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Detection of crustal deformation prior to the 2014 Mt. Ontake eruption by the stacking method

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Abstract

The phreatic eruption of Mt. Ontake in central Japan occurred in September 27, 2014. No obvious crustal deformation was observed prior to the eruption, and the magnitudes of other precursor phenomena were very small. In this study, we used the stacking method to detect crustal deformation prior to the eruption. The stacking method is a technique to improve the signal-to-noise ratio by stacking multiple records of crustal deformation. We succeeded in detecting a slight crustal deformation caused by a volume change in the shallow region beneath the volcano's summit from 1 month prior to the eruption. We also detected a slight crustal deformation that may have been caused by a volume increase in the deep region from one and a half months before the eruption. The magnitude of the volume change in the shallow region did not differ significantly in the 2014 eruption compared to the volume change during the small Mt. Ontake eruption in 2007, and the volume change in the deep region was rather smaller in 2014 than in 2007.

Keywords: Mt. Ontake, Precursor phenomena, Crustal deformation, Stacking method, GNSS

Background

Mt. Ontake volcano, which is located in central Japan, suddenly erupted on September 27, 2014 (Fig. 1). A small pyroclastic flow descended the mountain about 3 km toward the southwest, and large volcanic cinders were scattered around the summit within a radius of about 1 km [Japan Meteorological Agency (JMA) 2014]. Unfortunately, the eruption occurred in the daytime on a Saturday, when many climbers were around the summit crater, and there were more than 60 dead and missing. No significant precursor phenomena were reported prior to this eruption.

Mt. Ontake erupted for the first time in recorded history in 1979, and small eruptions occurred also in 1991 and 2007. The eruption of March 2007 was small; a slight ash fall was recognized on the snow around the crater in later field observations. However, clear crustal deformation, indicating inflation of the volcanic edifice, had been observed by the global navigation satellite system (GNSS) 3 months prior to the eruption (Takagi et al. 2007).

Although small earthquake swarms were observed a few weeks before the eruption in 2014, this activity soon calmed down. No further noticeable precursory phenomena were reported except a volcanic tremor and a tilt change 11 and 7 min prior to the eruption, respectively (JMA 2014; Kato et al. 2015; Maeda et al. 2015).

Because no magma migrates upward in the volcanic edifice during a phreatic eruption, the scale of related precursor phenomena is generally smaller than that of precursors of a magma eruption. When no precursor phenomena are detected until just before the eruption, as was the case in 2014, it is difficult to issue appropriate timely warnings of a volcanic eruption. For this reason, it is important to be able to detect precursor phenomena other than imminent seismic activity and tilt changes. Therefore, we examined whether it would have been possible to detect crustal deformation in GNSS data early enough for the information be used to predict the eruption. Validation of the occurrence of crustal deformation prior to a phreatic eruption and analyses on such slight deformation, even in hindsight, can contribute in

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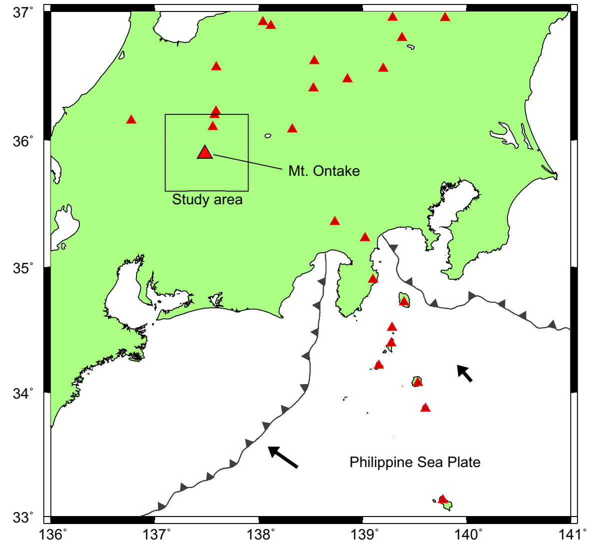

Fig. 1 Map of central Japan and the tectonic regime. The *large red triangle* indicates Mt. Ontake and *smaller red triangles* indicate other volcanoes. *Black arrows* show direction of motion of the Philippine Sea Plate, which is subducting beneath southwest Japan. The study area is enclosed by a *black rectangle*

important ways to our understanding of the processes of phreatic eruptions.

