Influence of the March 11, 2011 M_w 9.0 Tohoku-oki earthquake on regional volcanic activities

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Two days after the March 11, 2011, M_w 9.0 Tohoku-oki earthquake, Shinmoedake volcano, located on the Japanese island of Honshu, erupted. Was this eruption triggered by the Tohoku-oki earthquake? Could Mount Fuji and Changbaishan volcanoes also be triggered to erupt? By calculating changes in the regional stress-strain field that resulted from the earthquake, we find that Mount Fuji, Shinmoedake and Changbaishan volcanoes are all located in regions of volumetric expansion. The volumetric expansions at a depth of 10 km are up to ~220 nano-strain, ~8 nano-strain, and ~14 nano-strain, respectively, for the three volcanoes. The strain changes inferred from GPS co-seismic displacements also suggest that these three volcanoes are located in regions with surface areal expansion. Considering that the expansional stress may cause the opening of magma channels, exsolution of CO₂ gases stored in magma, and a series of positive feedback effects, the Tohoku-oki earthquake may result in an increase in the activity of these volcanoes. Attention should be paid to potential triggering of volcanic eruptions by stress changes induced by the Tohoku-oki earthquake.

2011 Tohoku-oki earthquake, Mount Fuji, Shinmoedake, Changbaishan, volumetric expansion, volcanic activities

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On March 11, 2011, a great earthquake, with a magnitude of M_w 9.0, occurred off the Pacific coast of northeastern Japan. The earthquake and associated tsunami caused massive destruction and a huge number of casualties. As of April 6, the official death toll was over 12000, and more than 15000 people were reported missing (<http://news.xinhuanet.com/english2010/world/2011-04/06/c13815236.htm>). Furthermore, the earthquake-induced nuclear leakage crisis lingered with no end at sight. On March 13, two days after the earthquake, Shinmoedake volcano erupted. This was the seventh eruption in a series that started on January 19, 2011 (<http://news.xinhuanet.com/world/2011-01/26/c121028245.htm>). Was this eruption triggered by the earthquake? What effect does the earthquake have on the activities of other volcanoes located in Japan and eastern China? By studying variations of the

stress-strain field induced by the earthquake, we can assess the impact of the earthquake on the activity of nearby volcanoes. This should be helpful in understanding the mechanisms of seismic triggering of volcanic eruptions and developing an early-warning system for volcano eruptions.

Shinmoedake volcano is located at the border between the Kagoshima and Miyazaki prefectures on the island of Kyushu; it is part of the Mount Kirishima cluster of volcanoes. The crater of the volcano is about 790 m in diameter. The 3-D P-wave velocity and Q structures beneath Kirishima volcano demonstrate high attenuation and a low velocity anomaly at a depth of ~10 km [1,2], indicating possible magmatic activities. Mount Fuji is located southwest of Tokyo, on the border between Shizuoka and Yamanashi prefectures in central Honshu. The 3-D P- and S-wave velocity structures suggest existence of supercritical volatile fluid, such as H₂O and CO₂, at depths of 7–17 km beneath Mount Fuji, and there might be partial melting of basaltic

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rocks at depths of 15–25 km [3]. Changbaishan volcano is located at the border between NE China and North Korea and has been active in the past. The most recent eruption was in 1903. Using a Mogi source model and GPS and InSAR data as constraints, Chen et al. [4] inverted the data to determine the location of the magma chamber at ~7.9 km depth below the Tianchi volcanic crater. Using an ellipsoid point source model and GPS and leveling data as constraints, Zhu et al. [5] estimated the magma source at a depth of ~10 km. Studies of the magma evolution history of Tianchi volcano by Liu et al. [6] revealed that there might be two magma chambers located in crust and mantle respectively.

The focal mechanism solutions provided by the ERI (Earthquake Research Institute, The University of Tokyo, http://outreacheri.u-tokyo.ac.jp/eqvolc/201103_tohoku/eng/#wphase), the USGS (U.S. Geological Survey, <http://earthquake.usgs.gov/earthquakes>), and Global CMT (the Global Centroid Moment Tensor project, <http://www.globalcmt.org/CMTsearch.Htm>) all indicated that the 2011 Tohokuoki earthquake was primarily a low-angle thrust event. The ARIA team at JPL and Caltech determined the coseismic GPS displacement field in the Japanese island arc region, which showed significant eastward displacements in northern Japan, with a maximum horizontal displacement of ~5.3 m and subsidence of ~1.1 m (<http://supersites.earthobservations.org/honshu.php>). Preliminary calculations of coseismic slip distributions, determined by inverting seismic waveform data and/or the GPS coseismic displacement field, demonstrated that fault rupture extended about 400 km along strike and reached a maximum displacement of ~30 m (<http://supersites.earthobservations.org/honshu.php>).

