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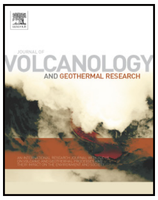

Structural evolution beneath Sakurajima Volcano, Japan, revealed through rounds of controlled seismic experiments

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ABSTRACT

Structural evolution beneath an active volcano is detected as the variation of seismic reflectivity through controlled seismic experiments, which is interpreted as being associated with discharging magma. The target of the present study is Sakurajima Volcano, which is one of the most active volcanoes in Japan. Six rounds of seismic experiments with controlled sources have been conducted annually at the volcano. Two seismic reflection profiles are obtained from the datasets for each successful round of experiments. The experiments reveal clear annual variation in seismic reflectivity at a depth of 6.2 km in the northeastern part of Sakurajima. The reflectivity is maximum in December 2009 upon the first intrusion of magma and decreases gradually until December 2013, which coincides with the inflation and deflation cycle of Sakurajima Volcano. Reflectivity variation occurred in the embedded clear reflector at depth. An evolving sandwiched structure in the intermediate layer is used as the reflector model. Lower-velocity magma embedded in the intermediate layer and its succeeding velocity increment explain the variation range of reflectivity. This is interpreted as a temperature decrease associated with discharging magma at depth. The present study describes a new approach for instantaneously sensing magma properties and for monitoring active volcanoes.

1. Introduction

Monitoring the movement of subsurface magma is essential to understanding volcanic activity. The properties and the amount of moving magma control the characteristics and intensity of the surface activity of a volcano. In order to monitor underground magma movement, various passive geophysical observations, such as leveling surveys, gravity observations, tilt observations, and seismological observations, have been conducted in volcanic areas (e.g., McNutt, 2015). Geodetic observations, including extensometer observations and leveling surveys, provide monthly to decade-scale chronicles of the underground movement of magma. Seismological observations provide instantaneous information on magma movement through the evolution of seismicity patterns and source mechanisms. However, these passive methods may not capture silent magma movement through spontaneous signals, such as seismic waves, from depth. For example, instantaneous disappearance of seismicity occurred before the eruption of Mt. Merapi in 2010 (Iguchi et al., 2011). Iguchi et al. (2011) reported that seismicity is not always an appropriate indicator of magma movement. Therefore, the establishment of an active monitoring method is needed in order to complement conventional passive methods.

A controlled source method may make up for this deficiency in passive methods. Previous seismic approaches for detecting structural evolution have used repeated seismic explorations. For example, in Iizuka et al. (1975), rounds of surveys were conducted using the refraction method in metropolitan areas. These surveys revealed that the first-arrival travel time is not an accurate indicator of expected variation in seismic velocity. Recently, Nishimura et al. (2005) applied the partial correlation method by Poupinet et al. (1984) to later phases of seismograms from repeated shootings and detected velocity variations associated with stress changes both from the M6.1 earthquake in the vicinity and from volcanic stress change in Iwate Volcano. Anggono et al. (2012) discussed velocity differences between pre-caldera and post-caldera states during caldera formation in the year 2000 at Miyakejima Volcano. Matsushima et al. (2004) presented an evolution of seismic reflectors during the production of geothermal fluid for a power plant through three rounds of seismic surveys at the Kakkonda geothermal field adjacent to Iwate Volcano.

Sakurajima Volcano, which is one of the most active volcanoes in Japan, is the target of the present study and is an appropriate field for monitoring magma movement. Sakurajima Volcano stands at the southern part of Aira Caldera, southern Kyushu, Japan (Aramaki, 1984). Sakurajima Volcano is an andesitic stratovolcano with a height of 1115 m that was formed 29 thousand years ago, just after the ejection of the Ito pyroclastic flow from Aira Caldera (Kobayashi et al., 2013). The present edifice is clustered into two parts, Kitadake (KT) and

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Minamidake (MD). At present, MD is active, whereas KT is dormant (Fig. 1).

