Monitoring eruption activity using temporal stress changes at Mount Ontake volcano

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Volcanic activity is often accompanied by many small earthquakes. Earthquake focal mechanisms represent the fault orientation and slip direction, which are influenced by the stress field. Focal mechanisms of volcano-tectonic earthquakes provide information on the state of volcanoes via stresses. Here we demonstrate that quantitative evaluation of temporal stress changes beneath Mt. Ontake, Japan, using the misfit angles of focal mechanism solutions to the regional stress field, is effective for eruption monitoring. The moving average of misfit angles indicates that during the precursory period the local stress field beneath Mt. Ontake was deviated from the regional stress field, presumably by stress perturbations caused by the inflation of magmatic/hydrothermal fluids, which was removed immediately after the expulsion of volcanic ejecta. The deviation of the local stress field can be an indicator of increases in volcanic activity. The proposed method may contribute to the mitigation of volcanic hazards.

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The local stress field around volcanoes represents the superposition of the regional stress field and stress perturbations related to volcanic activity. Temporal stress changes over periods of weeks to months are generally attributed to volcanic processes. Examining the focal mechanism solutions of volcano-tectonic (VT) earthquakes provides detailed information on the state of a volcano via the local stress field. This has the potential to contribute to prediction of eruptions over the short and medium term (weeks to months).

Mt. Ontake volcano is the second highest stratovolcano in Japan and is located at the southern end of the Northern Japan Alps. On 27 September 2014, around 11:52 hours JST (UTC+9), Mt. Ontake produced a hydrothermal (steam-type) eruption with a volcanic explosivity index (VEI) value of 2 (ref. 5). Mt. Ontake had been considered dormant until its first historical eruption in October 1979. The 2014 eruption struck on a sunny Saturday in the autumn foliage season, resulting in the worst volcanic disaster in Japan in the last 90 years: 58 people died and 5 are still missing.

Mt. Ontake is continuously monitored by several relatively dense networks of permanent seismic stations operated by Nagoya University, Japan Meteorological Agency (JMA), National Research Institute for Earth Science and Disaster Prevention (NIED), and Gifu and Nagano prefectures (Fig. 1a,b). The summit region of Mt. Ontake (Fig. 1a,b; latitude 35.875° N–35.900° N, longitude 137.44° E–137.50° E) is normally almost aseismic, with an average of less than one event (M < 0) per month, whereas the surrounding region is characterized by a high level of background seismicity (see Methods). The onset of VT earthquakes was observed on 31 August 2014 (Fig. 1b,c), reaching a peak on 11 September 2014 before decaying over time until the eruption, although the seismicity increased again between 15 and 21 September 2014 during this period. Long-period earthquakes with peak frequencies of 1–5 Hz were recorded beginning around 15 September, but less than 10 long-period events were detected in real time. Application of a matched-filter technique to continuous waveforms (23 August to 30 September 2014) resulted in detection of thousands of microseismic events, indicating that an increase in VT events was followed by an increase in the number of long-period events 5 days later. This detailed analysis also revealed that VT events beneath the craters migrated upwards as well as laterally in the NNW–SSE direction for the final 10 min preceding the eruption. The phenomenon synchronized with a rapid increase of pre-eruptive tremor amplitudes and with an unusual tiltmeter signal indicating summit upheaval. After the eruption, the magnitudes of events became larger (M < 1); in contrast, most pre-eruption events had a magnitude of less than 0.

The time history of volcanic earthquakes during the pre-eruption period was explained by the generic volcanic earthquake swarm model. In this respect, the history was similar to that associated with a previous minor eruption in 2007 (VEI = 0). However, unlike the 2007 eruption, the 2014 eruption was not preceded by active volcanic tremors and inflation of the volcanic edifice until 7 min before the eruption. The time scale for the precursor period was also different from that in 2007. In general, the various observations of precursor processes make eruption forecasting difficult, although changes in volcanic seismicity have been successfully used empirically for predicting eruptions.
The local stress field beneath volcanoes is directly influenced by the inflation of the ascending magma and magmatic/hydrothermal fluids1–4. As the focal mechanism solution of VT events contains information on the local stress field, the relationships between stresses and volcanic processes have been studied by examining focal mechanisms and using theoretical models with the aim to successfully predict eruptions1–4,12–17. However, systematic spatiotemporal changes in focal mechanisms do not necessarily indicate changes in the stress field18, because earthquakes can be triggered at faults that are misoriented to the stress field by a decrease in fault strength caused by an increase in pore fluid pressure19,20. This effect cannot be ignored when evaluating the local stress fields beneath active volcanoes because the existence of over-pressurized fluids is certain.

