Building a Scientific Understanding of Geohazards:
'Exploration into catastrophic earthquakes'
#2: Approaches from integration of drilling, monitoring, and numerical modeling

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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.

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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. 1) [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. 2) 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. 2). 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.

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Hisao Ito	JAMSTEC
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Masao Iwai	Kochi University
Koichiro Obana	JAMSTEC
Kyuichi Kanagawa	Chiba University
Toshiya Kanamatsu	JAMSTEC
Yasuyuki Kano	Kyoto University
Aitaro Kato	University of Tokyo
Naoyuki Kato	University of Tokyo
Kiichiro Kawamura	Fukada Geological Institute
Yukari Kido	JAMSTEC
Masataka Kinoshita	JAMSTEC
Reiji Kobayashi	Kagoshima University
Shuichi Kodaira	JAMSTEC
Weiren Lin	JAMSTEC
Fukashi Maeno	University of Tokyo
Yuta Mitsui	Kyoto University
Ayumu Miyakawa	Kyoto University
Kimihiro Mochizuki	University of Tokyo
Jim Mori	Kyoto University
Hiroyuki Nagahama	Tohoku University
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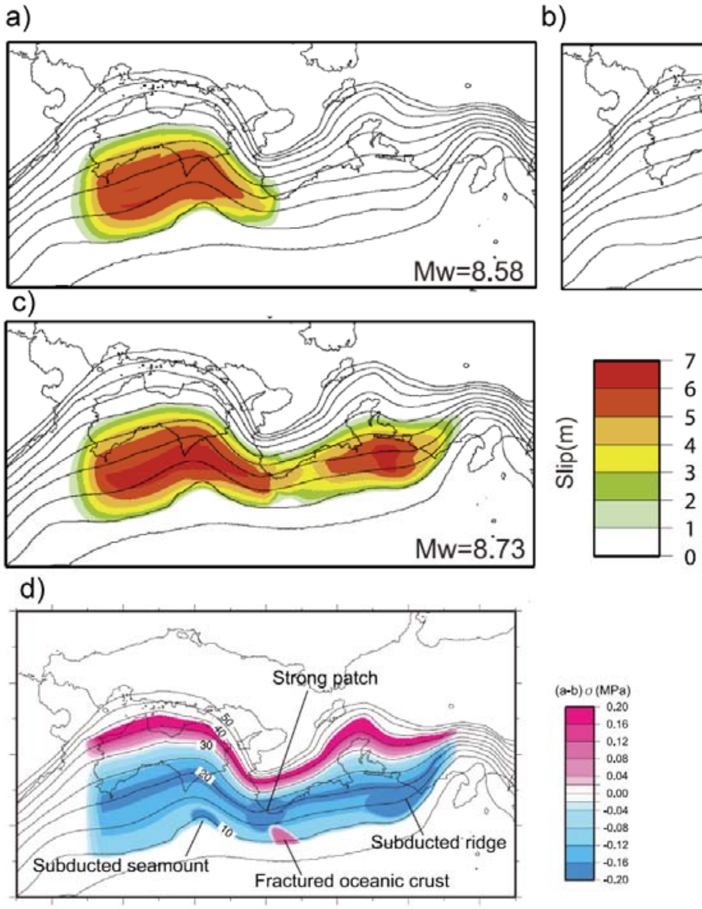

Figure 1. Simulated earthquake history along the Nankai Trough, Japan [Kodaira et al., 2006. Independent ruptures of a single asperity (a and b) and simultaneous failures of asperities (c) appears in the simulated earthquake cycle. In the simulation, heterogeneous distribution of frictional parameters is given to the plate boundary (d).

