Building a Scientific Understanding of Geohazards:

'Exploration into unprecedented volcanic catastrophes in the ocean: unveiling impact of gigantic caldera-forming eruption'

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

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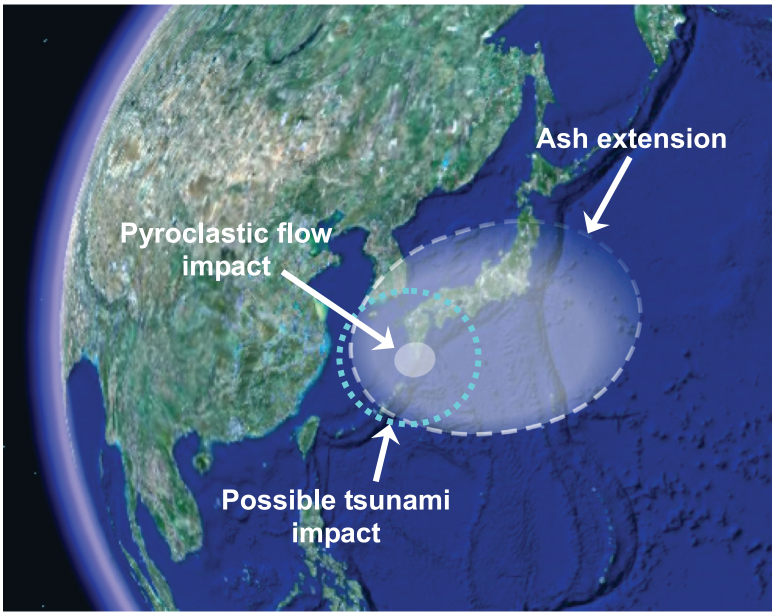

Figure 1. An example of the 'gigantic caldera-forming eruption'. This eruption occurred 7,300 years ago at Kikai caldera, Japan. Archeological records in southern Japan indicate this eruption have severely damaged to ancient human activities.

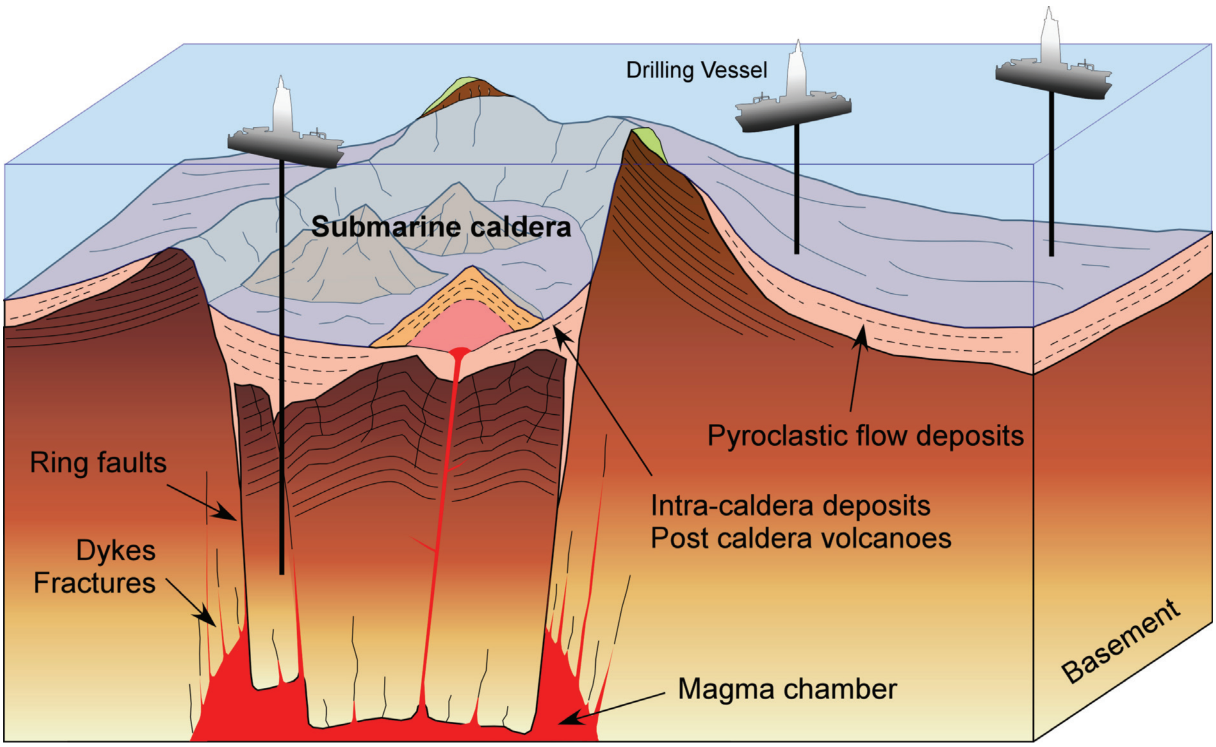

Figure 2. Idealized cross section of a large silicic magmatic system beneath ocean. Possible drilling sites are inside and outside caldera.