

## Remotely-triggered seismicity in the Hakone volcano following the 2011 off the Pacific coast of Tohoku Earthquake

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Seismic activity in the Hakone volcano at an epicentral distance of 450 km was remarkably activated just after the 2011 off the Pacific coast of Tohoku Earthquake. More than 1600 events were observed in the caldera of the volcano, from 15:00 on March 11 to 12:00 on April 2. To clarify the relationship between the occurrence of the main shock and the induced activity in the Hakone volcano, we investigated the spatial distribution of hypocenters and temporal changes of the seismicity, and we examined seismographs of the main shock to identify small local events during the passage of the surface waves. Hypocenters determined with the double-difference method are mostly distributed in the N-S direction, showing several clusters of seismicity. Focal mechanisms of major earthquakes are predominantly strike-slip having the  $P$  axis in the NNW-SSE direction. These features of the hypocenter distribution and the focal mechanisms are consistent with those of earthquakes that occur ordinarily in the Hakone volcano. The onset of the local event was initiated during the Love and Rayleigh waves from the main shock, suggesting that large dynamic stress changes of 0.6 MPa dominantly contributed to initiate the sequence of seismic activity.

**Key words:** Remotely-triggered seismicity, Hakone volcano, geothermal region, dynamic stress changes.

### 1. Introduction

The 2011 off the Pacific coast of Tohoku Earthquake occurred at 14:46 (JST = UT + 9 h) on March 11, 2011 with a Japan Meteorological Agency (JMA) magnitude ( $M_{\text{JMA}}$ ) of 9.0 (Fig. 1). The main shock was an inter-plate earthquake between the North American and the Pacific plates, and the rupture extended approximately 400 km along the Japan Trench (e.g. Honda *et al.*, 2011). JMA (2011) reported that seismicity away from the source region was remarkably activated just after the occurrence of the main shock, especially in volcanic or geothermal regions such as Mt. Nikko-Shirane, Mt. Yakedake, Nijima and Kozushima. Seismic activity in the Hakone volcano at an epicentral distance of 450 km was also notably activated after the main shock. More than 1600 events were observed in the caldera of the Hakone volcano, from 15:00 on March 11 to 12:00 on April 2. In this period, a total of 68 earthquakes occurred within the caldera that produced felt shaking at the summit of the Hakone caldera (Harada, personal comm.). The largest event, of magnitude 4.8, occurred 22 minutes after the main shock.

Several studies have shown that seismicity in volcanic or geothermal regions has been activated by passing surface or coda waves from a far-distant large earthquake (e.g. Hill *et al.*, 1993; Husen *et al.*, 2004; Prejean *et al.*, 2004). The purpose of this paper is to clarify the relationship between the occurrence of the  $M_{\text{JMA}} 9.0$  main shock and the induced

activity in the Hakone volcano. We show the spatial distribution of hypocenters and temporal changes of seismicity in the Hakone volcano after the main shock. Next, we examine the temporal correspondence of the passing of the seismic wave from the main shock and the occurrence of small local events, based on recordings of the main shock wave train.

### 2. Tectonic Setting and Swarm Earthquakes in the Hakone Volcano

The Hakone volcano is located at the northern boundary zone of the Izu-Mariana volcanic arc in central Japan (Fig. 1). There are many hot springs in the caldera. The hot springs in the Gora area are high-temperature and rich in sodium chloride, which is considered to be derived from the volatile phase from a deep-seated magma source beneath the Hakone volcano (Oki and Hirano, 1970; Matsuo *et al.*, 1985). Intense swarm activity has occasionally occurred in the caldera (Hiraga, 1987; Mannen, 2003). Strong ground motion and fumarolic activity has sometimes accompanied intense swarm activity (Mannen, 2003). The Hot Springs Research Institute of Kanagawa Prefecture (HSRI) has monitored activity of swarm earthquakes with a seismic network of 15 online stations that were installed in and around the Hakone caldera in 1989 (Fig. 1). The swarm activity in 2001, 2006, 2008 and 2009 were especially notable. From the precisely determined hypocenter distribution, Yukutake *et al.* (2010) indicated that most of the swarm earthquakes in the Hakone volcano are distributed on thin, vertically-oriented plane-like zones, which probably reflect a network of small faults developed by the interaction of Tanna and Hirayama Faults. Yukutake *et al.*

