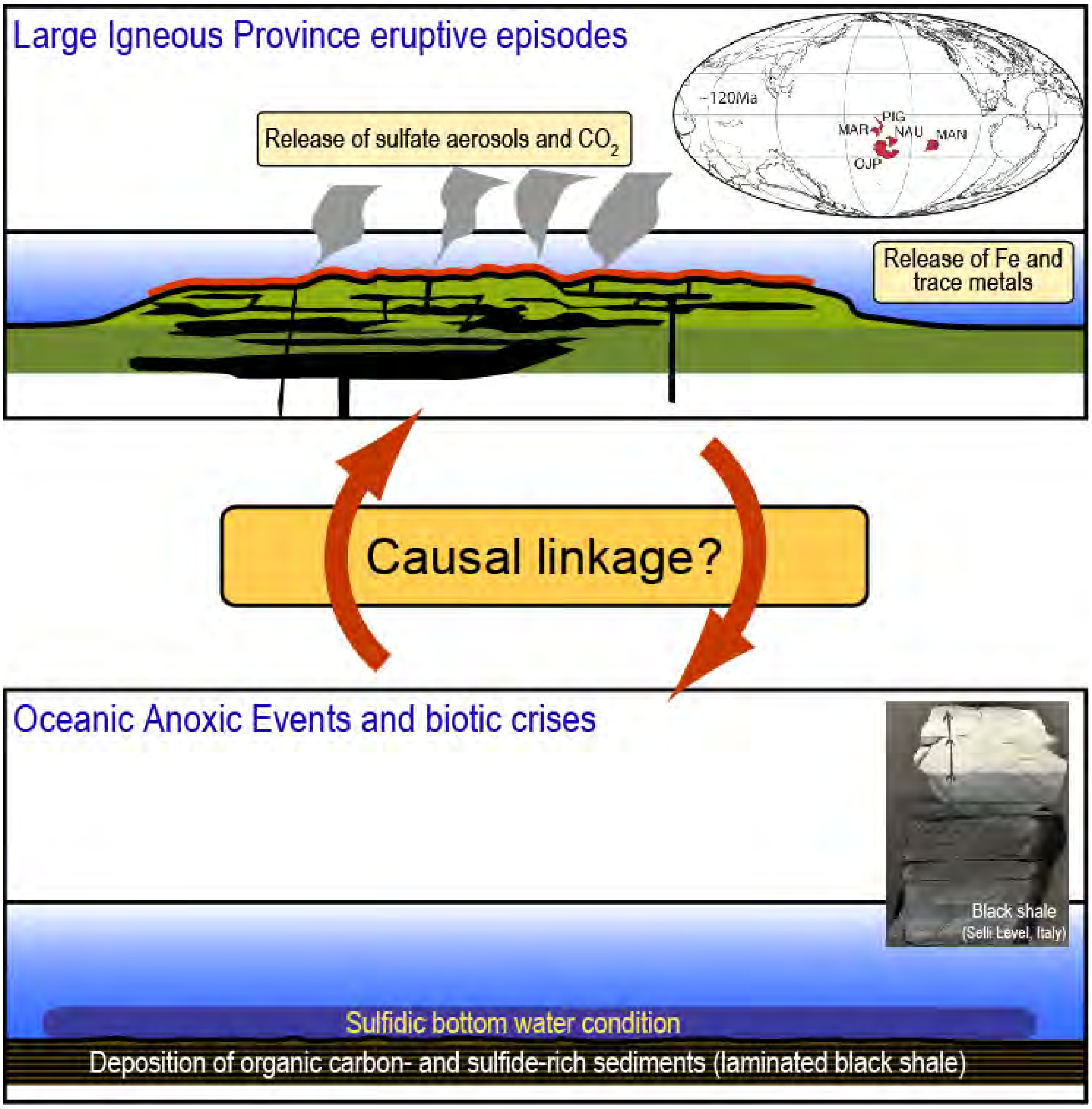


**Fig. IV-6**, Schematic images of the potential causal linkage between Large Igneous Province (LIP) eruptive episodes (top) and Oceanic Anoxic Events (bottom) during the middle of Cretaceous time. Paleogeographic reconstruction for for Ontong Java Plateau (OJP), Nauru (NAU), East Mariana (MAR), Pigafetta (PIG) basin flood basalts and Manihiki Plateau (MAN) formed during Aptian is after Eldholm and Coffin (2000).

# V. Science Implementation

## i. Technology Developments for beyond 2013 Ocean Drilling Program

Japan Domestic INVEST Workshop Technology Development Group*[13]

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### 1. Ultra deep drilling (Earth's Interior and Geohazard)

1.1 Earth's Interior: Mohole

As one of the important themes of Earth's Interior, Japanese scientists propose to reach to Moho as The "21st Century Mohole". It needs important technological breakthroughs:

(1) Great water-depth (<4500 m)

Records/plans of drill ship building and drilling in oil industry are designated in the Table below.

| Year | Water depth (m) | Drilling depth (m) | Drilling site or Drilling ship |
|---|---|---|---|
| 1999 | 3048 | 10668 | Transocean<br>Discoverer Enterprise |
| 2008 | 3051 | 3866 | GOM |
| 2009 | 3658 | 12192 | Transocean<br>Discoverer Clear Leader |

Riser and BOP technologies are most important elements for ultra deep water drilling.