Precise ephemeris data from the International GNSS Service (IGS), which are generally used for analysis of a slight crustal deformation, take 2 weeks to be available. To issue immediate volcanic warnings, however, it is necessary to use IGS ultra-rapid ephemeris data, which can be used for quasi-real-time analyses, rather than precise ephemeris data, which are not available as quickly. The signal-to-noise ratio (SNR) of GNSS data based on the IGS ultra-rapid ephemeris product is much smaller than the SNR when the IGS precision ephemeris is used (Hatanaka et al. 2003); therefore, detection of slight changes by a GNSS analysis using the ultra-rapid ephemeris product is expected to be difficult.

One possible way of detecting a small crustal deformation is to use the stacking method (Miyaoka and Yokota 2012), in which multiple records of time-series strain-meter data are stacked to improve the SNR. Small signals buried in the noise can be made visible by stacking. The stacking method is already being used by the JMA to monitor crustal deformation in anticipation of a future Tokai earthquake. Moreover, by using JMA strain-meter data, Miyaoka and Kimura (2016) succeeded in detecting long-term slow slip along the Philippine Sea Plate boundary.

In this study, we applied the stacking method to GNSS data to detect slight crustal deformation prior to the eruption of Mt. Ontake in 2014.

The stacking method

The technique of stacking multiple data records to improve SNR has been applied in various fields. For example, in seismic array processing (e.g., Johnson and Dudgeon 1993), seismic wave data are stacked to improve the SNR by assuming the direction of arrival of seismic waves and their apparent velocity and then shifting the time period covered by each data record. The basic principle of how SNR of the stacked data will be improved is described here. When we stacked multiple data records, signal components would be enhanced in strength, whereas the noise components would cancel each other. And if we stack m data records with the same signal magnitude S and same noise N, the signal of the stacked data becomes mS, and the noise $\sqrt{m}N$, respectively. As a result, the SNR of the stacked data becomes $\sqrt{m}S/N$, which is $\sqrt{m}$ times the original SNR.

Miyaoka and Yokota (2012) have applied this scheme to crustal deformation data. The stacking method was developed for the efficient detection of slow slip along a plate boundary by using JMA strain-meter data.

When stacking multiple data records, it is important to align them according to their expected polarity from the assumed source. A movement of the source, whether it is slow slip along a plate boundary or an inflation in a volcano, may lead to variation in the data records. In particular, the data may show extensional (positive) or contractional (negative) changes. If the source location does not spread or move greatly, the temporal changes are expected to be similar in shape except for their polarities. The polarities of multiple records of time-series data can be made the same by inverting the polarities of those data showing contractional changes. The data produced by stacking are expected to have a higher SNR than the individual data records.

The magnitude of the noise component (noise level) of the data can vary. If data with a high noise level are included in the stack, then the SNR of the stacked data may become worse. To equalize the weight of the noise in all data, all data are normalized by a certain noise level. For this purpose, the standard deviation of differentials in a certain time interval when no event is taking place is taken as the noise level. Here, this time interval should be set by considering the duration of a target event.

The stacked data are obtained as follows:

$$A(t) = \sum_{i=1}^{m} Y_i(t)c_i \tag{1}$$

where $A(t)$ represents the stacked data, and $Y_i(t)$ is a time-series data i; c_i is the stacking coefficient, obtained as

$$c_i = pol_i n_s / n_i, \tag{2}$$

where pol_i is $+1$ or -1, depending on the polarity of changes in data i. If pol_i is -1, then the polarity of the data is inverted. n_i is the noise level of data i, and n_s is any value, for example, the average of all noise levels.

Application to volcanic ground deformation

In this study, we applied the stacking method to GNSS baseline data observed around Mt. Ontake and assumed two pressure source geometries.

First, we assumed a spherical pressure source (Fig. 2a). All baselines crossing the volcano are assumed to extend when a spherical pressure source inflates beneath the summit, so there is no need to reverse the polarity of any data. In selecting baselines for stacking, we took into account differences in the expected response according to depth of the pressure source. The response of a short baseline to changes in a shallow source is expected to be stronger than that to changes in a deep source, whereas the response of a long baseline is expected to be relatively stronger to changes in a deep source. Therefore, we stacked data from three sets of baselines of similar length, short, medium, and long to produce short, medium, and long stacked data (Fig. 3a–c, respectively).