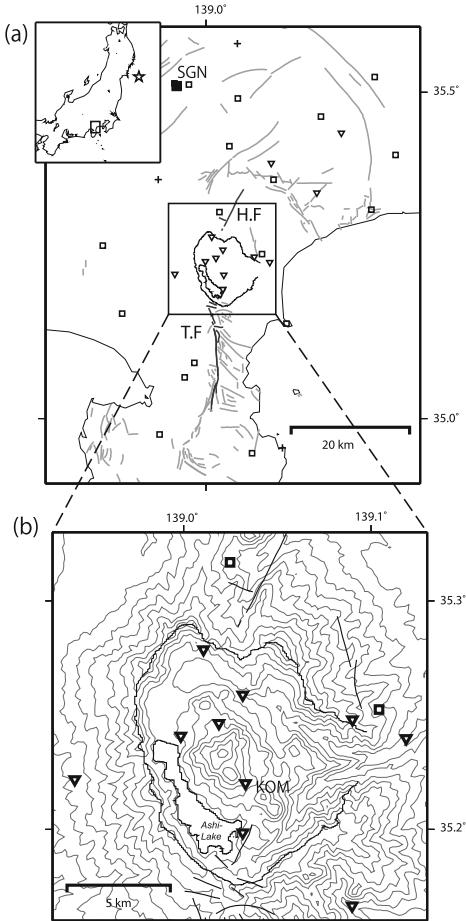


Fig. 1. (a) Map of the Hakone volcano, central Japan. Triangles, crosses, and squares indicate the HSRI, ERI and NIED Hi-net stations, respectively. Solid rectangle (SGN) shows the broadband seismic station (NIED F-net). Gray lines indicate surface traces of active faults (Research Group for Active Faults of Japan, 1991). H. F and T. F indicate the surface trace of the Hirayama and Tanna Faults. The rectangle corresponds to the region shown in Fig. 1(b). In the inset map, the study area is shown with respect to the Japanese Islands. A star indicates the epicenter of the 2011 off the Pacific coast of Tohoku Earthquake determined by USGS. (b) Magnification of the rectangular area shown in Fig. 1(a). Gray lines indicate contour lines at 100 m intervals. Waveforms observed at Komagatake station (KOM) are indicated in Figs. 3 and 4.

(2011) demonstrated a diffusion-like migration of hypocenters during the activity of August 2009, which suggests that pressurized fluid in the fault zone plays a substantial role in the occurrence of the swarm earthquakes.

### 3. Seismicity after the Great Earthquake on 11 March, 2011

Figure 2 shows the hypocenter distribution of local earthquakes that occurred in the period from 15:00 on March 11 to 12:00 on April 2, 2011. The time-magnitude diagrams from March 1 to 12:00 on April 2 are also shown. To determine the hypocenters, we used the double-difference (DD) method (Waldhauser and Ellsworth, 2000). As initial hypocenters for the DD relocation, we used the HSRI routine catalog in which hypocenters are determined using data from 39 online stations operated by the HSRI, National Research Institute for Earth Science and Disaster Prevention (NIED) Hi-net and the Earthquake Research Institute of the

University of Tokyo (ERI) (Fig. 1). We manually picked  $P$ - and  $S$ -wave arrival times,  $P$ -wave polarities, and the maximum amplitudes of earthquakes.