There have been five significant eruptions with lava flows throughout recorded history: 764, 1471–1476, 1779, 1914, and 1946 (Japan Meteorological Agency, 2013). The eruption in 1914 was the first destructive volcanic activity in modern Japan (Omori, 1922). During 1914, 1.34 km^3 of lava and 0.52 km^3 of pyroclasts were ejected (Ishihara, 1981). Magma has been continuously supplied to the reservoir beneath Aira Caldera since 1914 (Eto et al., 1997; Yamamoto et al., 2013, 2014). Since then, vulcanian eruptions have occurred frequently at the summit crater of MD from 1955 to the mid-1990s following the 1946 lava eruption. After slowing of the vulcanian eruptions at the summit in the late 1990s, explosive eruptions at Showa crater (SY), which was formed in 1939 (Tsuya and Minakami, 1940), on the east flank of the volcano resumed on June 2006. The frequency of explosive eruptions at SY has increased yearly since 2006. Recently, most explosive eruptions have occurred exclusively at SY, and activity is increasing. Iguchi et al. (2010) suggested the possibility of incipient major volcanic activity, similar to that in 1914, based on the uplift in the northern coast of Kagoshima Bay approaching a level similar to that before the 1914 eruptions, which is the cause of the current moderate activity.

Fig. 2 shows the volcanic activity record obtained by the extensometer at HART and the ash fall record in Kagoshima Prefecture since January 2007. The extensometer at HART, which is located 3 km northwest of the active craters of Sakurajima, records magma accumulation and discharge just beneath the craters. The extensometer records are provided by the Sakurajima Volcano Research Center, Kyoto University. Ash fall is collected by the Kagoshima Prefecture Office, and the amount of ash fall is estimated by the Japan Meteorological Agency (JMA) as a quantitative indicator of volcanic explosive eruptions. The sequence shown in Fig. 2 is divided into six phases, labeled I to VI, based on extensometer readings and ash fall. Phase I exhibits little movement and has a small amount of ash fall. Phases II and IV, which run from August 2009 to June 2010 and from November 2011 to June 2012, respectively, exhibit inflation and increasing ash fall. Phases III and V, which run from July 2010 to November 2011 and from June 2012 to February 2014, respectively, exhibit simple contraction and moderate ash fall. Phase VI, which runs from February 2014 to April 2015, exhibits contraction and a small amount of ash fall. Phases II and IV exhibited significant inflation and are considered to be periods of magma intrusion deep beneath Sakurajima (Iguchi et al., 2013).

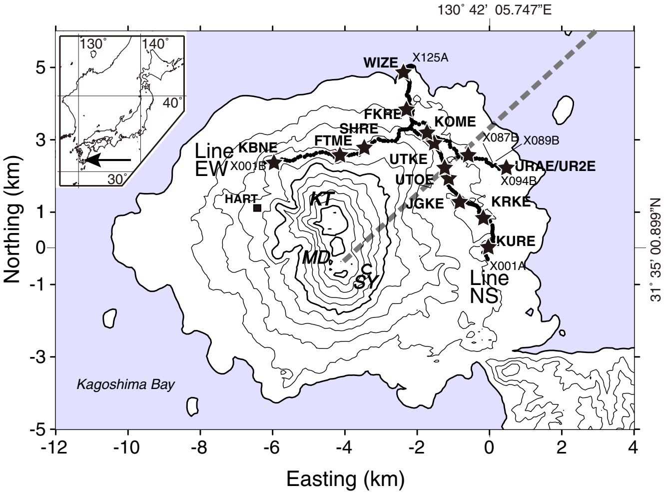

Fig. 1. Sakurajima Volcano. The inset shows the location of Sakurajima Volcano, which is indicated by an arrow. The stars indicate major shot points, and the dots indicate the locations of stations used. The gray broken line indicates the magma pathway (Hidayati et al., 2007). KT, MD, and SY indicate Kitadake summit, and Minamidake and Showa craters, respectively. The location of the HART extensometer station is indicated by the solid square. Contours indicate 100 m intervals produced from a digital 50 m-grid map (elevation) provided by the Geospatial Information Authority of Japan (GSI).

