Temporal variation of the ACROSS signals associated with 15-Aug-2015 intrusive event in Sakurajima volcano, Japan.

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Abstract

Temporal change in the transfer function (Green's function) was detected associated with an intrusive event in Sakurajima volcano, Japan. We have started monitoring magma transport process using an active monitoring system with an artificial vibration source called ACROSS in Sakurajima volcano island since September 2012. Our ACROSS system produces continuous seismic signal, which are routinely monitored with 20 permanent and 5 temporal seismic stations in and around Sakurajima volcano. The signals recorded at the seismic stations are transformed to transfer functions with a deconvolution by the source signal of ACROSS. We calculated the bi-hourly transfer functions in the period including the intrusive event. Many of the transfer function between the ACROSS source and the stations show remarkable change at the time of intrusive event on 15 August. This observation indicates structure change occurred in Sakurajima volcano associated with the intrusive event.

Keywords: artificial source, temporal variation, volcano

INTRODUCTION

Temporal changes in the propagation properties of seismic wave have long been regarded as a tool for monitoring the subsurface state, especially in tectonically active area such as earthquake source area and active volcanoes. For example, S-wave splitting in seismic waves (Crampin, 1994) by natural earthquakes have been used to monitor the temporal change in volcanic activity in many volcanoes (e.g., Gerst and Savage, 2004). Seismic interferometry using ambient noise, has recently been applied to detect the temporal variation of seismic propagation in volcanic regions to monitor their activity. Seismic interferometry has been applied to many volcanoes, such as Erebus (Gret and Roel, 2005), Merapi (Sens-Schoenfelder and Wegler, 2006) and Reunion Volcanoes (Brenguier et al. 2008) to monitor the temporal changes in volcanic activity.

Active sources can be used to detect temporal variations of seismic propagation properties in volcanoes. They have an advantage over natural sources because source parameters such as time and location are well constrained. The disadvantage of the artificial source is the availability of the source signal. High cost of deployment is a majour barrier for their wide usage. In spite of the disadvantage, several efforts are made to detect the temporal change. Nishimura *et al.* (2005) examined a temporal change in seismic velocity by repeating explosion sources for Iwate Volcano, northeasten Japan. Tsutsui *et al.* (2011) conducted repeating reflection seismic surveys in Sakurajima volcano, southern Japan.

Our source, ACROSS, which stands for Accurately-Controlled Routinely-Operated Signal System, have a remarkable advantage over traditional artificial sources. ACROSS was developed as a controlled source for long-term continuous monitoring (Kumazawa and Takei, 1994). The ACROSS source we use generates seismic signal by a centrifugal force of a rotating eccentric mass. The rotation is highly stabilized to maximize the stacking performance in order to increase the signal-to-noise ratio. The transfer functions between the source and receivers are calculated with a deconvolution of received signals with the source signal of ACROSS.

The first result of the ACROSS source operation was reported by Yamaoka *et al.* (2001) to show the potential of ACROSS source, which is deployed near the Nojima

fault in Awaji island causing the 1995 Kobe earthquake. The rotation is driven by an AC servo motor which is controlled by a feedback inverter. The rotation is driven so that the rotational angle is proportional to the number of pulses given to the inverter. As the pulse sequences given to the inverter is generated with a precise synchronization to a GPS clock, ACROSS can generate a GPS-synchronized seismic signal. As most of the seismic stations are operated with reference to a GPS clock, we can establish a remote synchronization between the ACROSS source and seismic stations. In the experiment in Awaji site, we succeeded in detecting a temporal change associated with strong ground motion by nearby earthquakes (Ikuta et al. 2002), which shows a sudden delay and gradual recovery of seismic velocity. It is interpreted as ground water movement based on the temporal change of anisotropy and strain in the ground (Ikuta and Yamaoka, 2004)

DEPLOYMENT OF ACROSS IN SAKURAJIMA

We deployed the ACROSS source at the northwestern flank of Sakurajima Volcano in March of 2012 (Yamaoka et al. 2014). ACROSS source is composed of rotational vibrators, lubricant circulators, a power control gear, and a PC-based controller as shown in Figure 1. Two vibrators with the same specification are deployed to cover a wider frequency range. Each vibrator rotates an eccentric mass around a vertical axis to produce sinusoidal signal. The force is proportional to the square of the rotational frequency and the maximum force is 1.0×10^5N at 25Hz. The vibrators are fixed to a foundation made of steel-reinforced concrete built in a rectangular pit.

