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Volcanic strain change prior to an earthquake swarm observed by groundwater level sensors in Meakan-dake, Hokkaido, Japan

Hiroaki Takahashi\textsuperscript{a}, Tomo Shibata\textsuperscript{b}, Teruhiro Yamaguchi\textsuperscript{a}, Ryuji Ikeda\textsuperscript{a}, Noritoshi Okazaki\textsuperscript{b}, and Fujio Akita\textsuperscript{b}

\textsuperscript{a} Institute of Seismology and Volcanology, Hokkaido University, Sapporo, Japan
\textsuperscript{b} Geological Survey of Hokkaido, Sapporo, Japan

Abstract

We installed and operated a low-cost groundwater level observation system at intermittent hot spring wells in order to monitor volcanic strain signals from the active Meakan-dake volcano in eastern Hokkaido, Japan. Data are sampled at 1 Hz and are transmitted to the data center in real time. Evaluation of the water level time series with theoretical predictive tidal strain and coseismic static strain changes has suggested that the wells penetrate to the artesian aquifer and act as a volumetric strain sensor. An active earthquake swarm with more than 400 events occurred at the shallower part of the volcano from January 9 to 11, 2008. Three independent wells recorded pre- to co-swarm groundwater drops simultaneously, which represented a decrease in volumetric strain. The total volumetric strain change during the three active days was estimated to be from 6 to $7 \times 10^{-7}$. The observed data, including changes in volumetric strain, absence of deformation in the GPS coordinates, and activation of deep low-frequency earthquakes, might imply possible deflation of a source deeper than 10 km, and these preceding deeper activities might induce an earthquake swarm in a shallower part of the
1. Introduction

The Meakan-dake volcano in eastern Hokkaido, Japan, is an active volcano with an elevation of 1,499 m (Fig. 1). The Meakan-dake volcano is a typical island-arc volcano associated with the subducting Pacific plate. Although historical records are limited, several phreatic eruptions have been recorded since 1955. Effusive rock compositions of this volcano are dacite, andesite, and basaltic andesite (Wada, 1991). Three major stages of explosive eruptive activity at 12 ka, 9 ka, and 5 to 6 ka were associated with the generation of pyroclastic flows, and successive lava effusions have continued fitfully over the last few thousand years. The most recent magmatic eruption was estimated to have occurred anywhere from several hundreds of years to thousands of years ago (Wada et al., 1997).

In 1956, the Japan Meteorological Agency (JMA) installed a seismograph, which has been operated routinely since 1973. The number of earthquakes per day sometimes exceeded 400 when an active earthquake swarm occurred (Fig. 2a). However, none of these earthquakes were felt because of their miniscule magnitude. Small phreatic eruptions in 1988, 1996, 2006 and 2008 occurred following an earthquake swarm.

Geothermal fields and hot springs are located on and near the volcanic edifice. Prior to 2004, the average temperature of active fumaroles in the summit crater (Fig. 1) had been approximately 400°C (Fig. 2b). However, a decrease in temperature was observed over the last decade, and recent data gathered during the spring of 2008 indicated that the temperature was less than 100°C (Fig. 2b).

Crustal deformation associated with volcanic activity can be used to investigate the
maggmatic and/or geothermal system beneath the volcanic edifice. However, recent
space geodetic techniques such as GPS and InSAR provide high-quality geodetic data,
strain observations can provide higher precise signals that cannot be detected by GPS
(e.g., Agnew and Wyatt, 2003, Ueda et al., 2005, Chardot et al., 2010). Although high
installation cost is one of main difficulties in establishing a new site, Hokkaido
University and the Geological Survey of Hokkaido started a low-cost groundwater level
change observation at intermittent hot spring wells to monitor the strain activity of the
Meakan-dake volcano. We herein report a volcanic strain event determined using the
newly proposed groundwater observation system.