Wang et al. [7] obtained the coseismic GPS displacements in north China and northeastern China using continuous GPS data from the Chinese and global IGS networks. These measurements attest to the impact of the earthquake on the continental region of northeast Asia, including most parts of northeastern and northern China. They record up to 32 mm of eastward motion in the border regions between China and North Korea.

The results above all indicate that Mount Fuji, Shinmoedake and Changbaishan volcanoes are located in the region mechanically affected by the 2011 Tohoku-oki earthquake. Based on the modeling result of coseismic slip distribution, we calculate the changes of stress-strain field associated with the earthquake, to study how the earthquake could affect the activity of these volcanoes.

We calculate the strain field based on the coseismic slip distribution model given by Wei et al. (http://www.tectonics.caltech.edu/slip_history/2011_taiheiyo-oki/). This model was obtained from the inversion of GPS coseismic displacement and seismic waveform data. It includes a fault that is 625 km long and 280 km wide with an upper edge at a depth of 5.35 km, striking 201° and dipping at 9° to the northwest. The maximum slip on the fault is 30 m. The reasons for choosing the slip distribution model of Wei et al. are (1) it is

constrained using both near and intermediate surface displacement field and teleseismic waveform data; and (2) it has good spatial resolution on slip distribution.

The calculations are performed in a 3-D linear elastic half-space [8]. We assume a P-wave velocity $V_p=6.7$ km/s and S-wave velocity $V_s=3.87$ km/s, and calculate the volumetric strain, which is the sum of the diagonal components of the strain tensor, in the region of 30°–46°N and 124°–150°E within the depth range of 0–100 km. The result shows that the volumetric strain is expansional throughout the region, except in the local area east of Hokkaido, where the strain is compressional (Figure 1). The volumetric strain on the Earth's surface is ~8 nano-strain in the Shinmoedake region, ~220 nano-strain in the Mount Fuji region, and ~14 nano-strain in the Changbaishan region. Figure 2 shows volumetric strains in different depths beneath Mount Fuji, Shinmoedake and Changbaishan volcanoes, showing an obvious expansion status in the crust and upper mantle.

Shinmoedake and Changbaishan volcanoes are located far from the epicentral region of the earthquake. The coseismic slip distribution model of Wei et al. does not predict the displacement fields of these regions very well. We therefore attempt to corroborate the modeling result using an independent dataset. We derive the surface areal strain by interpolating [9] the GPS coseismic displacement (ftp://sideshow.jpl.nasa.gov/pub/urs/ARIA/ARIA_coseismic_offsets.v0.3.table [7]) field directly. The results (Figure 3) show that Mount Fuji, Shinmoedake, and Changbaishan volcanoes are all located in the region of areal expansion, with expansion rates of ~203 nano-strain, ~85 nano-strain, and ~46 nano-strain, respectively. Because the magma chambers are located at depths of a few kilometers to several tens of kilometers below the surface, their activities should depend on the volumetric expansion rates at depth, not the areal expansion rates at the surface. However, the areal expansions at the surface derived from GPS coseismic displacements can be used to verify the model of Wei et al. by comparing them to the model predictions at the same locations on the surface. Based on Wei et al., the areal expansions at the surface locations of the three volcanoes are ~421 nano-strain, ~14 nano-strain, and ~23 nano-strain, respectively, which are consistent with GPS derived areal strains in terms of both signs and order of magnitude. The differences in the values are likely caused by the inaccuracy of the model of Wei et al. and uncertainties and interpolation errors of the GPS coseismic displacement data. Nevertheless, the conclusion is consistent with the two results: the three volcanoes are all located in the regions of volumetric expansion, and the consistency check between the two approaches strengthens reliability of the result. The differences in values should not degrade our conclusion through qualitative analysis concerning the triggering effect of the earthquake for the volcanic eruptions.

There are many historical records of volcanic eruptions following large earthquakes [10]. Walter et al. [11] performed

Figure 1 Volumetric strain induced by the 2011 Tohoku-oki earthquake, obtained using the coseismic slip distribution model of Wei et al. (shown in the lower-right corner of the figure).