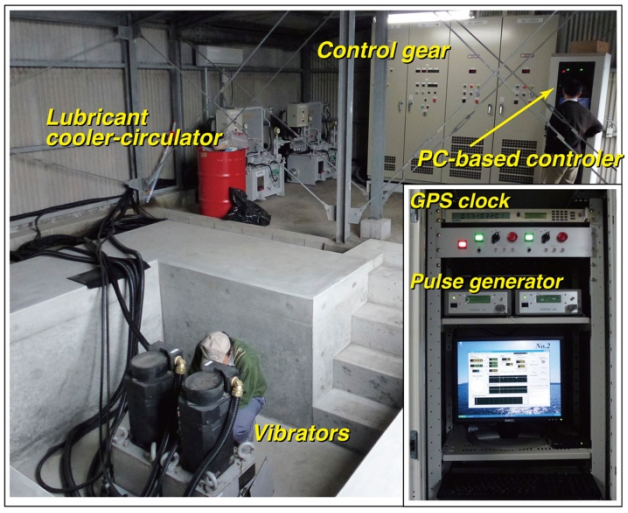

Fig.1 Deployment of ACROSS source at Sakurajima volcano.

The PC-based controller (Kunitomo and Kumazawa, 2004) can make precise operations on the motor. The controller can drive the vibrator so that it produces a sinusoidal force with frequency modulation (FM) by expanding and shrinking the intervals of the pulses given to the inverter. In Sakurajima, the sources cover a frequency range from 5 to 15 Hz, with one vibrator from 5 to 10Hz, the other from 10 to 15 Hz with FM operation. The PC-based controller switches the rotation direction automatically at regular time intervals. The switching interval is chosen to be two hours for Sakurajima. We can synthesize a linear vibration in any direction with a combination of the data by the two opposite rotations. Using this method, we synthesize both radial and transverse vibrations with reference to the station direction to calculate the transfer functions that relate to P and S waves.

The source site has an Internet connection for remote monitoring and remote control. It reduces the maintenance cost and shorten the time before fixing in case of trouble. For example, in the summer season, electric power outages and vibrators stoppages occur frequently due to unstable weather conditions, including heavy rains, lightning and typhoons. The vibrators can be restarted via the Internet connection using a VNC

protocol, which enables us to stop or restart the vibrator remotely, without visiting the site.

SOUCE OPERATION AND MONITORING

Figure 2 shows the location of ACROSS vibrator and seismic stations we used in this study. The seismic stations are located surrounding the summit. We used seismic stations operated by Japan Meteorological Agency (JMA), Sakurajima Volcano Research Center of Kyoto University (SVO) and Nansei-touko Observatory for Earthquake and Volcanoes of Kagoshima University (NOEV). Although many seismic station exist in Sakurajima island, only one ACROSS site is deployed. The more the sources are deployed, the better the resolution of subsurface image beneath Sakurajima becomes. With a limitation by the deployment cost we started the operation with only one ACROSS site. Sakurajima volcano is the most active volcano in Japan and regularly makes frequent explosions, more than 1000 times a year. We can expect some correlation between temporal variation of transfer functions and volcanic activity. The operation started in 12 September 2012, and a continuous operation can be achieved with some minor trouble. Operation sometimes stops due to power outrage in the island, mostly in summer season.

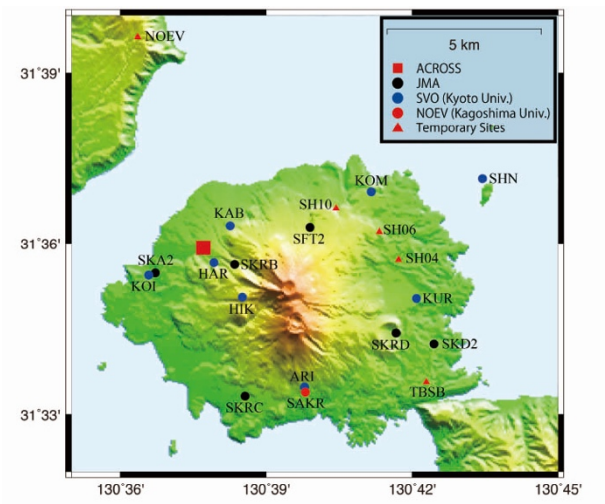

Fig.2 Location of ACROSS source and seismic stations in Sakurajima Volcano.