Here we propose a method to detect true temporal changes in the local stress field beneath Mt. Ontake by examining the focal mechanism solutions of VT events relative to the regional stress pattern. Enhanced volcanic activity causes significant stress perturbation with E–W tension, using the crustal structure controlled by the regional stress field. This results in a large deviation of the local stress field from the regional stress field before the 2014 eruption. We demonstrate that quantitative evaluation of temporal stress changes is an effective tool for eruption monitoring.

Results
Focal mechanism solutions of VT earthquakes. We estimated the focal mechanism solutions of 94 VT earthquakes in the summit region (August 2014 to March 2015) from S:P amplitude ratios and P wave polarity data obtained through the dense seismic networks (Fig. 1a) using the HASH software package21. In the analysis, we assumed that the source was double couple (DC) and considered three velocity models (Supplementary Fig. 1) to account for possible errors in the hypocentres and take-off angles (see Methods). These solutions (Supplementary Table 1) were classified into four types based on the angle of the pressure, null and tension axes (P, N and T axes, respectively) with respect to the horizontal22: normal faulting, strike–slip faulting, reverse and tension axes (P, N and T axes, respectively) with respect to (see Methods). These solutions (Supplementary Table 1) were classified into four types based on the angle of the pressure, null and tension axes (P, N and T axes, respectively) with respect to the horizontal22: normal faulting, strike–slip faulting, reverse and others (odd faulting) (Fig. 2a). The pre-eruption seismicity was dominated by normal faulting, which accounted for 7 (=41%) of the 17 events in this period. The mean orientation of the T axes during the precursory period was N75°E with an s.d. of 13° (Fig. 2b and Supplementary Fig. 2a). After the eruption, in contrast, 40 (=52%) of the 77 events showed reverse faulting, and normal faulting events became relatively rare (Fig. 2a). The mean orientation of the P axes during the post-eruption period was N101°E with an s.d. of 13° (Fig. 2c and Supplementary Fig. 2b), sub-parallel to the T axes of the precursory period, indicating that the local stress field was markedly different during the periods before and after the eruption.

Regional stress field around Mt. Ontake. To determine the relationships of the focal mechanism solutions to the regional stress field, we estimated the regional stress pattern around Mt. Ontake from 536 focal mechanism solutions (M ≥ 1) during a period of typical background seismicity (May 2012 to July 2014) using the centroid moment tensor (CMT) data inversion method23 (see Methods). The stress field was roughly characterized by strike–slip faulting in the entire region. The axes of the maximum and minimum compressive principal stresses were sub-horizontal in the summit region, oriented N64°W and N25°E, respectively (Supplementary Fig. 3), consistent with the previous studies24–26. The orientations of the maximum and minimum horizontal principal stress axes varied within

N57°W–N72°W and N17°E–N33°E, respectively (see Methods). In a different region with an active micro-seismic swarm (Fig. 1a; latitude 35.85°N–35.95°N, longitude 137.6°E–137.7°E) the stress pattern was very similar to that in the summit region, but the fluctuation ranges of the principal stress axes were smaller (<10°) because of sufficient data for the inversion.

Temporal evolution of misfit angles. We calculated the misfit angle φ of focal mechanisms between the observed slip vectors and theoretical slip vectors expected from the regional stress field on the basis of the concept that seismic slip occurs in the direction of the resolved shear traction acting on a pre-existing fault27,28 (see Methods). When the misfit angles are less than the estimation errors of the regional stress field and focal mechanism solutions, events are considered to be consistent with the regional stress field, because the actual slip vector agrees with the theoretical one within the estimation errors. For events in the summit region, the threshold value was ~65° (errors in stresses: <20°; errors in focal mechanisms: <45°). Focal mechanism solutions with φ ≥ 90° are considered highly inconsistent because the actual and theoretical slip vectors are opposite. Before the eruption, only 5 (=29%) of the 17 VT events were consistent
than a threshold value of 55° in the regional stress field (Fig. 1a) from the regional stress field. The thin red lines show another threshold angle (90°) to detect a large inconsistency of the local stress field to the regional stress field. The yellow hatched zones indicate enhancements of misfit angles above the threshold values.