Next, we assumed a tensile crack source (Fig. 2b). During the 2007 activity, some baselines connecting eastern and western GNSS observation points across the volcano were extended. Therefore, assuming a tensile crack with north–south strike we stacked data of baselines oriented nearly east–west (Fig. 3d). Baselines crossing the volcano in a direction normal to the opening direction of the crack would be expected to show contractional changes, but such baseline data were not available for either the 2007 or 2014 events, so we did not use any north–south baselines. Note that if any contractional data had been used for stacking, it would have been necessary to reverse their polarity. We call the data produced by stacking the data of the east–west baselines across the tensile crack Dike stacked data.

We adopted the standard deviation of the 30-day differential during the period from January to July 2014, just before the first 2014 activity was observed, as the noise level.

To minimize location errors, it is better to use IGS precise ephemeris GNSS data. However, those data cannot be used to detect a change in a shallow source near the summit in real time for the purpose of issuing volcanic warnings. Therefore, we used the IGS ultra-rapid ephemeris data analyzed by JMA to produce the short stacked data, which is most useful for detecting change in a shallow source. In the case of a deep source, there is often more time before a volcanic warning needs to be issued. Therefore, giving priority to the detection of slight changes, we used IGS precise ephemeris GNSS data for the medium, long, and dike stacked data.

We expected inflation of a spherical source to manifest as extensional changes in the short, medium, and long stacked data, and we expected expansion of a tensile crack source to cause extensional changes in the dike stacked data. We also expected to observe various response behaviors in the stacked data according to the source type and depth.

Results and discussion

We produced times series of short stacked data by various combinations of short baseline data (Fig. 4) to find the best SNR by trial and error. The stacked data show extensional changes around the beginning of September 2014 (Fig. 4b). Although slight changes were recognized in some of the original baselines (Fig. 4a; e.g., baselines 2, 3, 4, and 6), these extensional changes can be seen more clearly in the stacked data.

We similarly produced medium, long, and dike stacked data and compared them with the short stacked data (2 + 4 + 6) and between the 2007 (Fig. 5a) and 2014 activities (Fig. 5b). The 2007 eruption was very small, and the date and time of the eruption were initially unknown because the eruption was not detected visually. On the basis of later field investigation performed by JMA, the eruption was estimated to have occurred during the second half of March 2007. Despite the small scale of the 2007 eruption, we observed obvious extensional changes in the medium, long, and dike stacked data. In the case of the 2014 eruption, however, obvious changes like those in 2007 were not observed. Nevertheless, a slight extensional step-like change was recognized in the medium stacked data, and slight extensional changes were also seen in the long and dike stacked data. A contractional change was also seen in the long stacked data (discussed later). In the short stacked data, small extensional changes were observed in both the 2007 and 2014 activities, and the difference in the magnitude of the extensional change was not large between them.

We also recognized some temporal variations in the stacked data. The changes in the medium, long, and dike stacked data in 2007 activity started in the first half of December, approximately three and a half months before the eruption. The beginning of the short stacked data change was not clear in 2007 because of a gap in the data. The medium and long stacked data showed a gradual extension until the eruption, whereas the extensional rate in the dike stacked data changed abruptly in the first half of January. In the case of the 2014 activity, slight changes in the medium, long, and dike stacked data began in the middle of August, a month and a half before the eruption. In the short stacked data, a change was first observed in the beginning of September, roughly a month before the eruption.