Maeda et al. (2015) revealed the temporal variation of transfer function associated with volcanic activity using the observation data from 19 September 2012 to 21 July 2014. They stacked the transfer functions based on the time relative to individual eruptions to find an energy decrease in the later phase of the transfer functions for the period of active eruptions. This result shows that the subsurface structure of Sakurajima varies associated with its activity.

A major trouble happened in the August 4, 2014. The trouble is a malfunction of feedback inverter in the control gear, and it appeared that the inverter could not be fixed and should be replaced with normal one. As the inverter was an old one and could not find the same model to replace it, we need to mount a new-model inverter on the control gear. This requires an appropriate parameter set for the new inverter to adjust it to the exiting vibrator system. It required four months before restarting operation.

The operation, after fixing the malfunction of the inverter, started on 8 January 2015. The operation continued until 19 August 2015, when the operation suspended for disaster mitigation reason after the volcanic crisis on 15 August.

INTRUSIVE EVENT IN SAKURAJIMA VOLCANO

Around 7 o'clock in the morning of 15 August 2015, the most active earthquake swarm ever recorded in Sakurajima volcano began in the eastern side of the summit crater. Large crustal deformation was also observed associated with the earthquakes. JMA raised the warning level to 4 for the first time after the installation of the warning level, meaning preparing evacuation for the local residents. The seismic activity and

crustal deformation almost ceased in one day without any eruptons. Both strain analysis and interferometric analysis of Synthetic Aperture Radar (InSAR) revealed that the activity was caused by the intrusion of magma as a dyke to the shallow part. The volume of magma intrusion is estimated as $2.7 \times 10^6 m^3$ using data of GNSS, tiltmeters and extensometers (Hotta et al. 2016) and as $1.7 \times 10^6 m^3$ using InSAR data (Morishita et al. 2016). The top of the dyke was modeled at 1.0km and 0.4 km, respectively. Both studies show that Sakurajima volcano was very close to magmatic eruption.

CHANGE IN THE TRANSFER FUNCTION

We try to find the temporal variation of the transfer functions associated with the intrusive event. The transfer functions are calculated for each combination of direction component of source and receivers. As the ACROSS source in Sakurajima volcano excites rotational horizontal force, we synthesize radial and transverse linear force for the transfer functions. The signal at the seismometers are also converted to radial, transverse and vertical motion with respect to the direction from the source. Therefore, we can obtain transfer functions with 6 components.

We regularly obtain transfer functions using stacking data for one day. Stacking of one-day length provides sufficient signal-to-noise ratio to see the temporal change for most of the seismic stations in the island. Acturally, in the daily transfer functions, we can find a sudden change in the signal around 15 August, 2015.

To raise the temporal resolution in the change of transfer functions, we calculate the transfer function of the data that was obtained by stacking for two hours. In the operation of ACROSS source, we switch the rotation direction in every two hours. The transfer function is calculated with a combination of one-hour data before and after every direction switching. In this calculation transfer functions of 6 components can be obtained for every two hours. Fig.3 shows the series of transfer functions from 10 August to 19 August for three stations HIK, SKA2, SFT2. The component of the transfer function is transverse motion at the station by a transverse excitation at the source, predominating S wave. The transfer functions clearly changed at the time of the intrusive event, shown by an arrow. In the signal of the station HAR, which locates 1.0km in the direction of the summit from the ACROSS source, the change appears in most part of the transfer function, from early part to later part. In SKA2 (1.7km), which locates at the opposite direction from the summit with reference to the ACROSS source, the change is seen mostly in later part after 6 second. In SFT2 (3.6km), which locates to the north of the summit, the change appears in most part of the transfer function as seen in HAR. These observations show that the structure change occurred in the region of the volcano centering around the summit, presumably stress and/or strain change affected the propagation property of seismic wave.

CONCLUSION

We find a clear temporal change in the propagation property of seismic wave in Sakurajima by a continuous monitoring using an accurately-controlled seismic source (ACROSS). The structure change occurred in the direction of the summit from the source.