Regarding the riser, the axial resonance of the riser with the heaving of the drill ship should be avoided in case of ultra deep water drilling. The steel riser has been used for "Transocean Discoverer Clear Leader" for 3658 m deep water drilling. However, composite risers such as CFRP (Carbon Fiber Reinforced Plastic) riser are indispensable for 4000 m and over 4000 m deep water drilling. In case of CFRP riser, the axial period decreases and the resonance can be avoided.

Electro Hydraulic Multiplex Control System (EH-MUX) for BOP reduces response time normally encountered with hydraulic control system, which is now used for drilling vessel "Chikyu" for 2500 m deep water drilling. EH-MUX was used for "Transocean Discoverer Clear Leader" for 3658 m deep water drilling. Upgraded EH-MUX for 4000 m and over 4000 m deep water drilling will be developed without much difficulty.

(2) Deep subbasement drilling using riser technology (drilling depth below rig floor <12000 m)

"Transocean Discoverer Clear Leader" has a drilling capability of 12,192 m, which means that the deep subbasement drilling using riser technology almost exists. In case deeper drilling than 12,192 m is required, technologies such as "Riserless Mud Recovery" for upper hole and "Expandable Casing" for lower holes will be utilized in order to reduce the casing strings.

(3) Improvement of core recovery (quality and quantity) at the target depth interval

It is not easy to accomplish both the deep drilling under hostile conditions and coring for the entire depth interval. The drilling and coring strategy should be determined with careful evaluation of geology and petrophysical properties, cost and risk evaluation.

(4) Drilling, coring and logging at high temperature (250-300°C)

One of the key technologies for high temperature drilling is cool technologies of the borehole. There is already a drilling/coring results in extremely high temperature of 540°C by TDS (Top-drive Drilling System) cooling method. Because high temperature drilling/coring strongly depends on petrological conditions, it is highly necessary to drill a pilot hole to obtain necessary information prior to drilling of the main hole, and decide drilling strategy including the technology development time schedule. LWD has more advantages in terms of temperature if we can use TDS cooling method.

(5) Possible deep gas

It is important to reduce drilling risk to obtain information on possible gas and gas pressure beforehand.

(6) Technology development under combined hostile conditions

These have to been done in multi-stage: As the 1st stage, each element technology have to be developed, then as the 2nd stage, technology has to be developed under combined hostile conditions (Figure 1).

1.2. Deep drilling to asperity/non-asperity

To reach and drill into the asperity/non-asperity areas, it is necessary to drill deeper than the current capability of "Chikyu" (water depth:<4000 m and drill depth <10000 m).

To achieve ultra deep drilling, we need to solve the following problems:

(a) Drilling under great water-depth (>4000 m)

(b) Improved riser system (riser material etc), BOP system etc under great water depth.

(c) Deep subbasement drilling using riser technology

We have to solve the Wild Cat problem, high temperature problem etc.

(d) Wild Cat problem

In practical drilling of IODP boreholes, unexpected technological problems, such as borehole stability, abnormal high/low pressure (=lost circulation, kick etc), high shear/fault activation, cavity, toxic gas/fluid, have appeared under complex/coupled harsh environments. It is common in IODP that no a prior information from neighboring borehole is available for determination of drilling program. One of the solutions to this problem is a drill of pilot hole to collect geological information.

(e) Deep Seismic Imaging

Integrated analysis of 3D seismic, wide angle seismic survey, VSP and logging can be effectively used to image deep structure. Passive (microseismic) mapping/reflection can also provide deep seismic image. Development of repeatable downhole seismic sources, which has capability to radiate sufficient energy to the formation under high temperature/pressure environment, would be of importance to realize reverse VSP or cross-hole seismic measurement. Downhole multi-component seismic array is one of the few methods to collect full information on the seismic wave. Progress in operation temperature/pressure, sensitivity, frequency range, coupling to the borehole, detectability of 3D motion of the seismic signals, deployment/retrievement techniques in IODP boreholes are required for downhole seismic passive/active imaging in IODP projects.

In Fig. V-3, conceptional view of shallow drillings for paleo-events, deep faults and active seismic experiments is shown.

## 2. Core Recovery and Core Quality (For all the themes)

Core recovery and core quality are fundamental needs to maximize IODP sciences. Although core recovery rate has been improved since DSDP/ODP era, there are still significant problems for the specific science targets and specific lithologies.

Degree of core recovery strongly depends on variable conditions such as depth, lithology, physical properties as well as coring tools. Even if average core recovery is good, science could not be achieved without enough core recovery from the critical intervals or specific rock-type. Examples of problems due to low/none core recovery are; a) chert or alternating beds of chert/shale, b) carbonates, c) poorly consolidated sand intercalated with mud, d) sand/gravel in high latitude ocean, e) hydrothermal deposits, f) basaltic lava and sheeted dyke complex, and g) fault zones. Investigations are required for coring technologies, including but not limited to, update of ADCB, MDCB, APC, XCB, and RCB. Prioritization of those coring technologies should be linked to the specific scientific demands.

Core recovery and core quality are fundamental needs to maximize IODP sciences. Although core recovery rate has been improved since DSDP/ODP era, there are still significant problems for the specific science targets and specific lithologies.