The mean orientation of the T axes of pre-eruption events (N75°E ± 13°) was roughly perpendicular to the near-vertical plane (strike N15°W) on which the relocated hypocentres of VT events were concentrated and to the alignment of craters from the 2014 eruption (Fig. 2b,c). Prior to the 2007 and 2014 eruptions, very long-period earthquakes with a period of >20 s were recorded at broadband seismic stations: the sources of these earthquakes are modelled by tensile cracks with strikes of N20°W (for the 2007 event) and N6°W (for the 2014 event). These results suggest that a volcanic system exists beneath Mt. Ontake in which inflation is driven by magmatic/hydrothermal fluids propagating upwards in a vertical crack. We suggest that the inflation caused a stress perturbation with E–W to ENE–WSW propagation upwards in a vertical crack. We suggest that the inflation caused a stress perturbation with E–W to ENE–WSW.
Five years after the first historic eruption of Mt. Ontake in 1979, the local stress field (Fig. 4a and Supplementary Fig. 3), indicating that the Mt. Ontake eruption conduit followed structures with orientations controlled by the regional stress field32,34. When the inflationary pressure is sufficiently high, clockwise rotation of the maximum and minimum principal stress axes occurs ahead of a propagating tensile crack (Fig. 4b)35. Strong tension may weaken the principal horizontal compressive stresses, meaning that the (vertical) intermediate principal stress becomes the maximum stress, resulting in a local stress field characterized by normal faulting with E–W tension (Fig. 4c). An increase in b-values during the pre-eruption period, although the values gradually declined from 16 September 2014 to just before the eruption, may be related to strengthening of the tensile stress field due to the enhanced hydrothermal activity6,36.

As the hypocentral depths during the post-eruption period were systematically <1 km shallower than those before the eruption6, we cannot rule out that the regional stress field in the summit region is heterogeneous on a small scale. If the regional stress field was locally characterized by E–W tension in the source region of the precursory events, stress perturbation with E–W tension would increase the deviatoric stress, which would promote seismic slip with positive changes in the Coulomb failure function37. As the summit region is usually aseismic, activation of normal faulting with E–W tension can be an indicator of an increase in volcanic activity.

The time history of average misfit angles showed another slight enhancement in November 2014 other than that in January–February 2015. This indicates that re-pressurization of magmatic/hydrothermal fluids beneath Mt. Ontake commenced again at the beginning of October 2014. The decreases in misfit angles following the two enhancements indicate that some de-pressurization of magmatic/hydrothermal fluids, for example, as a result of an undetected minor eruption, occurred at the end of November 2014 and February 2015.

The local stress field in the peripheral swarm region (Fig. 1a) slightly deviated from the regional stress field for a week before the 2014 eruption. An inversion analysis of focal mechanism solutions, repeated precise levelling measurements, magnetotelluric measurements, and geochemical analyses of water and gas samples demonstrated the presence of over-pressurized fluids in the region38-41. The porous network in the underground rock around Mt. Ontake is not well-known42. However, pore fluid pressures in the peripheral swarm region may have been increased by the volcanic processes at Mt. Ontake, which in turn may have caused temporal changes in the stress field of the peripheral swarm region. In that case, interaction between the volcanic eruption and inland earthquakes would be important. Five years after the first historic eruption of Mt. Ontake in 1979, the Western Nagano Prefecture earthquake (Mj 6.8) occurred in the southeast flank of the volcano in 1984 (Fig. 1a): the two events may have been linked.

Spatiotemporal changes in the local stress field have been reported at many volcanoes through stress inversion and/or by examining the P and T axes of focal mechanism solutions12-16. However, focal mechanisms are controlled by not only stresses but also fault strength, which is influenced by pore fluid pressures19,20,38,43,44. As earthquakes release stresses on pre-existing faults by shear faulting, a decrease in fault strength due to an increase in pore fluid pressures can trigger events on faults that are misoriented to the regional stress field19,20,44. From a data set of biased focal mechanism solutions by over-pressurized fluids, we may overestimate changes in the stress field or yield apparent stress rotation20 because the method of stress inversion attributes spatiotemporal variation in focal mechanisms only to those stresses. The method of shear-wave splitting analysis is also useful to detect temporal changes in the local stress field30,31, but a similar problem with apparent stress rotation has been reported45. In contrast, the average misfit angle of focal mechanism solutions in the context of regional stress patterns is crucial in detecting true temporal changes in local stress fields. However, we may underestimate temporal changes in stresses because the method attributes variation in focal mechanisms to changes in fault strength as much as possible. When assessing temporal changes in focal mechanisms, ideally the effects of stresses should be separated from those of fault strength (pore fluid pressures).