From the time-magnitude diagram (Fig. 2(c)), we can see that the seismicity in the Hakone volcano abruptly increased just after the main shock. 1688 events occurred in the period between 15:00 on March 11 and 12:00 on April 2. During the year before the main shock, an average of 20 events per month were recorded in the Hakone volcano (Honda, 2011). The first event of the swarm-like activity in the volcano occurred 17 minutes after the main shock (15:03, March 11). At 15:08 on March 11, the largest event with a local magnitude of 4.8 occurred in the southern part of the caldera (Fig. 2(a, b)). Although the seismicity increased abruptly on March 20, 22 and 31, the occurrence rate of earthquakes decayed with time (Fig. 2(c))

The epicenters distribute mostly in the N-S direction, in several clusters (Fig. 2(a, b)). The focal mechanisms of the major earthquakes are strike-slip having the  $P$  axis in the NNW-SSE direction. These features of the hypocenter distribution and the focal mechanisms are consistent with those of the earthquakes that ordinarily occur in the Hakone volcano (e.g. Yukutake *et al.*, 2010). The seismicity following the main shock occurred primarily at sites that were previously seismically active. However, several earthquakes were observed around the northern end of the Tanna Fault outside the caldera (Fig. 2(a)), where the seismicity was rather low before the main shock.

### 4. Seismicity during the Main Shock Wave Train

Next, we examined broadband and band-pass-filtered recordings of the main shock wave train to look for local events hidden in surface wave arrivals that were missed in the HSRI catalog. For this analysis, we used low-pass-filtered broadband waveforms from the station SGN (NIED F-net) and band-path-filtered waveforms from the borehole high sensitive station KOM (Fig. 1). We found a burst of several shocks during the time of large amplitudes for the Love and Rayleigh waves from the main shock (Fig. 3). These shocks were clearly recorded only at the KOM station (Fig. 1(b)), so it was not possible to locate them by the routine method. Consequently, none of these shocks is contained in the HSRI catalog. Because the  $S-P$  times for these earthquakes are less than one second (Fig. 4), it is likely that these earthquakes occurred in the Hakone volcano.

### 5. Discussion

We found that the onset of seismicity in the Hakone volcano began during the passing of the Love and Rayleigh waves with a period of  $>10$  s from the main shock. We calculated dynamic stress changes induced by the surface wave following the method of Hill *et al.* (1993). The peak dynamic stress changes during the surface waves were roughly 0.6 MPa. We also estimated static stress changes around the Hakone volcano caused by the main shock, based on the fault source model by the Geographical Survey Institute (2011). Static stress changes are calculated using the formula presented by Okada (1992).  $\Delta CFF$  calculated for the location and orientation of the  $M 4.8$  earthquake that occurred just after the main shock (Fig. 2) is +0.04 MPa. The