Core recovery is a complicated issue as there are many variables that interface and affect it (e.g., rpm, circulation rate, weight on bit [which is in turn affected by heave], torque, type of cutting shoe [for XCB coring system], any notable problems with the coring system [i.e., core catchers stuck open or check valves plugged, etc.], hole stability, and offset of the ship from where the hole was spudded [which changes the length of the drill string],amount of heave to name a few).

Extensive use of cuttings, side-wall cores, and logging is also important to complement the cores in case of low/no core recovery.

Core quality issues are also significant problems and are divided in to four categories: (1) core disturbance, (2) contaminations, (3) magnetic properties, and (4) core orientation. Enhanced core recovery and coring without disturbance should be considered for post 2013 ocean drilling program.

## 3. Monitoring and Observatory (Geohazard, Geochemistry and Microbiology)

### 3.1. Monitoring while drilling

As is shown in the Geohazard WS report (Morgan et al., 2009), development and application of certain *in situ* tools could greatly expand understanding of *in situ* pressures and stress state. Pore pressure can be measured with downhole tools or with instrumented boreholes such as Circulation Obviation Retrofit Kits (CORKs) in rather soft formation. For the hard formation, we have to develop new technologies, such as packer injection/fracturing test.

Vertical stress can be evaluated from density data. Meanwhile, horizontal stress has not been measured within DSDP/ODP/IODP projects. We already have several new ideas for the stress tensor determination, which do not rely on unreliable rock strength estimates.

Large-scale hydrologic tests can also help to up-scale the core measurements and small interval packer tests. These tests include injection tests, slug tests, and cross-borehole pressure tracer studies.

*In situ* geotechnical tools are used routinely in the geotechnical community and should become an integral part of IODP Geohazards investigations (Morgan et al., 2009). These tools have been applied mainly for soft formations. Incorporating these types of measurements into IODP operations in hard formations would increase the quality of petrophysical data of near-surface sections prone to failure.

### 3.2. Long term monitoring and borehole observatory

In the ODP period, mainly hydrological monitoring (Kastner et al., 2006) and ocean seismic observatories (Suyehiro et al., 2006) have been developed. In the IODP period, the LTBMS (Long Term Borehole Monitoring system), which enable us monitoring in deep riser boreholes, was developed by IODP SOC budget as the first attempt of ED proposal.

In the Phase 2 of IODP, several new ideas are proposed:

(1) Geochemical/microbiological monitoring
(2) Real time monitoring during active experiments for Geohazard
(3) Real time monitoring in/around the asperity and non asperity region of great earthquakes
(4) Construct seismic network for deep Earth structure

For the Earth structure studies, the following ideas are presented.

1) Seismic tomography with ambient noise to reveal the crust and upper-mantle structure beneath the Pacific Ocean around Japan.
2) Imaging of seismic discontinuities beneath an oceanic area (Moho, lithosphere-asthenosphere boundary, 410- and 660-km discontinuities, and the other unknown boundaries).
3) New seismic observations of core phases in oceanic areas.

For these purposes, the followings are necessary

(a) Deployment of the multi-boreholes or observatory array rather than an isolated borehole that is a representative for a global-scale configuration as proposed by the International Ocean Network (ION). (b) Broadband and high sensitivity seismometer should be installed in a hard basement, not a sediment layer.

Innovation in the data recovery must be considered.

Distribution and mobility of water along and across faults in broad time scale (e.g. interseismic, coseismic and postseismic) must play a significant role to control the fault properties, especially coefficient of friction. The mechanism of low frequency earthquakes in accretionary prisms may also be revealed by deformation analysis of core samples and geophysical monitoring. It is fundamental for revealing spatial variation of frictional parameters along the seismogenic zone to locate all of diverse kinds of slip events as precisely as possible. This requires development of stable, sensitive and long-term monitoring network of broad-band seismic and geodetic sensors. Sub-bottom sensor installation techniques developed by the ODP-IODP and long term borehole monitoring system (LTBMS) developed by IODP provide us with great opportunity to realize the network. The monitoring system for this sake should be composed of instruments distributed over wide area and those installed deep into the seismogenic zone.

Durability of the system under high temperature and high pressure must be realized for the monitoring. Because number of monitoring stations may be limited, multicomponent seismic monitoring can provide maximum information on the seismic wave. Reliable fixing mechanism of the seismometers to borehole is of importance. Distributed fiber-optical sensors, where fiber itself detects the seismic signals, have potential to realize widely distributed seismic monitoring network.

*In situ* monitoring system of 3D tectonic stress is of importance to interpret behavior of sesimogenic zones. Development of downhole tools for estimation of magnitude of 3D stress field will be highly appreciated. Downhole clinometers and strain meters can also provide information on dynamic behavior of the seismogenic zones.

Integration with on land/ seafloor data and collaboration with other community

To conduct these proposals, collaboration with the technical working group is crucial. Data integration, sharing the technical and scientific experiences with other community will help IODP borehole monitoring and observatory.

Data management

Open data policy and quick data distribution is inevitable to ensure the integration the IODP borehole observatory with other observatory system such as on land/ seafloor/global observatory system. The data format should be compatible with the standard, the system description/evaluation and calibration must be disclosed and the requests from the scientists must be appreciated to improve the system.