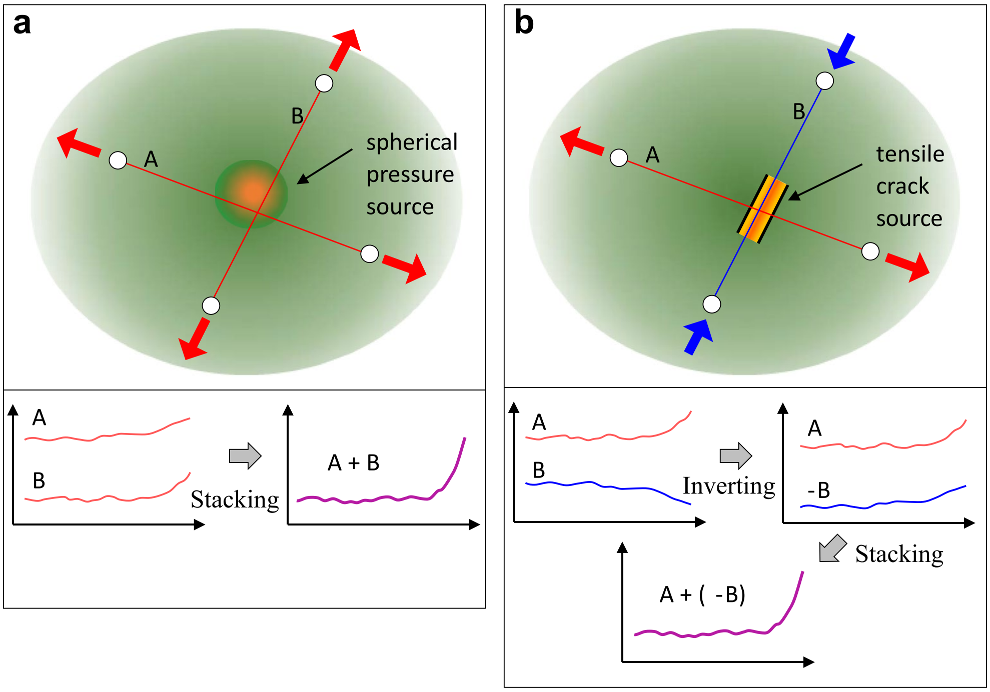

Fig. 2 Schematic diagrams of the stacking method. **a** The *top panel* shows two GNSS baselines extending across a spherical pressure source, and the *bottom panel* shows how an improved SNR is obtained by stacking time-series data for the two baselines. **b** The *top panel* shows two baselines crossing a tensile crack source. One baseline (*A*) is extended by the opening of the crack, and the second baseline (*B*) is contracted. By stacking the time-series data for the two baselines after first reversing the polarity of the data for baseline *B*, the SNR is improved (*bottom panel*)

Next, we examined relative differences in the responses in each stacked data set depending on the pressure source type and its depth. The purpose of this confirmation is to see the relative differences among each stacked data. We did not evaluate each source parameter in detail, for example by determining its exact depth or volume, but in this calculation, it was not necessary to specify the actual source parameters to see relative differences. We examined two source types, a spherical pressure source and a tensile crack source. We assumed that each source was at each depth of 1 km, from 20 km depth until the sea level (0 km depth) below the summit, and that the tensile crack source was a vertical fault 1 km long by 1 km wide with a north–south strike. It was not necessary to specify the magnitude of the volume change to see the relative difference. We calculated the displacement of each GNSS site, following Mogi (1958) and Okada (1992), using MaGCAP-V software (Fukui et al. 2013), and summed the data for the baseline using Eq. (1). The elevation of observation sites around Mt. Ontake ranges widely, from 400 to 2200 m. With this software, it is possible to correct the difference of station altitude by setting the source depth at a relative value from the station elevation, in the calculation for each observation station.

We focused primarily on the difference in the responses between the short stacked data and the other stacked data. The response to changes in a deeper spherical pressure source was larger in the medium, long, and dike stacked data than in the short stacked data, but the response to changes in a shallow source was larger in the short stacked data than it was in the other stacked data (Fig. 6a). The responses in the medium, long, and dike stacked data to a deeper tensile crack source were larger than that in the short stacked data (Fig. 6b).

Next, we examined contractional changes in the long stacked data shown in Fig. 5b. The study area is in a compressional stress field associated with subduction of the Philippine Sea Plate beneath southwest Japan (see Fig. 1), so the crust around Mt. Ontake is generally contracting. In fact, from 2005 to 2014, the long stacked data show contraction, except for a coseismic extensional change coinciding with the great 2011 Tohoku earthquake (Fig. 7). Moreover, the long-term change accelerated during summers and slowed each winter; these seasonal changes are considered an effect of weather conditions. The stacked data were designed to show extension changes due to inflation of the source, but the polarity of such changes is opposite to that of the supposed change

