論文の内容の要旨

Comprehensive detection and spatio-temporal distributions of deep low-frequency earthquakes in volcanic areas all over Japan

（日本全国の火山地域で発生する深部低周波地震の網羅的検出と時空間分布）

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Deep low-frequency (DLF) earthquakes occur at depths of roughly 30 km in which regular crustal earthquakes rarely occur. The dominant frequencies of DLF earthquakes are about 1−10 Hz, which are lower than those of regular earthquakes with similar magnitudes. There are two types of DLF earthquakes; tectonic DLF earthquakes occur along the subducting plate interface and inland DLF earthquakes occur near active volcanoes or active faults. DLF earthquakes near volcanoes are considered to be affected by fluid in the lower crust because they often occur in or around of low-velocity anomalies. However, the generating mechanisms of DLF earthquakes and relationship with the surrounding structure are still unknown because hypocenters of DLF earthquakes do not have a good resolution due to their weak signals. In this study, I focus on the inland DLF earthquakes beneath volcanoes in order to reveal the structures in which DLF earthquakes occur and the relationship between DLF earthquakes and volcanic activities.

The relationship between activities of DLF earthquakes and surface volcanic activities such as eruptions was discussed so far because we have observed many DLF earthquakes beneath active volcanoes. For example, DLF earthquakes were observed before the 1986 eruptions of Izu-Oshima volcano and 1991 eruptions of Pinatubo volcano.

Recent studies also showed increases of DLF earthquakes before the eruptions in Klyuchevskoy volcano in Russia and Hakone volcano in Japan. However, the number of observations of DLF earthquakes associated with volcanic activities is small and the relationship between DLF earthquakes and volcanic activities is still unknown in many volcanoes. Although the Japan Meteorological Agency (JMA) observe DLF earthquakes in Japan and construct the catalog of DLF earthquakes, the catalog does not completely cover entire activity of DLF earthquakes due to their weak signals and DLF earthquakes associated with eruptions have not been observed from the JMA catalog. Besides, detailed spatial and temporal evolution of DLF earthquakes has not been constrained even in the volcanoes in which DLF earthquakes associated with eruptions have been observed.

To reveal detailed activities of DLF earthquakes, I applied following three analyses to DLF earthquakes occurring in 52 regions all over Japan. The first analysis is the network correlation coefficient method for the precise relocation of hypocenters of DLF earthquakes. The second analysis is the classification of DLF earthquakes into some groups in each region based on waveform correlation of every earthquake pair. Third, more DLF earthquakes were detected from continuous velocity seismograms of high-sensitivity seismograph network (Hi-net) operated by National Research Institute for Earth Science and Disaster Resilience (NIED) between April 2004 and December 2018 based on the matched filter technique. Combining the results of the three analyses, I revealed hypocentral distributions and activities of DLF earthquakes.

Relocation analysis revealed that hypocenters of DLF earthquakes concentrate into some small isolated groups with separations of several kilometers in the vertical direction in most regions. For example, DLF earthquakes occur in four groups with the intervals of 5 km between 20 and 35 km depths in Hijiori, northeastern part of Japan, even though the JMA catalog showed vertically continuous distribution. As for quantifying temporal activity patterns of DLF earthquakes, I defined the swarm ratio for each group of all regions and generally classified the activity patterns into two types; episodic and constant occurrences. In many regions, only constant occurrences of DLF earthquakes were observed, on the other hand, 12 regions included groups that show episodic occurrences of DLF earthquakes. Episodic DLF earthquakes have similar waveforms, magnitudes distribution with high b-values, and low maximum magnitudes compared to constant DLF earthquakes. These results suggest that episodic DLF earthquakes may repeatedly occur in the concentrated similar smaller-scale sources and constant DLF earthquakes may occur in different sources closely located.

DLF earthquakes associated with volcanic activities were observed in five volcanoes. In Kirishima, which is one of the most active volcanoes in Japan, activation of DLF earthquakes at a depth of approximately 25 km was observed between December 2009 and September 2011, in which subplinian eruptions of Shinmoe-dake occurred. Such a two-year activation in DLF seismicity was well correlated with crustal deformation caused by the volume change of a magma reservoir at a depth of 8 km. The waveforms and hypocenters of DLF earthquakes during the activation period were different from those during other periods. Although the hypocenters of activated DLF earthquakes and not activated DLF earthquakes are close to each other within 0–5 km, temporal activity patterns of those DLF earthquakes were clearly different. The activated DLF earthquakes were characterized by the waveforms with lower dominant frequencies and deeper hypocentral locations compared to DLF earthquakes during the other period. The DLF earthquakes can be divided into four types and the activated types were switched at the transitions of the eruption styles. Besides, the waveforms and hypocenters of DLF earthquakes associated with the 2018 eruptions were different from those associated with the 2011 eruptions. These results suggest that DLF earthquakes could be triggered by various fluid paths those are altered by the eruptive process. The fluid paths of the 2018 eruptions might be different from those of the 2011 eruptions.

Activations of DLF earthquakes associated with volcanic activities were also observed in other four volcanoes, Meakan, Sakurajima, Ontake, and Hakone. In Meakan and Sakurajima, DLF earthquakes correlated with volcanic activities occurred only in some limited groups and other groups of DLF earthquakes show constant occurrences or episodic occurrences with no correlation with eruptions or crustal deformations. In addition, DLF earthquakes associated with eruptions had low dominant frequencies, similar to those in Kirishima. Time-lags between activations of DLF earthquakes and eruptions are a few hundred days in Kirishima and Meakan, while a phreatic eruption occurred after only 20 days from the activation of DLF earthquakes at the 2014 eruption of Ontake. As a result, the five volcanoes in which associations of DLF earthquakes with eruptions were divided into two categories based on activities of DLF earthquakes and time-lags between activations of DLF earthquakes and surface activities of the volcanoes.

As a result of this study, a model of structure around hypocenters of DLF earthquakes is proposed. In previous model, DLF earthquakes distribute in or around of low-velocity anomalies on a scale of about 10 km. However, the discrete distributions of DLF earthquakes suggest that DLF earthquakes occur on a scale corresponding to heterogeneities of 0–5 km. One of possible candidates of such heterogeneities is formed by sill-like magma discussed in petrological studies instead of a volumetric magma body. Furthermore, different spatio-temporal distributions of DLF earthquakes in each group suggest that they are triggered by fluid flow through many paths forming a complicate network in the lower crust. Although it is difficult to predict eruptions based on the monitoring of DLF earthquakes at this moment, the accuracy of predictions of eruptions may be improved by a more comprehensive analysis of DLF earthquakes.