**4. Core/cuttings-log-seismic-monitoring integration (CCLSMI)**

CCLSMI is important for several reasons:

(1) Extensive use of cuttings, side-wall cores, and logging is also important to complement the cores in case of low/no core recovery.

(2) Because physical properties are scale dependent, we need to construct physical model from the analysis of core/cuttings-log-seismic-monitoring results.

**5. Site Surveys**

According to the Geohazard WS Report (Morgan et al., 2009), standard site surveys for geohazard objectives can provide two types of information:

(1) Definition of the geophysical, stratigraphic, and structural framework of the area capable of generating the Geohazard. Swath bathymetry and acoustic backscatter imagery are necessary to identify morphological features associated surficial depositsor subsurface structure (i.e., for placement of boreholes or observatories). Seismic reflection profiling, particularly in 3D, serves to constrain the internal structural and stratigraphic architecture of the region with which to interpret past events and their temporal and spatial distribution.

(2) Pinpointing the exact locations for future drilling and assessing what knowledge would be gained at each site. Information can be gleaned from high-resolution seafloor acoustic images coupled with 3D seismic reflection images to identify reflections and impedance contrasts that might indicate target horizons, fault traces, or fluid pathways. Submersible dives can provide detailed information at the proposed point of entry, including local fluid or heat flow data.

Pre-drilling monitoring of microearthquake, seafloor gradient/displacement, and temperature anomaly in near seafloor sediment would be also effective to pinpoint the target in Geohazard drilling. Related technologies for site surveys need higher resolution/reliability than currently existing ones to collect information on hazardous structure, such as extension and homogeneity of asperities, microscopic distribution and orientation of existing water saturated fractures, for successful Geohazard drilling.

In addition to these, we need to establish a strategy for deep imaging as described in 1. Ultra deep drilling (e) Deep Imaging section.

**6. New strategy for technology developments**

Technology developments will play more important role in the post 2013 ocean drilling program. The technology developments, especially those for “Chikyu” will be a key to accomplish IODP science, such as deep drilling under deep water depth and high temperature, and deep borehole observatory.

These technology developments should be accomplished by close collaboration between IOs, IODP SAS and scientists from the early stage.