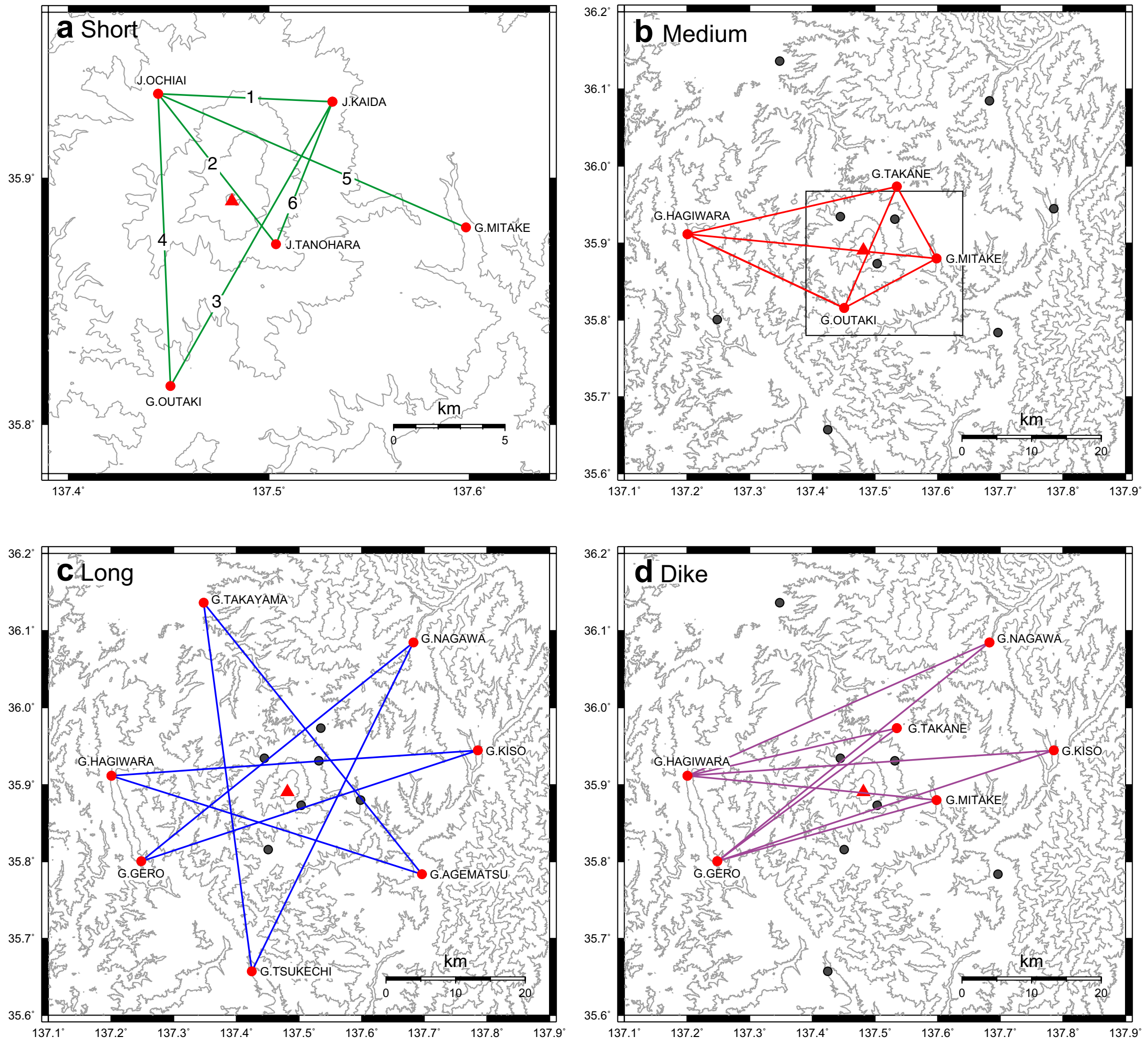

Fig. 3 Location of GNSS sites around Mt. Ontake and the combinations of baselines used to produce the **a** short, **b** medium, **c** long, and **d** dike stacked data

in this compressional stress field. Therefore, the cause of the extensional changes in the stacked data of the 2007 and 2014 activities can be considered to be inflation of the source due to volcanic activity.