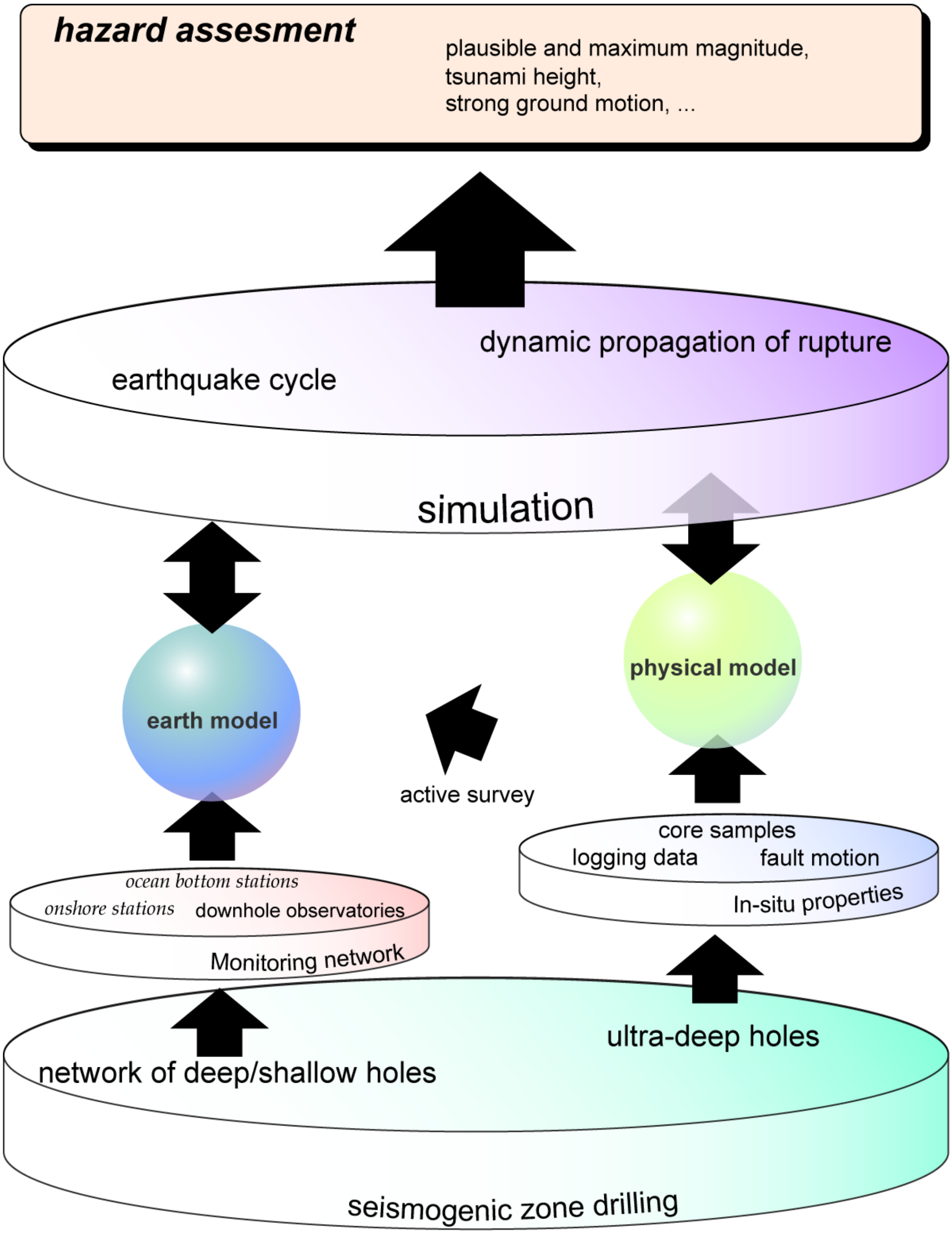

Figure 2. Strategy of IODP for scientific understanding of earthquake geohazards.

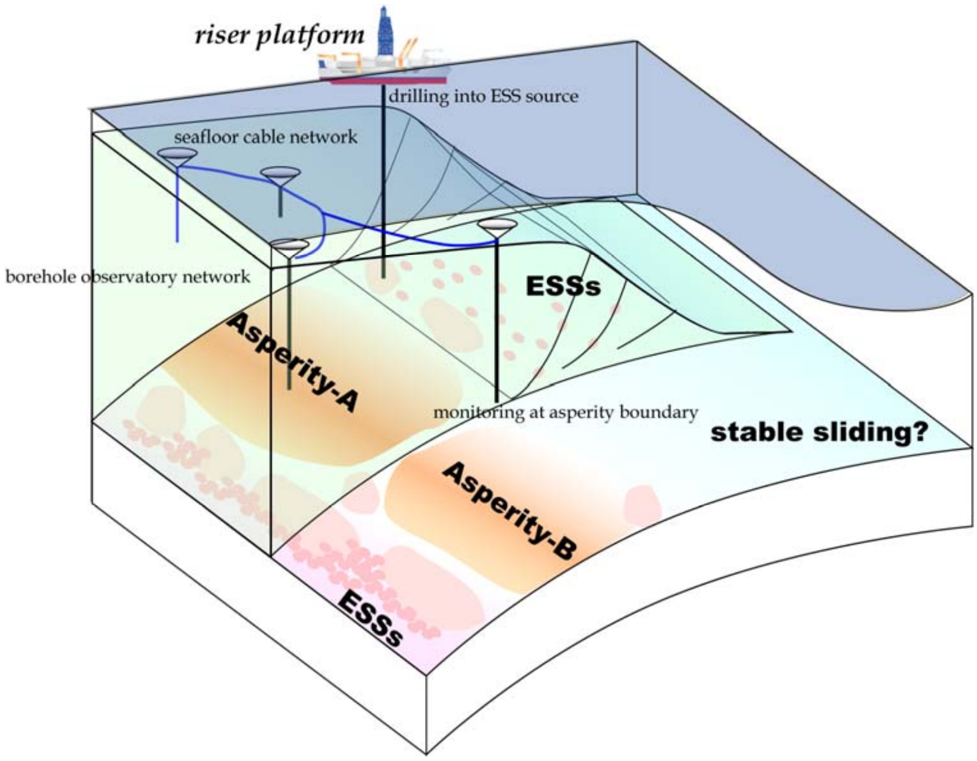

Figure 3. Conceptual view of seismogenic drilling for IODP geohazard.