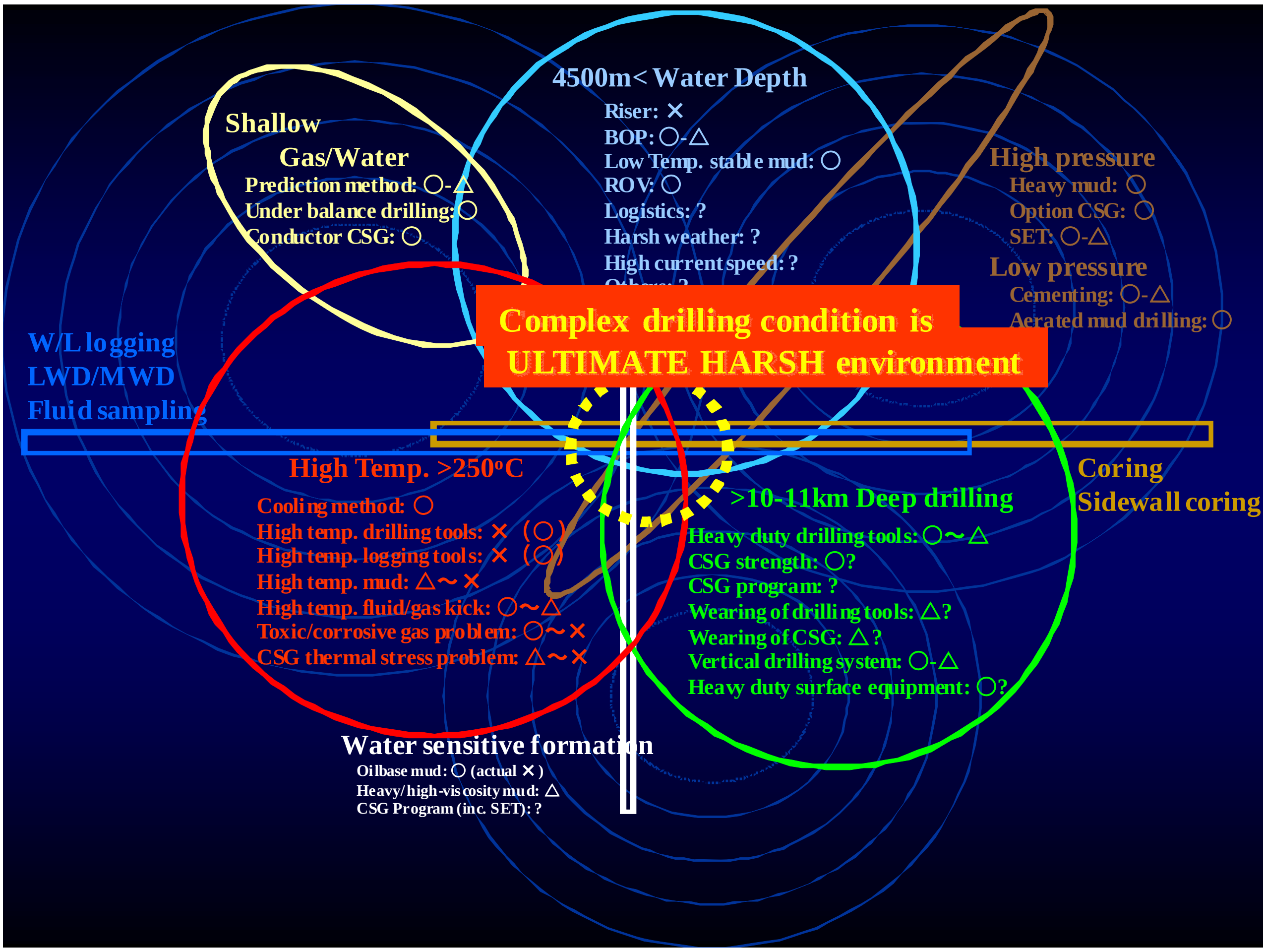


**Fig. V-1**. Drilling difficulty at complex harsh condition.
Each element technology has been developed/evaluated independently. Under complex harsh environment, performance will be reduced and unexpected problem may arise.

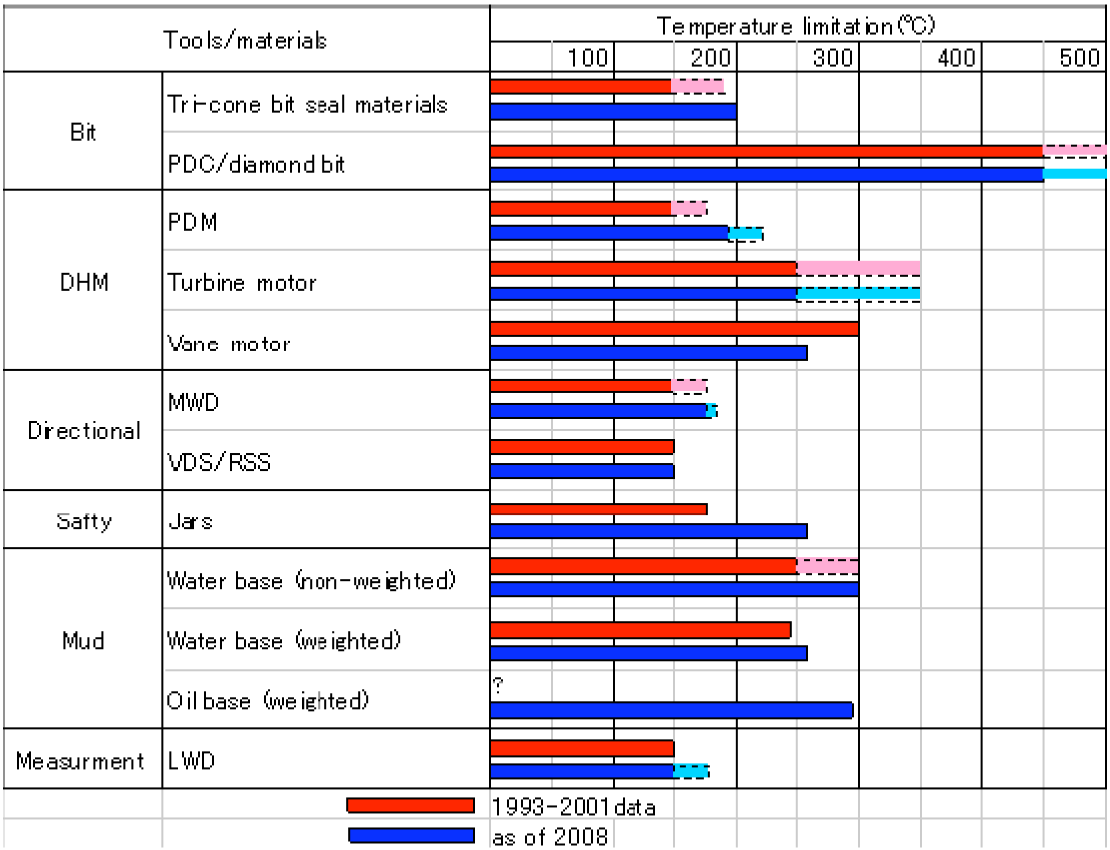


**Fig. V-2**. Temperature limitations of drilling.

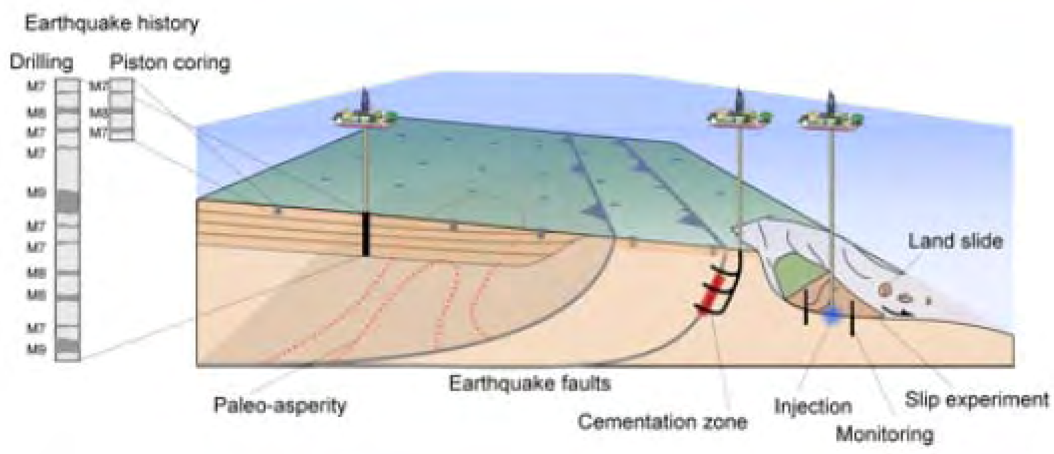


**Fig. V-3**. Conceptional view of shallow drillings for paleo-events, deep faults and active seismic experiments.

# ii. Strategy: Toward the new frontier of ocean drilling projects - needs of maximum utilization of platform capabilities to reach to the fundamental scientific goals