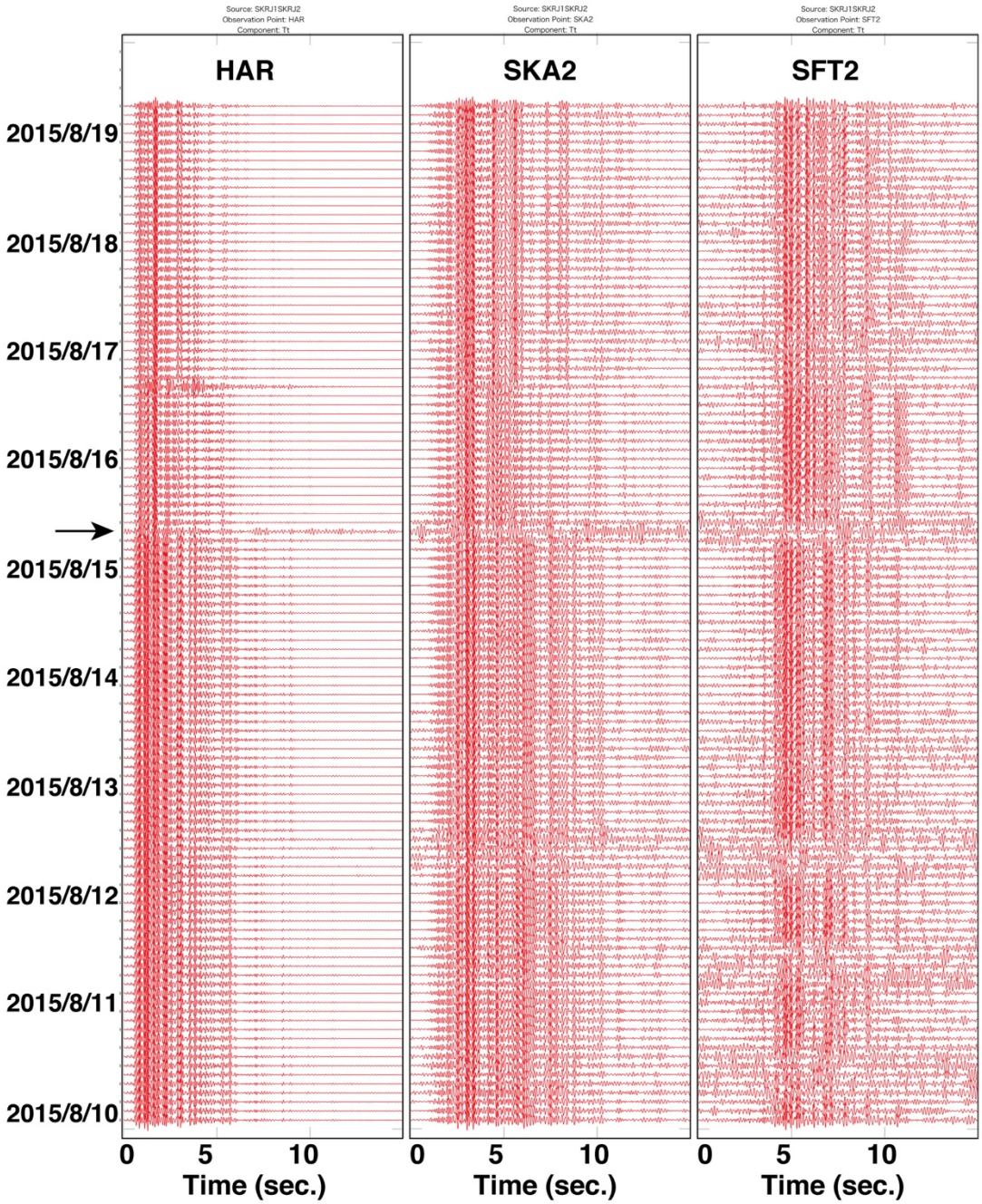

Figure 3. Transfer functions that are calculated for every two hours for the stations HAR, SKA2 and SFT2. Refer the location of the stations in Figure 2. Arrow shows the time of the intrusive event at the eastern side of the crater. Noise at the time of the intrusive event is caused by intensive seismic activity associated with the intrusion.

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