2. Groundwater level observation

Several studies have shown that, under proper conditions, artesian groundwater acts as
a volumetric strain sensor (Wakita, 1975, Roeloffs, 1988, Quilty and Roeloffs, 1997,
al., 2010, Gahalaut et al., 2010). The suggested volcanic strain signals might also be
observed as groundwater level changes. In order to monitor volcanic unrest signals
using groundwater level data, we used three preexisting intermittent hot spring water
wells, AK1, AK3, and AK4, which are situated approximately 8 km NNE from the
volcano summit (Fig. 1). The parameters of each well are listed in Table 1 (Kawamori et
al., 1987). Well AK1 had a borehole depth of 1,061 m with a strainer located at a depth
of between 518 and 1,061 m, whereas wells AK3 and AK4 had shallower boreholes (92
and 57 m) with strainers located at depths of between 24 and 55 m and between 41 and
57 m, respectively. These facts indicate that AK1 and AK3-4 penetrate different aquifers.
In order to measure the groundwater levels, in April of 2006, we installed a water
pressure measurement sensor (Druck PTX1830) approximately 5 m below the water surface. The hydraulic heads from the ground surface are 1 m for AK1 and 0.5 m for AK3 and AK4. The sensor resolution is less than 1 mm. A barometric pressure sensor was also deployed at the same location in order to eliminate barometric pressure effects on the water levels. The obtained data are converted to digital signals using a 24-bit AD converter at a sampling rate of 1 Hz and are transmitted in real time to the data center at Hokkaido University via IP protocol. A precise time calibration is accomplished by on-site GPS receivers every two hours. All data are stored in a crustal deformation database system (Yamaguchi et al., 2010) and are distributed to concerned institutions in pseudo-real time.

The proportion of the groundwater level to crustal strain was evaluated by Saito (2008). He analyzed raw water level data for a period of one month using BAYTAP-G tidal analysis software (Ishiguro et al., 1981, Tamura et al., 1991). The time series of the tidal response, the barometric pressure response, and the irregular and trend components were deconvoluted. The barometric component was obtained using barometric pressure data observed at the observation site. Clear responses to tidal components were observed at AK1 and AK4, suggesting that these wells are under artesian influence. In contrast, a less clear response was observed at AK3, indicating that this well is not under artesian influence. Based on these observations, Saito (2008) concluded that the sensitivity coefficients of the M2 tidal component (period: 12.42 hours) were dominant and had a smaller phase difference. The coefficients of volumetric strain to the groundwater level were estimated by comparing the theoretical volumetric tidal strains of earth and ocean loading calculated using GOTIC2 tidal loading computation software (Matsumoto et al., 2001), and the observed tidal components were decomposed by
BAYTAP-G software. The strain sensitivities to the M2 tidal constituent, \( W_s \), were calculated as follows:

\[
W_s = \frac{T_w}{T_t}
\]

where \( T_w \) and \( T_t \) are the water level and theoretical amplitude of the M2 tidal component, respectively (Table 1).

In order to validate the above procedure, a suitability test of the response coefficient was conducted by comparing coseismic water level changes with theoretical values observed at AK1. The result also indicated properness of the water level coefficients to volumetric strain. In addition, a suitability test by Saito (2008) revealed that the actual coseismic response of AK4 was not consistent with the theoretical values, and he suggested applying an inflow model to this well. The above considerations indicate that AK1 has a good response to strain changes for a wide range of periods, whereas AK4 has a good response only for phenomena having a period longer than the M2 tide. The observations on AK3 can be used as supplemental data.

3. Volcanic earthquake swarm and groundwater level changes

An earthquake swarm began at 17:00 on January 9, 2008. Note that we hereinafter use Japan Standard Time (JST) (GMT+9). The number of earthquakes increased until 12:00 January 10 and then decreased until 23:00 January 10. The hypocenters of the volcanic earthquakes determined by the Sapporo district Meteorological Observatory (SMO) of the JMA volcano observation network were concentrated just under the summit crater at an elevation of 0 to 0.5 km (Fig. 3). The maximum number of hourly earthquakes exceeded 40, and the total number of earthquakes over a three-day period was 624. None of the earthquakes were felt because the maximum magnitude was less than 0.5.
Webcams installed by the JMA and other institutes did not capture any anomalous activity, such as smoke escaping from active vents. Moreover, the GPS stations operated by the JMA did not detect any signals during this swarm (Fig. 4).