Figure 2 Volumetric strains at different depths beneath three volcanoes.

statistical analyses of volcanic eruptions following $M \geq 9.0$ megathrust earthquakes, and found that most eruptions occurred at volcanoes that are located within the dilatation areas produced by the earthquakes. They proposed a mechanism for volcanic eruption triggered by earthquake-induced volumetric expansion. According to their theory, the same strain changes may enhance the unclamping of fracture systems and allow the opening of dykes for magma intrusion [11]. Volumetric expansion or ascending basaltic magma will lead to the exsolution of CO_2 [11,12], which decreases the magma's density and viscosity and enhances

the ascent of gas bubbles and magma. Such a reaction would cause additional depressurization, further volatile exsolution [13], and volumetric expansion of the gas. A positive feedback loop may eventually lead to an eruption [11]. On the other hand, exsolution of water may stop this process [14] as it causes the viscosity of the ascending magma to increase, resulting in magma stagnation. This is more likely to be the case for H_2O -rich silicic magmas [11,14]. The interaction between silicate melts and gases following coseismic depressurization may be the key process that leads to increased magma overpressure and even-

Figure 3 Areal strain induced by the 2011 Tohoku-oki earthquake, derived from GPS coseismic displacement field.

tually to an eruption [11].

Eruption triggering depends also on the conditions of magmatic system prior to the earthquake [10], i.e. magma composition, state of equilibrium of the magma and volatiles, magma overpressure, the strength of the host rocks, and on the type, size, and offset distance of the earthquake. Because of such inherent complexity in magmatic systems and associated feedbacks, triggered eruptions may occur with a delay of days, months, or years after an earthquake. If a volcano is on the edge of eruption prior to an earthquake, even a small volumetric expansion induced by the earthquake may trigger its eruption. Before March 11, 2011, Shinmoedake volcano had erupted seven times in the preceding two months, starting with a first eruption on January 19, 2011. This reveals that the volcano was already unstable and close to eruption. Although the dilatation induced by the 2011 Tohoku-oki earthquake is only ~ 8.0 nano-strains, it still triggered a large eruption two days after the earthquake.

After the March 11 mega-earthquake, thousands of earthquakes occurred around Mount Fuji. Although most of the events were rather small, there was a M_w 6.4 earthquake that occurred on March 15 with a hypocenter just under Mount Fuji. According to our numerical modeling, the dilatation induced by the Hokoku-oki earthquake around Mount Fuji is about 220 nano-strains. Because of the existence of basaltic magma at depths of 15–25 km beneath Mount Fuji

[3], exsolution of water is less likely. Therefore, volumetric expansion may lead to magma ascension and increase the risk of volcanic eruption.

As previously mentioned, Changbaishan volcano is a modern volcano with the potential to erupt [15–17]. Deep seismic reflection studies showed that there is a magma chamber under the Changbaishan volcanic region that is manifested as a region of low seismic velocity and high electrical conductivity [18], suggesting that the volcano may be at a stage of initial perturbation or disturbance. Deformation results obtained from GPS, leveling, and tilting measurements during 2002 and 2003 in the Changbaishan volcanic region revealed significant outward expansion relative to the center of Tianchi crater and rapid uplift displacements close to the Tianchi crater [19]. These observations are characteristic of classic active magma chamber expansion and magma upwelling. Although the GPS and leveling data recorded from 2003 to 2005 indicated that the deformation activity in this region was decreasing, deep seated uplift and expansional deformation and shallow magmatism in the volcanic region were still detected [20]. Some studies suggested that the crustal magma chamber beneath the Tianchi volcano is composed of trachyte and pantellerite [6]. The volumetric expansion caused by the 2011 Tohoku-oki earthquake may lead to exsolution of H_2O there, which in turn may increase the viscosity of magma

and limit the ability of the magma to be uplifted. However, the mantle magma chamber beneath the Tianchi volcano mainly has an alkaline basalt composition [6]. Volumetric expansion there again may lead to the exsolution of CO₂, which in this case decreases the density and viscosity of the magma and promotes its ascent and depressurization. Therefore, the 2011 Tohoku-oki earthquake could increase the eruption potential of the mantle magma beneath Tianchi volcano.

The occurrence of large earthquakes that change the regional stress-strain field will furthermore cause afterslip on the fault plane and viscoelastic relaxation in the lower crust and upper mantle. Such deformational process may last for years, decades, or even centuries. The seismic moment released by afterslip following a large interplate earthquake, in some cases, could even be comparable to that which is released in the coseismic rupture [21–23], and the viscoelastic relaxation in lower crust and upper mantle could affect much greater regions. Such a scenario would further increase the eruption potential of Changbaishan volcano. For this reason, it is vitally important to pay close attention to the volcanic activity of Changbaishan, and closely monitor stress and strain variations in the region.

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