Executive committee of the IODP section, J-DESC*[14]

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## 1. Introduction

Previous efforts of the deep-sea drilling projects relied on generations of non-riser drilling platforms operated mainly by the USA and greatly extended our knowledge on plate tectonics, paleo-environmental changes, and deep biosphere. With initiation of IODP in 2003, the Japanese IODP community is honored to share equal responsibilities with the USA and European IODP communities to extend new frontier of the ocean drilling projects together with other membership countries. Three different types of drilling platforms are now available: riser/non-riser Chikyu, reformed JOIDES Resolution (JR: non-riser), and Mission Specific Platform(s). This provided the best opportunity human kind ever encountered to explore much deeper and wider scientific targets lying underneath the seafloor.

For the continuing effort to maximize the scientific achievements and for the success of the future IODP, effecteve utilization of capability of each drilling platform in a manner to maximize outcome is necessary. Especially, maximum utilization of riser drilling capability of Chikyu would be a key aspect to extend the frontier toward the deep oceanic crusts. Furthermore, future development of Chikyu riser capability at greater water depths would extend potential drilling targets to wider areas of the ocean. Nevertheless, we, Japanese IODP community, found some difficulties in developing riser drilling proposals in the current system. We suggest following four issues to be considered: 1) Chikyu is essentially built for ultra-deep drilling, 2) enhanced planning/support system, 3) needs of revised proposal evaluation/nurturing processes, and 4) let’s do it together.

## 2. Toward the new frontier of ocean drilling projects

### 2.1. Chikyu is essentially built for ultra-deep drilling

The distinctive function of Chikyu is riser drilling, which provides stable deep boreholes and sample recoveries in a closed system. Chikyu is the only available ship at current state of the IODP, that has potential to extend our knowledge to deeper part of the Earth’s crusts; MOHO discontinuities or deep seismogenic zones. There would be, however, a lot of potential use of the riser drilling even for shallow drilling proposals, especially for deep biosphere. We encourage any proposal to utilize the capability of riser drilling of Chikyu. Nevertheless, fundamental function and the most ambitious scientific target for Chikyu is obviously the recovery of samples from ever reachable depths of the Earth's crusts. We believe that the expectations of the taxpayers, our fundamental supporters, are also there.

### 2.2. Enhanced planning/support system

Site characterization for riser (ultra-deep) drilling requires specific data package including 3D or large-scale 2D multi-channel seismic reflection surveys, and it is almost impossible for most scientists to acquire the site survey data by their individual funding efforts. Thus, the next phase of the scientific ocean drilling program requires a new scheme for science planning with a structure of an enhanced support by the program so that we can accomplish science objectives using the multi-platforms more effectively. The requirement is the most urgent for riser (ultra-deep) drilling planning, and an early involvement of the Implementing Organization will be required.

### 2.3. Needs of revised proposal evaluation/nurturing processes.

JR, Chikyu and the Mission Specific Platforms have the most suitable scientific targets depending on the capability of each platform. Providing sufficient information on riser and non-riser capabilities (technology, advantages and limitations) to potential proponents is important at the beginning. To maximize the utility of each platform, we also believe in the necessity of multiple evaluation processes (or criteria): submitted proposals should be evaluated and nurtured in the most appropriate way for each platform.

### 2.4. Let's do it together

As long history of the ocean drilling programs has demonstrated, this worldwide community kept extending the frontier of earth sciences and produced numerous brilliant scientists. This is probably the best, or even unique example that showed how such international, united effort can produce fruitful scientific achievements. So, let's do promote ourselves together. To continue the successful ocean drilling sciences, we believe that we need to promote most ambitious proposals that maximize the utilities of each platform. Japanese IODP community needs your help, as much as you need ours. May the future IODP scientists be good rivals of the past ocean drilling scientists!

Table V-1. List of proposed riser drilling sites in this white paper.

| | Drilling Site | Drilling Theme |
|---|---|---|
| 1 | Around ODP Site 1256 (Costa Rica) | 21st Century Mohole, Deep Biosphere and Subseafloor Aquifers |
| 2 | The east of north Hawaiian arch | |
| 3 | The eastern Pacific plate off Mexico | |
| 4 | Kikai caldera | Mega-Volcanic Eruptions |
| 5 | Asperity zone along the Pacific cost of Japan | Megathrust Earthquakes, Long-Term Monitoring |
| 6 | Juan de Fuca Ridge | |
| 7 | East Pacific Rise | |
| 8 | Lau Basin | Deep Biosphere and Subseafloor Aquifers |
| 9 | Nankai Trough | |
| 10 | Mariana Forearc | |
| 11 | Indian Ocean | |
| 12 | Mid Atlantic Ridge | |
| 13 | Okinawa Trough | |
| 14 | northwestern Pacific off the Shimokita Peninsula of Japan | |
| 15 | Gulf of Mexico | |