In this study, focal mechanism solutions were derived with a DC approximation because the magnitudes of events were low (M < 1). In a volcanic environment, however, the moment tensors of VT events may have non-DC, isotropic or compensated-linear-vector-dipole (CLVD) components46,47. In general, the inner tensor product48 of a moment tensor and the regional stress tensor seems to be useful instead of the misfit angle to detect temporal changes in the local stress field (see Methods). Earthquakes release part of the stress field, and so the moment tensor of events must be somewhat similar to the stress tensor23. Thus, dissimilarities between the moment tensors and the regional stress tensor can be an indicator of temporal changes in the local stress field. The moving average of inner tensor products were calculated from DC moment tensors converted from focal mechanism solutions: the results indicated that the inner tensor product has a strong negative correlation with the misfit angle (Supplementary Figs 6a and 7a). Depressions of inner tensor products were detected in the precursory period, November 2014 and January to February 2015. Very similar results were obtained using possible non-DC moment tensors (Supplementary Figs 6c and 7b). This additional analysis showed that temporal stress changes can be robustly detected from the present data set although non-DC components were significant.

If seismic networks are improved, we could expect more earthquake focal mechanisms with better quality, which would provide higher resolution information on temporal changes in the local stress field and on the regional stress field. If we can monitor the temporal evolution of average misfit angles over a long period of time with multiple eruptive episodes at a particular volcano, the results would be useful for predicting eruptions by comparing current with previous behaviour. The minor eruption of Mt. Ontake in 2007 was undetected in real time but discovered afterwards by onsite investigation. By applying our approach to the data associated with such examples, this approach can be quantitatively evaluated.

The degree of temporal change in the local stress field depends on the magnitude of the stress perturbation caused by volcanic processes relative to the background stress level1-4,17. To create a

![Figure 4](image-url) **Figure 4 | Stress field rotation caused by volcanic activity.** (a) The regional stress pattern in the summit region. (b) Horizontal stress rotation. (c) Vertical stress rotation. The stress pattern is shown by the focal spheres (lower hemisphere projections) in which nodal planes are the maximum shear planes. The blue, light green and red arrows show the axes of the maximum (σ1), intermediate (σ2) and minimum (σ3) compressive principal stresses, respectively. The pink dashed line in (a) indicates the position of possible inflating cracks. The pink arrows mark the main direction of crack opening.
practical warning system for volcanic eruptions, the absolute level of the local stress field (that is, rock strength) and/or the pressure threshold of magmatic/hydrothermal fluids required to trigger an eruption must be quantitatively evaluated, although differences in tectonic stresses, magma composition and local geology make it difficult to apply a single threshold to multiple volcanic systems. Nonetheless, the temporal stress changes observed using this approach can provide crucial constraints on the absolute stress level and the pressure threshold when combined with numerical modelling of the loading process and fluid pressurization. This is a promising method for understanding the signals that indicate an imminent eruption.

Methods

Seismicity and focal mechanism solutions. To examine the seismicity around Mt. Ontake, we used CMT data inversion and P and S wave polarities of P waves for 11,057 events (May 2012 to March 2015) that were automatically detected by the WIN system69. We used these data to construct an earthquake catalogue for the Ontake region (Fig. 1a). Over 98% of the 475 events in the summit region have M < 1. We also manually picked seismic events in the Ontake region by examining continuous waveforms in a 2-month window encompassing the eruption (30 August 2014 to 31 October 2014) to understand the changes in the number of seismic events at the summit region (Fig. 1c).

