Deep low-frequency volcanic earthquakes and their implication for deep crustal processes in the magmatic arc

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Under temperatures and pressures of the lower crust and the upper mantle, rocks typically deform in a ductile manner, and it is unlikely that a sufficient deviatoric stress accumulates to generate brittle failure. However, earthquakes do occur in the upper mantle and in the lower crust beneath active volcanoes, and they are known as volcanic deep low-frequency earthquakes (VDLFs). They release energy mostly in the low-frequency range (<5 Hz), and are characterized by emergent arrivals and long-duration codas. VDLF activity observed at depths of 10-50 km in Japan, the Philippines, Alaska, and the Western US (Power et al., 2004; Ukawa, 2005; Nichols et al. 20011) has generally been attributed to magma transport in the mid-to-lower crustal and uppermost mantle regions. However, because VDLF seismicity is infrequent, with relatively weak and emergent signals, the relationship between deep magma transport and seismic radiation remains poorly understood. Dense seismic observation systems in boreholes, such as the high-sensitivity seismograph network "Hi-net" in Japan (Obara et al. 2005), are effective at detecting not only non-VDLFs (Obara, 2002) but also VDLFs. Since 1997, the Japan Meteorological Agency has routinely detected and located DLFs using the Hi-net dataset, and have identified DLFs in and around most quaternary volcanoes in Japan (Takahashi and Miyamura, 2009). Several studies have attempted to estimate source mechanisms of VDLFs in Japan. The first attempt, carried out by Ukawa and Ohtake (1987), provided a single force as the source mechanism of a VDLF beneath Izu-Ohshima by using the particle motion directions of *S*-waves. More recently, strike-slip type and non-double-couple source mechanisms were obtained using waveform inversions for VDLFs in Northeast Japan (Nishidomi and Takeo 1996; Okada and Hasegawa, 2000). Nakamichi et al. (2003; 2004) estimated the source mechanisms of Mts. Iwate and Fuji through the moment tensor inversion of spectral ratios of body waves, using data from a dense seismic network. The authors explained the source mechanisms as the motion of a tensile crack coupled either with a shear crack or with a chamber. No significant common features have been found in these estimated source mechanisms of VDLFs in Japan. The depths of VDLFs correspond to the depth interval where CO_2-rich fluids are expected to be liberated from ascending basaltic magmas, suggesting that such fluids play an important role in facilitating earthquake instabilities in the presence of tectonic stresses. The striking temporal correlation between VDLF activity and CO_2 gas emissions has been pointed out by Mammoth Mountain (Hill, 1996) and Izu-Ohshima (Watanabe, 2013). However, a temporal correlation between the VDLF activity and surficial geological and shallow geophysical activity is currently debated. The intrusion of basaltic magma before the eruption of Mt. Pinatubo in 1991 was correlated with VDLFs (White, 1996), and temporal correlations are clear for the 1998-1999 unrest of Mt. Iwate, where VDLF seismicity started 5 days before the initiation of the volcano tectonic (VT) seismicity (Nakamichi et al., 2003). We are currently investigating this correlation for the volcanic activity of Sakurajima, which is located in the southern part of the Aira caldera. There is a correlation between VT and VDLF seismicity in the Aira caldera since 2000. For example, both VT and VDLF increased in number between 2017 and 2018. On the other hand, no clear correlation between the VDLF seismicity and the eruption activity of Sakurajima volcano has been identified thus far.

Keywords: Deep low-frequency volcanic earthquake, Non-double-couple source mechanism, Volcanic activity