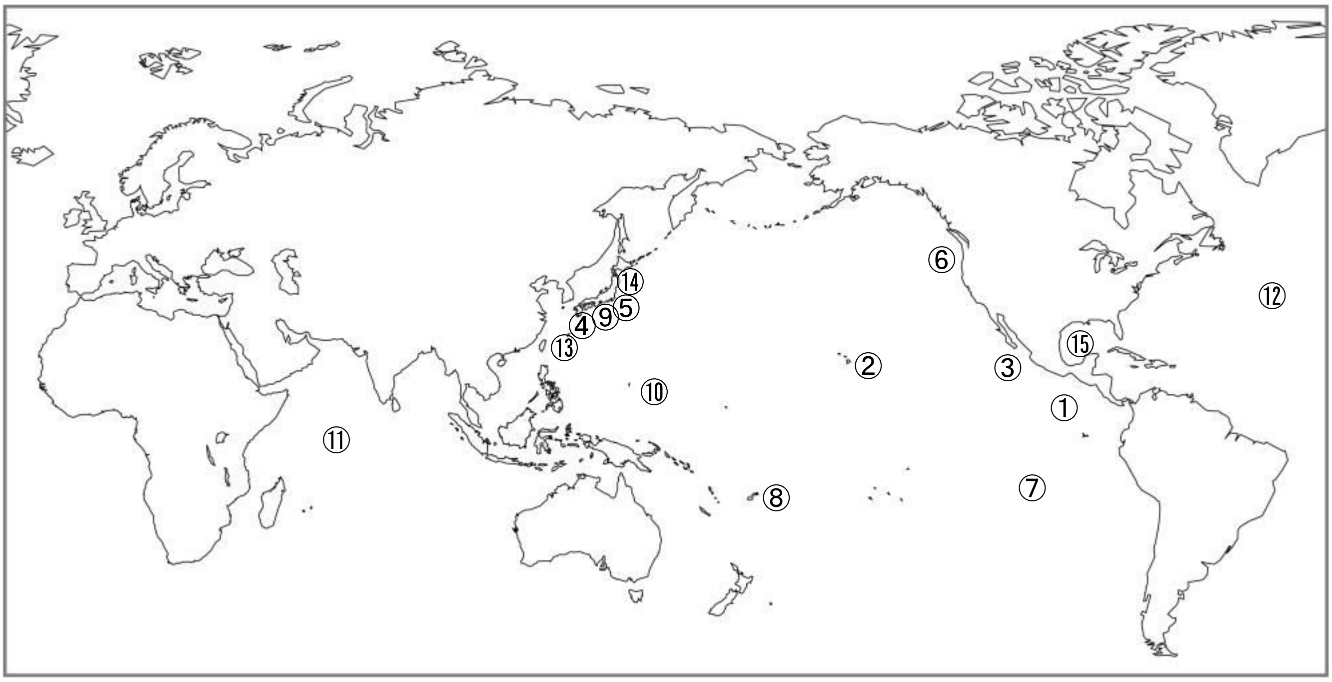


**Fig. V-4**. Map showing proposed riser drilling sites in this white paper. See Table V-I for each site name.

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| KUMAGAI | Hidenori | JAMSTEC |
| KURAMOTO | Shinichi | JAMSTEC |
| KUROYANAGI | Azumi | Ocean Research Institute, University of Tokyo |
| KYO | Masanori | JAMSTEC |
| MACHI | Sumiaki | Kanazawa University |
| MACHIDA | Shiki | Ocean Research Institute, University of Tokyo |
| MACHIYAMA | Hideaki | JAMSTEC |
| MASAGO | Hideki | JAMSTEC |
| MATSUMOTO | Ryo | University of Tokyo |
| MATSUMOTO | Takeshi | University of the Ryukyus |
| MATSUURA | Fumihiro | University of Tokyo |
| MISAWA | Ayanori | Ocean Research Institute, University of Tokyo |
| MITSUI | Yuta | Kyoto University |
| MIYAHARA | Hiroko | University of Tokyo |
| MIYAIRI | Makoto | SK Engineering Co., Ltd |
| MIYAKAWA | Ayumu | Kyoto University |
| MIYASHITA | Sumio | Niigata University |
| MIYAZAKI | Tsuyoshi | JAMSTEC |
| MOCHIZUKI | Kimihiro | Earthquake Research Institute, University of Tokyo |
| MOCHIZUKI | Nobutatsu | AIST |
| MOE | Kyaw Thu | JAMSTEC |
| MORI | James Jiro | Disaster Preventaiton Research Institute, Kyoto University |
| MORISHITA | Tomoaki | Kanazawa University |
| MORIYA | Kazuyoshi | Waseda University |
| MORONO | Yuki | JAMSTEC |
| MOTOYAMA | Isao | University of Tsukuba |
| MUTA | Kunihiro | JAMSTEC |
| NAGAHAMA | Hiroyuki | Tohoku University |
| NAKANISHI | Ichiro | Kyoto University |
| NAKATANI | Masao | Earthquake Research Institute, University of Tokyo |
| NAMEGAYA | Yuichi | AIST |
| NARAOKA | Hiroshi | Kyushu University |
| NARUSE | Hajime | Chiba University |
| NIIDA | Kiyoaki | Hokkaido University |
| NOMAKI | Hidetaka | JAMSTEC |
| NUNOURA | Takuro | JAMSTEC |
| OBANA | Koichiro | JAMSTEC |
| ODA | Hirokuni | AIST |
| OHARA | Yasuhiko | Japan Coast Guard |
| OIWANE | Hisashi | Ocean Research Institute, University of Tokyo |