Prior to this earthquake swarm, the lowering of the groundwater level began at the three wells simultaneously, indicating a decrease in volumetric strain. Figure 5 shows the changes in the original water levels, the barometric pressure, and the corrected water levels of AK1 for two weeks before and after the event. Although a clear water level decrease was observed in the original record corresponding to the swarm activity around January 10, the fluctuation of the water level was influenced by barometric pressure and tidal strain. In order to eliminate these noises in the groundwater level data, we applied BAYTAP-G tidal analysis software with barometric pressure data (Ishiguro et al., 1981, Tamura et al., 1991). Note that no precipitation effect was considered because snow cover was observed until mid-December. Figure 6 indicates the corrected water levels of the three wells. These independent wells showed the water decreasing coherently. This should correspond to a real phenomenon because the three wells are spatially independent and have different depths. Figure 6 also shows the dilatational strain recorded by a quartz tube strain meter at a nearby TES station located 25 km east of the AK wells (Fig. 1b). Comparison with TES dilatation clearly indicated that the groundwater signals at the AK wells were not tied to regional phenomena (Fig. 6). Note that the linear dilatational trend at the TES station is a portion of secular deformation signal. The above consideration strongly suggests that these water signals were related to local events induced by the volcanic unrest of the Meakan-dake volcano.

Changes at the three wells appeared to begin before earthquake swarm occurrence. A differential rate of water level change at AK1 indicated that the water table fall started at
20:00 January 8 (Fig. 6), which is approximately 21 hours prior to earthquake swarm initiation (Fig. 6). This clearly indicates that tensinal dilatation had progressed at the AK wells without showing earthquake activity. The earthquake swarm began at almost the maximum water table drop during the period of interest. All of the water levels decreased and did not recover until at least 20 January. The amplitudes of the total water decrease at AK1, AK3, and AK4 were approximately 25 cm, 3 cm, and 4 cm, respectively. The sensitivity coefficient difference (AK1 is 5.8 times larger than AK4) is consistent with that of the water level change values. In fact, the volumetric strain values calculated using the estimated sensitivity coefficients was of approximately the same order (Table 1).

The above results provide an idea of how to evaluate the unknown sensitivity of AK3. The AK wells are located in close proximity to each other relative to the distance to the deformation source location. This allows us to assume that the geometrical effect generated by source parameters is small. Hence, the volumetric strain changes at the three wells should be equivalent if the source exhibits radial symmetry. The coefficient of AK3 was estimated through comparison with the AK1 and AK4 water drop values (Table 1). This also implied that AK3 might act as a volumetric strain sensor for a period of a few days.

4. Discussion

The observed data strongly suggested that water level changes were related to the volcanic unrest of the Meakan-dake volcano. However, the biased location of the wells did not allow us to estimate the deformation source parameters of the strain event. The JMA have operated a continuous GPS network in this volcano for some time (Fig. 1).
Baseline length changes for a month including an earthquake swarm period suggested that this network can detect a displacement signal of more than a few centimeters (Fig. 4). We assumed detection resolutions of 1 cm and 2 cm for the baseline and vertical components, respectively. No significant displacement signals exceeding the above resolutions were observed before, during, or after the swarm, which provides a strong constraint for deformation source modeling.

We used water level and GPS data to estimate the depth and volume change of the deformation source. A buried point source, the Mogi model (Mogi, 1958), was assumed for modeling. The lack of GPS displacement for all of the baselines suggested that point source location estimation based on these data would be impossible. The epicenters of both the shallower earthquake swarm (Fig. 3) and the deep low-frequency earthquakes (DLEs) were concentrated just beneath the summit crater. Wherefore, we fixed the horizontal location of a point source to the summit crater a priori. The depth and volume change were valuable for modeling. The displacement and strain field was computed using Okada’s (1992) formula, and the Poisson ratio and Lame’s constant were set to 0.25 and $\mu = \lambda$, respectively.

We evaluated the variation change of root mean square (rms) residuals by changing the depth and volume parameters following a grid-search procedure. The grid intervals were set at 1 km for depth and 0.001 km$^3$ for volume change. We first examined a point source at a depth of 3 km because the hypocenter depth of the earthquake swarm was concentrated near sea level (Fig. 2). The depression volume of 0.004 to 0.005 km$^3$ well explained the water level data, but coincidently induced a displacement of more than a few centimeters on GPS baselines and vertical components. This was not consistent with the observed data, and, as such, indicated that the water drop might not be due to
shallowest source deflation.

