White Paper

Building a Scientific Understanding of Geohazards:
‘Exploration into catastrophic earthquakes’
#1: Approaches from shallow geological record.

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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 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.

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

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.

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

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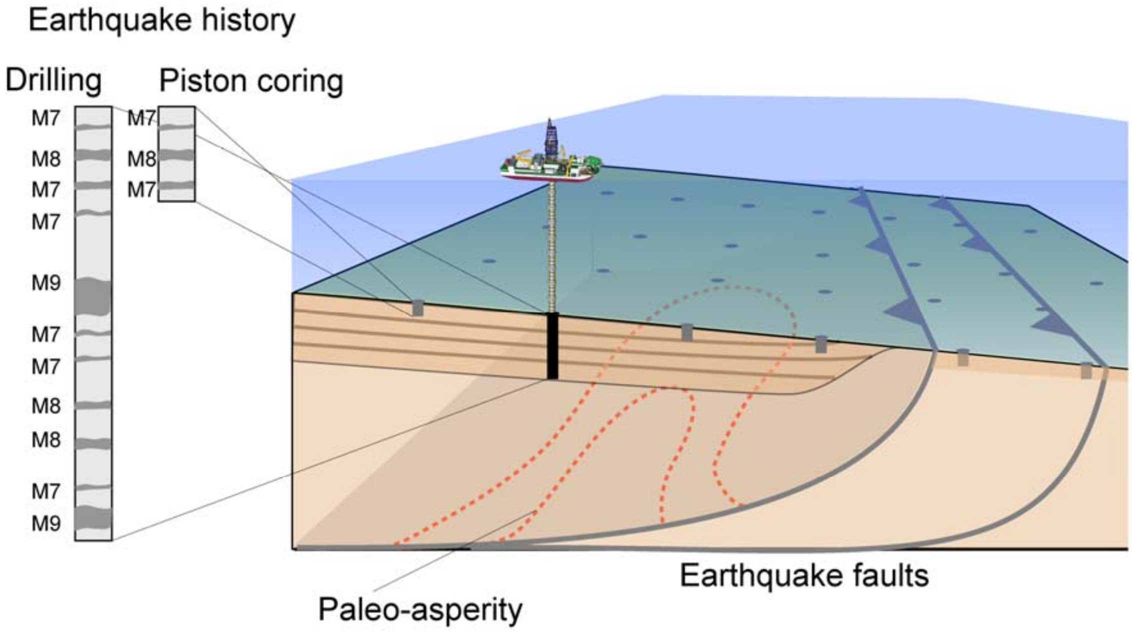

Figure 1. Conceptual view of systematic shallow drillings for IODP seismic Geohazards.