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| OKAZAKI | Yusuke | JAMSTEC |
| OKINO | Kyoko | Ocean Research Institute, University of Tokyo |
| OKOCHI | Naohiko | JAMSTEC |
| OMURA | Kentaro | National Research Institute for Earth Science and Disaster Prevention |
| OSAWA | Osamu | Schlumberger K.K. |
| OTSUKA | Hironori | Ocean Research Institute, University of Tokyo |
| PAKU | Jin-Oh | Ocean Research Institute, University of Tokyo |
| SAITO | Satoshi | JAMSTEC |
| SAKAGUCHI | Arito | JAMSTEC |
| SAKAMOTO | Tatsuhiko | JAMSTEC |
| SAKUMA | Sumio | Geothermal Engineering Co., Ltd |
| SANADA | Yoshinori | JAMSTEC |
| SANO | Takashi | National Museum of Nature and Science |
| SANO | Yuji | Ocean Research Institute, University of Tokyo |
| SATO | Hiroaki | Kobe University |
| SATO | Hiroshi | Senshu University |
| SATO | Toshinori | Chiba University |
| SAWADA | Ikuo | JAMSTEC |
| SAWADA | Ken | Hokkaido University |
| SHIBATA | Satoshi | Yokohama National University |
| SHIMA | Nobukazu | Kobe University |
| SHIMIZU | Kenji | JAMSTEC |
| SHITO | Azusa | JAMSTEC |
| SHUKUNO | Hiroshi | JAMSTEC |
| SUETSUGU | Daisuke | JAMSTEC |
| SUGANUMA | Yusuke | Ocean Research Institute, University of Tokyo |
| SUNAMURA | Michinari | University of Tokyo |
| SUTO | Itsuki | Nagoya University |
| SUYEHIRO | Kiyoshi | JAMSTEC |
| SUZUKI | Atsushi | AIST |
| SUZUKI | Katsuhiko | JAMSTEC |
| SUZUKI | Noritoshi | Tohoku University |
| TADA | Ryuji | University of Tokyo |
| TAIRA | Asahiko | JAMSTEC |
| TAKAGAWA | Shinichi | Institute of Industrial Science, University of Tokyo |
| TAKAHASHI | Futoshi | Tokyo Institute of Technology |
| TAKAHASHI | Kozo | Kyushu University |
| TAKAHASHI | Kyoma | JAMSTEC |
| TAKAHASHI | Yoshio | Hiroshima University |
| TAKAI | Ken | JAMSTEC |
| TAKANO | Yoshinori | JAMSTEC |
| TAKASHIMA | Reishi | Hokkaido University |
| TAKAZAWA | Eiichi | Niigata University |
| TAKENAWA | Keiji | JAMSTEC |
| TAKEUCHI | Nozomu | Earthquake Research Institute, University of Tokyo |
| TAMURA | Akihiro | Kanazawa University |

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| TAMURA | Hajimu | JAMSTEC |
| TAMURA | Yoshihiko | JAMSTEC |
| TANAKA | Mitsuru | University of Tokyo |
| TANI | Kenichiro | JAMSTEC |
| TANIKAWA | Wataru | JAMSTEC |
| TANIOKA | Kei | Ocean Research Institute University of Tokyo |
| TATSUMI | Yoshiyuki | JAMSTEC |
| TO | Akiko | JAMSTEC |
| TOCZKO | Sean Treacy | JAMSTEC |
| TOKI | Tomohiro | University of the Ryukyus |
| TOMARU | Hitoshi | Kitami Institute of Technology |
| TONAI | Satoshi | Ocean Research Institute, University of Tokyo |
| TOTANI | Yoko | MEXT |
| TSUJI | Takeshi | Kyoto University |
| UEDA | Akira | Kyoto University |
| UMETSU | Keita | AESTO/J-DESC office |
| URABE | Tetsuro | University of Tokyo |
| WADA | Kazuyasu | JAMSTEC |
| WATANABE | Tsuyoshi | Hokkaido University |
| WATANABE | Yoshiyasu | Tokai University |
| YABUTA | Hikaru | Osaka University |
| YAMAGUCHI | Kosei | Toho University |
| YAMAGUCHI | Tatsuhiko | Nagoya University |
| YAMAGUCHI | Yasuhiko | Ocean Research Institute, University of Tokyo |
| YAMAMOTO | Masanobu | Hokkaido University |
| YAMAMOTO | Shinya | Institute of Low Temperature Science Hokkaido University |
| YAMAMOTO | Yuji | Center for Advanced Marine Core Research, Kochi University |
| YAMAMOTO | Yuzuru | Kyoto University |
| YAMANAKA | Toshiro | Okayama University |
| YAMAOKA | Kyoko | Ocean Research Institute, University of Tokyo |
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