The rms distributions for each depth and volume change parameter are shown in Fig. 7. Note that the rms for GPS baselines and vertical components were computed based on the root-mean for the sum of each squared residual, and each rms is normalized by the apparent value. The rms distribution of both GPS baselines (Fig. 7a) and the GPS vertical component (Fig. 7b) exhibit bilateral symmetry, and a deeper source provides a lower rms, which indicates that a deeper source is preferable to a shallower source. The gradient rate along the lateral axis is also smaller for a deeper source and larger for a shallower source.

On the other hand, the rms of the AK1 volumetric strain indicates an asymmetric distribution (Fig. 7c). The left- and right-hand segments are due to the deflation and inflation of the point source, respectively. Small, broad rms segments appear in the left-upper side. This rms distribution indicates that deflation is preferable to inflation. The local rms minimum appearing in right-lower side might not be correct because of the inconsistency with the rms maps of GPS baselines and vertical data. However, these three rms maps do not provide the optimal parameters because no common minimum spot was identified. Proper weighting for joint data treatment is difficult due to differences in data quality. Nevertheless, comparison of the three rms distribution maps may provide a clue for searching for reasonable parameters. For example, a source at a depth of greater than 10 km with a deflation of 0.01 km$^3$ generates a smaller rms than a shallower depth. No signal at TES station was also consistent with above assumption. These considerations with respect to the rms maps suggest that the observed data might be explained well by the possibility of a deeper source having a deflation volume of approximately 0.01 km$^3$. A strain observation array with a proper station distribution is
Takahashi and Miyamura (2009) found that the activity of DLEs in the Meakan-dake volcano is the second highest among Japanese quaternary volcanoes. Source mechanism studies of DLEs have suggested possible crack openings caused by fluid (Nakamichi et al., 2003). Activation of DLEs prior to eruption or magmatic unrest had been reported at several volcanoes (White, 1996, Nakamichi et al., 2003), and DLE activations without successively eruption have also been reported (Nichols et al., 2011). In the Meakan-dake volcano, more than 800 DLE events were recorded during the decade before the 2008 earthquake swarm. The epicenters and DLEs were concentrated just beneath the summit crater at depths of 20 km and 25 km, respectively (Takahashi and Miyamura, 2009). These findings imply the possible presence of fluid and/or magma in the DLE hypocenter region. The cumulative number of DLEs and shallow volcanic earthquakes (SVEs) as determined by the JMA during the earthquake swarm is shown in Fig. 8. An increase in the number of DLEs started the night of January 8 at a depth of between 15 and 20 km nearly simultaneously with the water table decrease at the AK wells.

The observed groundwater level and GPS data suggest a possible interaction between deeper deflation and the shallow earthquake swarm. The rapid response of shallower seismic activity to DLEs activations were observed during the Mt. Pinatubo (White, 1996) and Mt. Iwate (Nakamichi et al., 2003) unrests. In the Meakan-dake volcano, a delay of only one day of shallower activity posteriori to the initiation of strain signals implied that a possible upward volatile migration generated the swarm. However, observed data that indicating no eruption, no change in smoke amount and active vent temperature did not seem to support this idea (Fig. 2).
Self-potential surveys suggested a possible permeable layer at around sea level (Matsushima et al., 1994, Zlotnicki and Nishida, 2003). Volcanic gases, e.g., H$_2$S, SO$_4$, and CO$_2$, have high water solubility (National Astronomical Observatory of Japan, 2010). If we accept the hypothesis that upward volatile migration occurred as the water table descended, then the lack of surface phenomena might suggest that the aquifer acted as a barrier due to the dissolution of ascending volcanic volatiles in water. Chemical component analysis of hot spring water 2 km west of the summit crater reveals very higher concentration of H$_2$S to be 34.99 mg per liter and of SO$_4$ to be 1,615 mg per liter, respectively (Geological Survey of Hokkaido, 1980). This also implies possible volcanic gas dissolution in the shallower aquifer. Continuous chemical component analysis of hot spring water may provide clues to help clarify the interaction between the shallower aquifer and volcanic volatile migration.