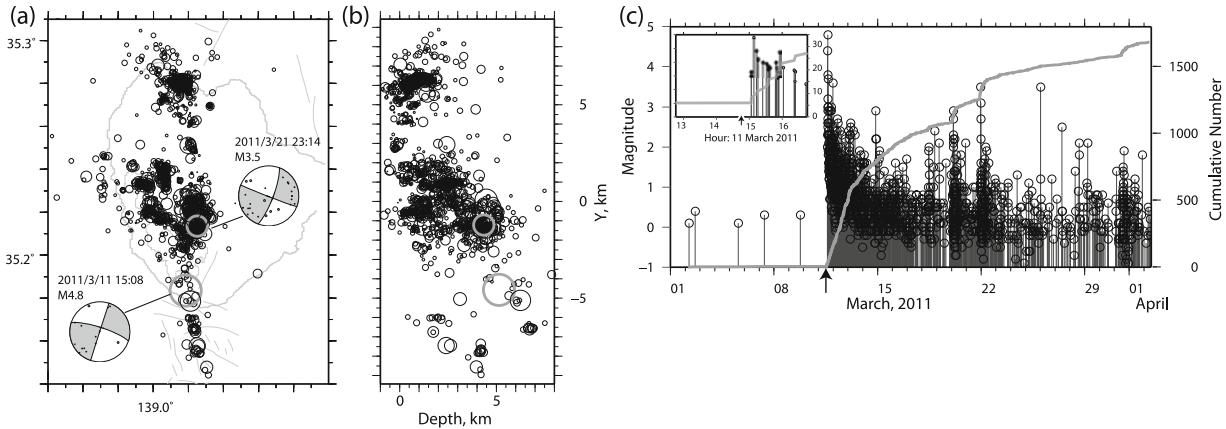


Fig. 2. (a) Map of earthquake hypocenters and (b) depth section along the N-S direction, as determined by the double-difference method. Focal mechanisms of major events are shown in Fig. 2(a), which were determined by HSRI routine analysis. (c) Time-magnitude diagram and cumulative number of the events which occurred in the period from 0:00 on March 1 to 12:00 on April 2, 2011. An arrow shows the occurrence time of the 2011 off the Pacific coast of Tohoku Earthquake. Magnification of the time-magnitude diagram within  $\pm 2$  h from the main shock occurrence time is shown in the inset map.

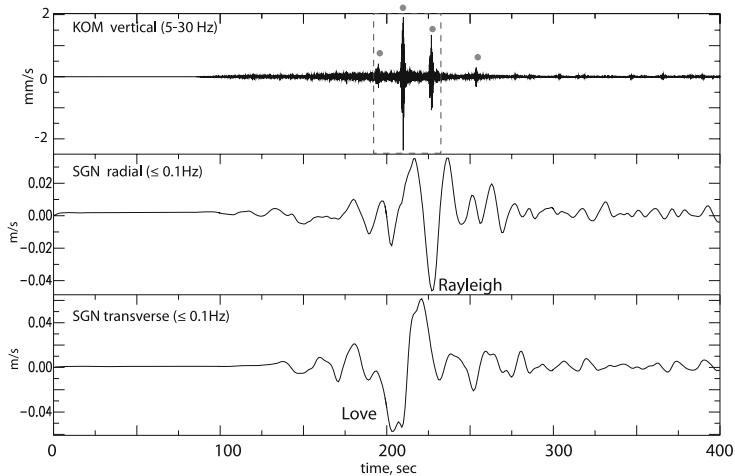


Fig. 3. Observed velocity waveforms from the 2011 off the Pacific coast of Tohoku Earthquake (top) filtered with a passband from 5 to 30 Hz at the borehole high sensitive station KOM and (middle and low) filtered with passband less than 0.1 Hz at the broadband station SGN (40 km north of the Hakone volcano). Zero is taken at 14:46 on March 11, 2011. The two station locations are shown in Fig. 1.

magnitude of static stress changes caused by the main shock is significantly smaller than that of dynamic stress changes. Moreover, it seems that seismicity during the main shock wave train is high during the arrival of large amplitude Love and Rayleigh waves (Fig. 3). Belardinelli *et al.* (2003) indicated that large dynamic stress changes can trigger earthquakes without a time delay. The instantaneous response of the seismicity to the arrival of the large amplitude surface waves (Fig. 3) strongly suggests that the dynamic stress changes predominantly contributed to initiate a sequence of seismic activity in the Hakone volcano. Belardinelli *et al.* (2003) also showed that static stress changes can trigger earthquakes with a wide variety of time delays, while dynamic stress changes can only cause instantaneous failures. Since the previous studies showed that a static stress change of 0.01 MPa promoted seismicity (e.g. Hardebeck *et al.*, 1998), the static stress changes of 0.04 MPa may be large enough to trigger earthquakes. Indeed, in the Hakone volcano, Yukutake *et al.* (2011) demonstrated that the static stress changes of 0.01–0.045 MPa probably triggered the

swarm earthquakes in the later stage of the 2009 activity. The long duration of the seismicity over a month and its slow decay (Fig. 2(c)) might suggest that the static stress changes were responsible for the activity as well as the dynamic stress changes.