The exact target area is the northeastern part of Sakurajima. Based on the source mechanisms of the volcano–tectonic earthquakes and ground deformations in and around the caldera, the area is a possible magma feeder zone connecting MD and the depth of the caldera (Hidayati et al., 2007; Eto et al., 1997) (Fig. 1). Although the target area is a possible magma feeder zone, seismicity is lower than that in the conduit zone just beneath the craters. Iguchi et al. (2011) suggested that lower seismicity does not always imply inactive magma. Tsutsui et al. (2013) conducted a reflection seismic survey in this area in 2008 and obtained seismic sections and a velocity structure model for the areas north and east of Sakurajima. Their seismic survey provided the foundation for the present study.

The present study was conducted in order to detect the seismic reflectivity change associated with the progress of volcanic activity and to clarify magma movement beneath the surface.

2. Seismic experiments

Six rounds of experiments were conducted from 2009 to 2014. The times at which these experiments were conducted are indicated by the arrows in Fig. 2. Seismograms generated by chemical explosions are used. Twenty kilograms of dynamite were detonated in each shot hole. A vertical seismometer (natural frequency: 4.5 Hz) and a recorder LS-8200SD (Kurashimo et al., 2006) were installed at each station. The recorders run with a sampling interval of 2 ms.

Two profiles, namely, lines EW and NS, are established in the east foot and the northern flank of the volcano. Line EW passes 3 km north of MD, and line NS passes 3.5 km northeast of MD. The lines intersect northeast of the craters of interest (Fig. 1). Line EW contains 104 stations: X001B–X051B, B099–B102, B201–B207, and X054B–X095B. Line NS contains 125 stations: X001A–X125A. Each station was placed within 1 m of its original location for each round of experiments (see the Electronic supplement). One hundred four stations were deployed along line EW over a distance of 6690 m, with a typical spacing of 71.0 m. The common mid-points (CMPs) along line EW were spaced at intervals of 35.5 m and are numbered from 0 to 188. These points represent seismic imaging points. One hundred twenty-five stations were deployed along line NS over 5650 m with a typical spacing of 46.3 m. The CMPs along line NS are spaced at 23.2 m intervals and are numbered from 0 to 250.

The detailed locations of shot points for each site are shown in Fig. 3. Shot holes at each site are located within 40 m of the 2009 hole, except for shots URAE and UR2E, and KRKE. Shot UR2E has been carried out in place of shot URAE since 2011.

The principal experiments (referred to as the 2009, 2010, 2011, 2012, and 2014 experiments, respectively) were conducted on 10 December 2009, 9 December 2010, 15 December 2011, 13 December 2012, and 4 December 2014 (see the Electronic supplement). In these experiments, a single-hole shooting using 20 kg of dynamite was conducted at each shot point. A total of 14 shots were conducted (KBNE, FTME, SHRE, KOME, URNE, URAE, KURE, KRKE, JGKE, UTOE, UTKE, KMME, FKRE, and WIZE), and 228 stations were placed along lines EW and NS at locations identical to those of Tsutsui et al. (2013). Station X095B was placed to the east of station X094B onward since 2011 in order to fill the gap generated by the replacement of the east-end shot. A total of 225 stations were deployed on these lines for each year. The actual numbers of stations deployed on the lines in 2009, 2010, 2011, 2012, and 2014, were 225, 228, 229, 229, and 229, respectively. The rates of successful data retrieval were 97.8%, 98.7%, 99.6%, 97.4%, and 98.7% in 2009, 2010, 2011, 2012, and 2014, respectively.

The experiment was conducted only along line EW on 5 December 2013 (see the Electronic supplement) and stations were thinned out because of logistic restrictions. A total of 74 of the 104 stations along line EW were placed at their original locations. A single-hole 200 kg