Based on above, we evaluate the observation result described in the first half of this chapter. Because in 2014, the changes in the long stacked data began earlier than those in the short stacked data, it is inferred that the pressure source migrated; that is, the source inflation may have started in a deeper region and moved to a shallower region. This interpretation is reasonable because it would reflect the rising of substances such as magma or gases exsolved from magma from depth to the shallower region. The stacked data results indicate that the period from the beginning of inflation of the deeper source until the eruption was shorter in the 2014 activity than in the 2007 activity.

The magnitude of the response in the short stacked data was not very different between the 2007 and 2014 activities. If the depth of the source was similar for the two events, the amount of inflation in the shallow region would not be very different. However, the magnitude of the response in the medium, long, and dike stacked data was much smaller in the 2014 activity than in the 2007 activity; these results indicate that the amount of inflation of the deep source was smaller in 2014 than in 2007. Nakamichi et al. (2009) suggested that a magma intrusion occurred, on the basis of their analysis of very-long-period seismic vibrations associated with the 2007 activity. Therefore, we inferred that no new magma

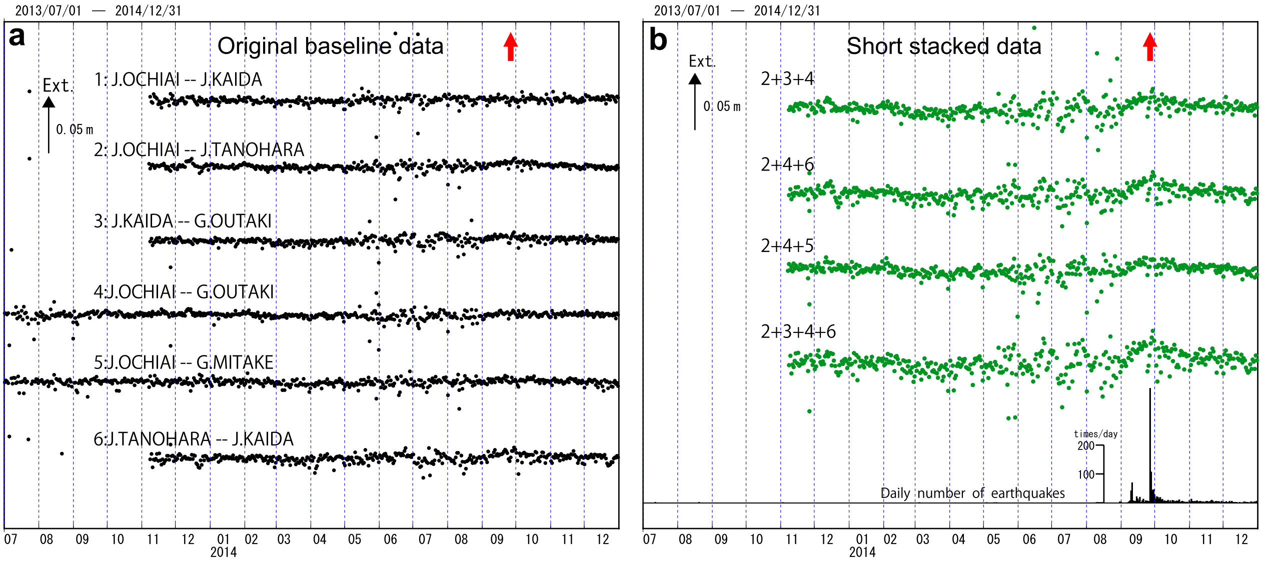

Fig. 4 **a** Time series of short baseline data and **b** short stacked data produced for various combinations of short baselines. The number of earthquakes detected daily is also shown in **b**. The numbers above each times series in **b** (e.g., 2 + 3 + 4) correspond to the original baseline numbers in **a** (see also Fig. 3a). Upward changes represent extension by inflation of the pressure source. Slight extensional changes prior to the eruption (indicated by the *red arrow* in *each panel*) can be recognized in the stacked data