A schematic diagram of the possible volcano system of the Meakan-dake volcano is shown in Fig. 9. The time series of the observation data, the existence and activation of DLEs, the possible deflation of a deeper source, and the shallow seismic activity imply a strong relationship between these phenomena. However, no obvious migration processes, such as earthquakes, were documented along possible channels between the deep and shallow active zones. This puzzling feature was also exhibited by the 1991 Mt. Pinatubo catastrophic eruption (White, 1996). Unmodeled but likely mechanisms in volcanic fields, e.g., viscoelastic and/or anelastic responses, should also be considered in the future. Detailed monitoring by hydrologic and mechanical parameters is required in order to confirm a realistic model that can fully explain observed data. A strain observation array that has sensitivity to mid-crustal depth will be fundamental in order to clarify the conduit process between the DLE epicenter and the shallower seismic


5. Conclusion

We have started groundwater level observations at intermittent hot spring wells near the active Meakan-dake volcano using a low-cost system. Simultaneous lowering of the water level prior to a volcanic earthquake swarm was recorded at three independent wells. The total volumetric strain changes associated with an earthquake swarm was 6 to $7 \times 10^{-7}$. Proper point source (Mogi model) parameters were sought using water level and GPS data. Although optimal parameters were not defined because of an insufficient data set, several assumption and residual distribution maps suggest a possible deflation source at a greater depth (>10 km) with a volume change of approximately 0.01 km$^3$. Synchronization in space and time between DLE activation and possible deflation source activity was recognized. Although the timeline of deeper activities and a shallower earthquake swarm might imply that the earthquake swarm was triggered by upward migrating volatile, no physical model or observation data were presented. The observation data of the present study clearly demonstrate low-cost groundwater level observation at existing wells can record volumetric strain with high precision, on the order of $10^{-7}$. The proposed monitoring system can be easily expanded because of the numerous unused hot spring wells that exist near active volcanoes.

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References


Saito, T., 2008. Responses of the groundwater level to crustal strain: observation of 1Hz sampling at Akan hot-spring wells in Hokkaido, Japan, Master thesis of Hokkaido University, 72pp.


Figure captions

Fig. 1 (a) Map showing the geographical location of the Meakan-dake volcano indicating the tectonic background. The dashed lines show the plate boundaries. (b) Close-up of the rectangular area shown in Fig. 1(a). The nearest TES strain station and GPS station (0496) are also indicated. (c) Location of well stations (AK1, AK3, and AK4), GPS stations (0497, 9014, 0561, and 0182), and active vent 96-1, at which temperature observations were made. An inset rectangular is used in Fig. 2.

Fig. 2 (a) Number of volcano earthquakes per day, and (b) temperature recorded at active vent 96-1 crater shown in Fig. 1(c), from January 2000 to October 2008.

Fig. 3 Hypocenter distribution of the earthquake swarm from January 9 to 11, 2008, as determined by the Sapporo District Meteorological Observatory of the Japan Meteorological Agency. Hypocenters were estimated using data from more than four stations. The horizontal and origin time errors were less than 400 m and 0.2 s, respectively.

Fig. 4 Baseline length changes between the GPS stations shown in Fig. 1.

Fig. 5 Time series of the original water level, barometric pressure, and corrected water level by BAYTAP-G at the AK1 station for two weeks before and after the earthquake swarm of January 9 through 11, 2008.

Fig. 6 Water level data of the AK1, AK3 and AK4 wells. Tidal effects were eliminated using BAYTAP-G tidal analysis software. Dilatational strain records at the TES station, and the number of earthquakes per hour as counted by the Sapporo District Meteorological Observatory of the Japan Meteorological Agency are also indicated. The initiation of the water table fall of AK1 and the initiation of the earthquake
swarm are indicated by dotted and dashed lines, respectively.

Fig. 7 The rms residual distribution maps. (a) the rms summation of each GPS baseline, (b) the rms summation of each GPS vertical component, and (c) the rms of volumetric strain change of AK1. Contouring is performed using a normalized apparent rms value for each data type.

Fig. 8 Cumulative number of deep, low-frequency earthquakes (DLE), and shallow volcanic earthquakes (SVE).

Fig. 9 Schematic diagram of the volcanic unrest during January 2008. DLE: deep, low-frequency earthquake, SVE: shallow volcanic earthquake. Note that no earthquakes were observed between the deep and shallow active zones during the swarm period.
Table 1 Parameters of observation wells.

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<th>Volumetric strain coefficient (mm/10^8 strain)</th>
<th>Water level change (cm)</th>
<th>Volumetric strain change (microstrain)</th>
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Coefficient of AK3 is deduced from swarm-related water change comparing to AK1 and AK4.
Fig. 1
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Fig. 3
Figure

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Fig. 7
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