論文の内容の要旨

論文題目

Physical mechanism of volcanic tsunami earthquakes repeating at submarine volcanoes

（海底火山体で繰り返す火山性津波地震の物理メカニズム）

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Anomalous tsunami earthquakes have repeatedly occurred at submarine volcanoes near Torishima Island in Japan and Curtis Island in New Zealand. All centroid moment tensor solutions obtained for these earthquakes were non-double-couple types dominated by vertical compensated-linear-vector-dipole (vertical-CLVD) components, indicating an atypical source mechanism of volcanic origin. Despite their intermediate-class seismic magnitudes of M_w 5-6, large amplitude tsunamis with peak amplitudes of tens of centimeters were observed at tide gauges across wide regions after the earthquakes. Considering their volcanic origins and the efficiency of tsunami excitation, these can be regarded as "volcanic tsunami earthquakes." Previous studies have proposed several possible models for the physical mechanism of such earthquakes based on seismic analysis. However, their shallow source depths and remote locations (far from developed seismic networks) have made it difficult to determine the physical mechanism reliably via seismic data. Although tsunami records have also been used to explore the mechanism, limitations of past tsunami analyses (such as lack of good records and lower computational accuracy) have prevented detailed source modeling. Therefore, the physical mechanism of volcanic tsunami earthquakes has yet to be determined. In this study, I aimed to determine the physical mechanism by constructing kinematic source models of volcanic tsunami earthquakes through an

interdisciplinary approach based on tsunami analysis, as well as modeling of long-period seismic waves and crustal deformation.

I first estimated an approximate tsunami source, or initial sea-surface displacement, caused by a volcanic tsunami earthquake near Torishima Island in 2015 (the 2015 Torishima earthquake) with high-quality tsunami records at an array of stations equipped with ocean-bottom pressure gauges. The peak location of the initial sea-surface uplift was constrained over a submarine caldera by comparing tsunami ray-tracing simulations with dispersion properties observed at the array. In order to obtain the profile of the tsunami source, I assumed an axially symmetric profile over the caldera to compute tsunami waveforms at the array. By comparing the synthetic and observed waveforms, I modeled a central uplift > 1 m with a smaller peripherical subsidence surrounding the caldera structure. Synthetic tsunami waveforms showed good agreement to observations at both the array and a tide-gauge station. The estimated tsunami model implied a possible source mechanism related to characteristic structures below the submarine caldera, such as a vertical opening of a shallow horizontal crack that would generate tsunamis efficiently with little release of long-period seismic energy.

Next, I explored a kinematic source model of the 2015 Torishima earthquake that explained observed tsunami and long-period seismic waves. To constrain candidates for fault geometries capable of causing the earthquake, I estimated its detailed initial sea-surface displacement by comparing more accurate synthetic tsunami waveforms with tsunami records from different observation networks (the Dense Oceanfloor Network system for Earthquakes and Tsunamis (DONET) and the Deep Sea Floor Observatory (DSFO) off southwestern Japan and the Deep-ocean Assessment and Reporting of Tsunamis (DART) in the offshore deep ocean), as well as the array. This confirmed that the earthquake generated large uplift concentrated just above the caldera floor and clear outside subsidence along the rim structure. Therefore, I hypothesized a composite fault model consisting of a ring-fault structure and a horizontal fault as a possible source model. Next, I developed an efficient inversion method using tsunami waveforms to estimate fault slips and applied it to multiple assumed fault models with different fault parameters, such as the dip angle and ruptured portion of the ring fault as well as the depth of the horizontal fault. From the slip distributions of the multiple fault models obtained by the inversion of tsunami waveforms, I constructed a point seismic moment tensor source to synthesize long-period seismic waves at regional stations of the Japanese broadband seismic network (F-net) and Global Seismograph Network (GSN). Finally, I obtained a composite source model composed of thrust slip along an inwardly down-dipping ring fault extending along three-quarters of the caldera rim structure along with the instantaneous vertical opening and closing of a horizontal fault at approximately 2 km depth. This slip model sufficiently explained both the tsunami and long-period seismic wave records, confirming its plausibility as a kinematic source model of the 2015 Torishima earthquake.

A similar approach was also applied to another volcanic tsunami earthquake near Curtis Island in 2017 (the 2017 Curtis earthquake). After estimating an approximate tsunami source location from tide-gauge records on the North Island and remote islands of New Zealand, the initial sea-surface displacement was estimated by the inversion of tsunami waveforms. This revealed similar characteristics to the 2015 Torishima earthquake, i.e., large uplift over a caldera-like structure with a clear boundary of the uplifted area along the rim structure. I next inverted tsunami waveforms to estimate slip distributions on different assumed fault geometries, then examined the validities of the slip models by comparing synthetic long-period seismic waveforms with the records at regional stations at New Zealand, Australia, and islands along the Tonga-Kermadec Ridge and in Melanesia. Finally, I obtained a kinematic source model composed of a ring-fault slip on the southwestern part and a horizontal crack opening at < 5 km depth.

These modeling studies revealed that composite slip models of ring-fault and horizontal-crack structures in submarine calderas quantitatively explained both the tsunami and long-period seismic records for the two events. Previous analyses of volcanic tsunami earthquakes have common characteristics to attribute them to thrust slips on a ring fault induced by magmatic pressure inside a horizontal crack at shallow depth below submarine calderas. The mechanism is quite similar to the "trap-door faulting" observed at the Sierra Negra caldera in the Galápagos. The ability of these intermediate-class seismic magnitudes to create large tsunamis can be theoretically and synthetically explained by the atypical mechanism at shallow depth in the crust. Although some elements of the moment tensor of the complex fractures in shallow crust cannot be constrained seismologically, observable elements sensitively reflect ring-fault geometries. These properties enable us to obtain source information from moment tensor analysis using long-period seismic waveforms. Most of the repeating earthquakes showed similarities in these observable elements, implying that their ruptures occurred at almost identical ring-fault structures in the submarine calderas. Through this study, the physical mechanism of volcanic tsunami earthquakes was successfully determined with kinematic source models validated quantitatively by both tsunami and seismic records. The results provide new and specific pictures of peculiar tsunami earthquakes repeatedly occurring in active submarine calderas.