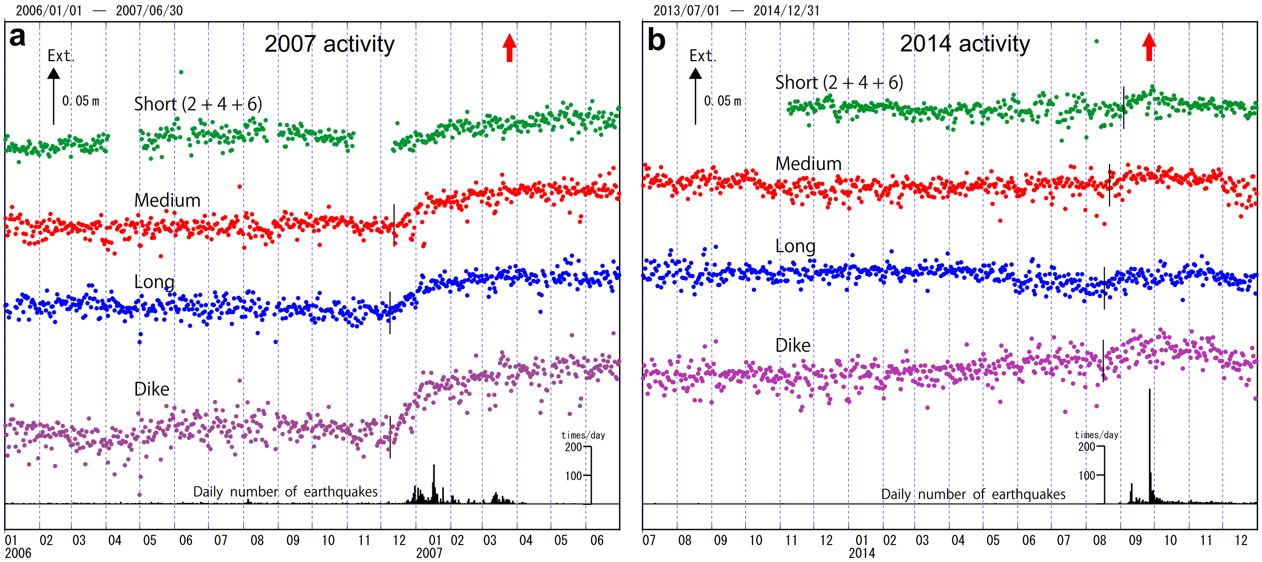

Fig. 5 Short, medium, long, and dike stacked data for the **a** 2007 and **b** 2014 eruptions. The number of earthquakes detected daily is also shown. *Upward changes* represent extension by inflation of the pressure source. *Red arrows* indicate the timing of each eruption, and the *vertical black bars* show when the first changes in the source were detected

intrusion occurred in 2014, or that a much smaller amount of magma intruded in 2014 than in 2007.

To summarize, we were able to detect slight changes prior to the eruption in 2014 in the short stacked data by a quasi-real-time analysis using IGS ultra-rapid ephemeris data. Therefore, the stacking method effectively enhanced our ability to detect volcanic activity in GNSS monitoring data. Thus, because volcanic activity can be monitored on a quasi-real-time basis without waiting up to 2 weeks for IGS precise ephemeris data to become available, it is possible to issue short-term volcanic eruption warnings. We also applied the stacking method to IGS precise ephemeris