We estimated focal mechanism solutions from S/P amplitude ratios and P wave polarity data using the HASH software package after improving its code66. The improved software allows calculation of take-off angles taking into account the elevations of seismic stations. To calculate S/P amplitude ratios, we pre-processed velocity seismograms by integrating them to obtain the displacement and filtering with a bandpass window of 5–20 Hz. The parameters for determining focal mechanism solutions were as follows: polarity picks > 8; maximum azimuthal gap < 90°; and signal-to-noise ratio > 1.2. The fractions of reversed polarities to the final focal mechanism solutions were 19% on average. We obtained 94 relatively well-constrained focal mechanism solutions with RMS fault plane uncertainties of < 45°, 53 of which possessed uncertainties of < 35° (Supplementary Table 1).

CMT data inversion analysis. The CMT data inversion method63 derives the stress pattern from a large amount of CMT data for earthquakes using Akaike’s Bayesian information criterion64. We targeted the region around Mt. Ontake (latitude 35.62° N–36.16° N, longitude 137.3° E–137.9° E, depth 0–20 km) as the model region. We distributed 2,475 (15 × 15 × 11) tri-cubic B splines (basis functions) with equal spacing of 5 and 2.5 km local supports (grid intervals) in the horizontal and vertical directions, respectively, to represent the regional stress field. For the analysis, we used CMT data converted from focal mechanism solutions with RMS fault plane uncertainties of < 35° (May 2012 to July 2014) using the well-known relationship between moment magnitude and seismic moment62. From the data set, we determined the best estimates of the model parameters (expansion coefficients of the basis functions) using the Yabuki–Matsu’ura inversion formula65. Each component of the stress tensor at any location was obtained as a superposition of the basis functions (Supplementary Fig. 3). Note that only the relative values of the six stress components are meaningful, not the absolute values. Estimation errors were obtained using an L2-norm of error tensors62. We also evaluated the variation of principal stress axes using a bootstrap method with 100 data sets in which each converted moment tensor was rotated around an arbitrary vector within uncertainties. The estimation errors in the principal stress axes were 15–20° and 5–10° in the summit and peripheral swarm regions, respectively (Fig. 1a).

Evaluating misfit angles. For each focal mechanism solution, we calculated the theoretical slip vector (that is, the direction of the resolved shear traction on a nodal plane) using Cauchy’s formula, given the regional stress pattern at the hypocenter. As the true fault plane, we selected the nodal plane with the smaller angular difference between the actual and theoretical slip vectors of both nodal planes and defined the angular difference as the misfit angle.

Detecting temporal stress changes from moment tensors. The inner tensor product is a quantity used to measure the closeness of two tensors60 and ranges from −1 to 1, where +1 indicates that the two tensors are exactly the same (other than their sign), −1 indicates that they are opposite. By examining the effects of non-DC components of moment tensors to our conclusion, we first converted the focal mechanism solutions of 94 VT events (Supplementary Table 1) to DC moment tensors67, calculated the inner tensor products between the converted moment tensors and regional stress tensors, and evaluated the moving average of inner tensor products (Supplementary Figs 6a and 7a). For each event, we calculated a possible CLVD moment tensor, considering the axes of focal mechanism solutions and the P wave polarity data (Supplementary Fig. 6b). In the calculation, we assumed that the directions of the axial tensional and compressive dipoles were parallel to those of the T and P axes of events of reverse and normal faulting66, respectively. Otherwise, when the number of dilatational/compressive first-motion data was larger than that of compressive/dilatational data, we assumed that the CLVD moment tensors were calculated in the same manner as for reverse and normal faulting events, respectively. For remaining events, the CLVD moment tensors were obtained at random. We linearly combined these CLVD moment tensors to obtain non-DC moment tensors, where the weights of the CLVD moment tensors were assumed to be 30% of the DC moment tensors (Supplementary Fig. 6c). The possible moment tensors can explain the polarity data as well as the DC moment tensors (Supplementary Fig. 5). Using these possible moment tensors, we evaluated the moving average of inner tensor products, indicating that effects of non-DC components were small for detecting temporal changes in the local stress field (Supplementary Fig. 7). The isotropic moment of moment tensors does not influence the calculation of inner tensor products because the trace of the regional stress tensor inferred from focal mechanism solutions is zero.

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Author contributions
T.T. conceived the study, processed and analysed seismic wave data, interpreted the results, and wrote the paper. A.K. and Y.Y. helped in data processing. T.T., A.K., Y.Y. and T.T. performed the field work.

Additional information
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