Prejean *et al.* (2004) indicated that dynamic stress changes induced by the 2002 Denali Fault Earthquake ( $M_w$  7.9), Alaska, remotely triggered seismicity in a geothermally active region of the west coast of the United States, such as Long Valley, the Geysers geothermal field and Mount Rainier. Peak dynamic stress changes from the Denali Fault Earthquake at these sites are 0.01–0.09 MPa, that is a small order of magnitude compared with those of the main shock. We examined whether the seismicity in the Hakone volcano showed temporal changes in response to prior large distant earthquakes: the 2003 Tokachi-oki earthquake ( $M_{JMA}$  8.0) and the 2008 Iwate-Miyagi Nairiku earthquake ( $M_{JMA}$  7.2). The peak dynamic stress changes caused by these earthquakes are 0.04 and 0.02 MPa, respectively, around the Hakone volcano. Unfortunately, high-

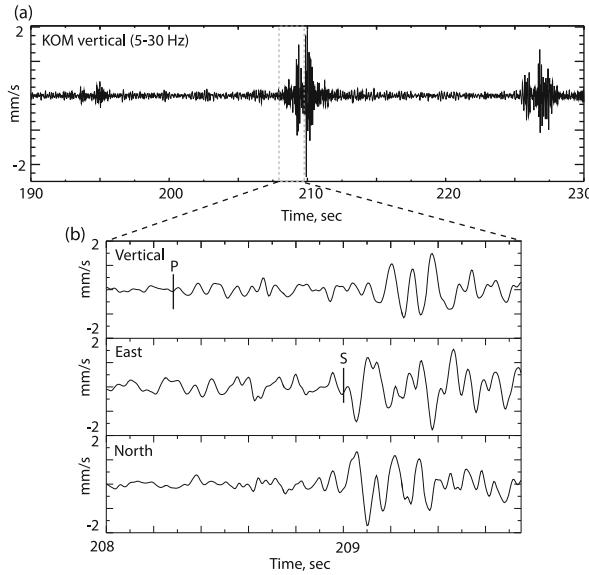


Fig. 4. (a) Magnification of the broken rectangle in the top trace of Fig. 3. (b) Detail of record from (a), showing phases from local events which occurred in the Hakone volcano. Three traces indicate the vertical, east and north components from the top to the bottom.

dynamic-range instruments had not yet been installed for the HSRI station network at the occurrence times of these earthquakes. Since the waveforms of the stations within the caldera were saturated during large ground motion, we could not look for local shocks hidden in the surface wave arrivals. However, we did not find any significant temporal change in the seismicity in the HSRI catalog following these earthquakes. This suggests that the dynamic stress threshold to initiate triggered activity in the Hakone volcano might be high compared with the geothermal regions in the west coast of the United States or the threshold might be changed according to the tectonic stress level in the study region.

## 6. Conclusions

Seismic activity in the Hakone volcano was significantly activated just after the occurrence of the 2011 off the Pacific coast of Tohoku Earthquake. The onset of seismicity was initiated during the Love and Rayleigh waves from the main shock. The seismic activity persisted for approximately one month, with more than 1600 events occurring. The large dynamic stress changes of 0.6 MPa probably contributed to initiate a sequence of seismic activity. The features of the hypocenter distribution and the focal mechanisms are almost consistent with those of the earthquakes that ordinarily occur in the Hakone volcano. We would like to note that seismicity around the northern end of the Tanna Fault was activated after the main shock, where earthquakes were previously hardly observed. We installed 21 offline temporary stations in and around the Hakone caldera prior to the main shock and we are continuing the observation. Temporal and spatial distribution of the induced earthquakes and their focal mechanisms determined from this dense seismic network will help us to quantitatively understand the physical processes of the triggering in the region.

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