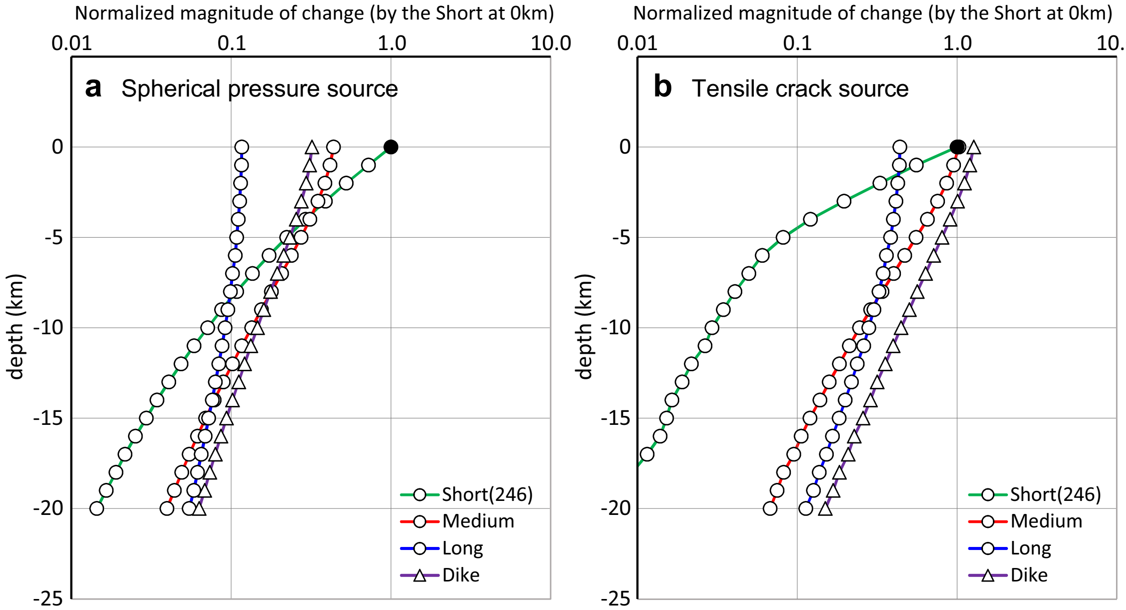

Fig. 6 Theoretical changes in each type of stacked data according to the depth of the pressure source assuming **a** a spherical pressure source and **b** a tensile crack source. The *horizontal axis* shows the magnitude of the change in each stacked data normalized by the magnitude of change in the short stacked data at 0 km depth (*black dots*)

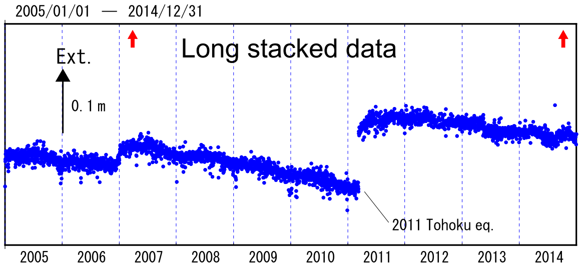

Fig. 7 Long stacked data for a 10-year period (2005–2014). The long-term trend is one of contraction. Short-term acceleration and slowing of the rate of change in the data are interpreted as caused by annual changes in weather conditions

data for baselines of different lengths and produced medium, long, and dike stacked data. Although our results are qualitative, because we could not determine the absolute source depth or the absolute magnitude of changes in the source, we could recognize relative differences in source depth from behavioral differences in the stacked data. Also, we inferred that the different behaviors seen in the medium and long stacked data compared with the dike stacked data reflect source-type differences though more information is needed to investigate source-type behaviors in more detail.

The stacking method is applied simply by using Eq. (1) to stack time-series data, and no special analyses or resources are required.

Conclusions

In this study, for the purpose of detecting crustal deformation preceding the eruption of Mt. Ontake in 2014, we applied the stacking method to GNSS data. As a result, we observed a slight change in short stacked data across the volcano about a month before the eruption. This result reflected a pressure increase in the shallow region beneath the volcano preceding the eruption.

We applied the same analysis to the 2007 activity data and also recognized clear changes in the stacked data. We inferred that these changes indicated a magma intrusion into a deep region. In contrast, although slight extensional changes in the 2014 activity data were recognized in the medium, long, and dike stacked data about a month and a half before the eruption, the magnitudes of these changes were small compared with those in the 2007 activity.

The changes that began in the medium, long, or dike stacked data moved to the short stacked data over time. We therefore inferred that the stacked data revealed movement of a pressure source to a shallower region from a deeper region. These results show that it is possible to monitor the behavior of pressure sources at different depths simply by using stacked data for a combination of baselines of different lengths, without any complicated analyses being necessary.

The changes in the short stacked data began only 1 month before the eruption; therefore, it would not be possible to issue early volcanic warnings on the basis of such short-term changes by using IGS precise ephemeris GNSS data for the analysis. However, we showed that is it possible to detect slight changes in the short period before an eruption by using quasi-real-time IGS ultra-rapid ephemeris data. Thus, the application of the stacking method to GNSS data can improve the effectiveness of short-term monitoring of volcanic activity.

Abbreviations

JMA: Japan Meteorological Agency; IGS: International GNSS Service; SNR: Signal-to-noise ratio.

Authors' contributions

KM analyzed the GPS data by the stacking method and drafted this manuscript. AT carried out a part of the quantitative analysis and discussed the volcanic activity. Both authors read and approved the final manuscript.

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Competing interests

The authors declare that they have no competing interests.

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