Deformation Source Revealed From Leveling Survey in Jigokudani Valley, Tateyama Volcano, Japan

Kohei Hotta (✉ hotta@sus.u-toyama.ac.jp)

Faculty of Sustainable Design, University of Toyama <https://orcid.org/0000-0001-8968-0038>

Shigekazu Kusumoto

Kyoto University Graduate School of Science Faculty of Science: Kyoto Daigaku Rigaku Kenkyuka
Rigakubu

Hidenori Takahashi

University of Toyama Faculty of Science Graduate School of Science and Engineering: Toyama Daigaku
Rigakubu Daigakuin Rikogaku Kyoikubu Rigaku Ryoiki

Yuichi S Hayakawa

Hokkaido University Graduate School of Environmental Science: Hokkaido Daigaku Daigakuin Kankyo
Kagakuin Chikyu Kankyo Kagaku Kenkyuin

Research Article

Keywords: Tateyama volcano, Midagahara volcano, Dislocation source model, leveling survey, temporal change

Posted Date: October 22nd, 2021

DOI: <https://doi.org/10.21203/rs.3.rs-989577/v1>

License: © ⓘ This work is licensed under a Creative Commons Attribution 4.0 International License.

[Read Full License](#)

Version of Record: A version of this preprint was published at Earth, Planets and Space on February 18th, 2022. See the published version at <https://doi.org/10.1186/s40623-022-01593-7>.

Abstract

We modeled vertical deformation detected from leveling survey in Jigokudani valley, Tateyama volcano, central Japan. In Jigokudani valley, uplift of 4 cm/year was previously detected during the period from 2007 to 2010 by Interferometric Synthetic Aperture Radar (InSAR). To confirm whether this inflation has continued to the present, we conducted leveling survey in Jigokudani valley since 2015. Most bench marks showed subsidence up to 5.6 cm during the four-year period from October 2016 to September 2020, while a bench mark locates at the center of the leveling route uniquely showed uplift of 1.6 cm. We applied a dislocation source model to the deformation using a grid search method. A crack with a length of 350 m, a width of 100 m, a strike of N117°E and a dip of 61° is located at a depth of 50 m near the center of Jigokudani valley (Koya jigoku and the new fumarolic area) where highly activating recently. Closing of the crack of 344 cm yields volume decreases of 120,400 m³. Striking direction of the crack is parallel to the line of which are old explosion craters (Mikurigaike and Midorigaike ponds) and corresponds to current maximum compressive stress field in the region of Hida Mountains including Tateyama volcano. The deformation source of the previous period from 2007 to 2010 detected from InSAR was estimated to be at a depth of 50 m and a gas chamber was correspondingly found from the audio-frequency magnetotelluric (AMT) survey. The estimated crack in this study is also located at a similar position of the gas chamber which was also identified from AMT survey. During the period from 2015 to 2016, the crack opened (i.e., inflated) and the inflation stopped during the next one-year period from 2016 to 2017. During the period from 2017 to 2020, the crack turned to closing (i.e., deflation), probably because of the increase in emission of volcanic fluid or gas with a formation of a new crater at the western side of Jigokudani valley (Yahata jigoku) during the period from 2017 to 2018.

1. Introduction

Tateyama (or Midagahara) volcano is an andesitic volcano which locates in the Hida mountains, central Japan (Fig. 1). Although this volcano has not experienced magmatic eruptions in historical times, at least four phreatic eruptions have been occurred over the past 10,000 years (Kobayashi, 1980). The last phreatic eruption is presumed to have occurred in 1836 (Nakano and Ito, 1998). Such eruptions have created many craters including Mikurigaike and Midorigaike ponds in the striking direction of WNW-ESE. Currently, fumarolic activity have been continuing in Jigokudani valley or “Jigokudani”, meaning “hell valley” in Japanese, which was formed during this approximately 40,000 years (Harayama et al., 2000). The fumarolic activity became violent in 2011, making the region around Jigokudani valley keep-out area (Japan Meteorological Agency, 2013). Before that, ground uplift up to 4 cm/year was detected from Interferometric Synthetic Aperture Radar (InSAR) during the period from 2007 to 2010. The deformation was revealed to have been caused by inflation of deformation source at a depth of approximately 50 m from the surface (Kobayashi, 2018). The deformation source was interpreted to be corresponding to the shallow gas chamber detected from the audio-frequency magnetotelluric (AMT) survey which was found at a depth of approximately 50 m beneath Jigokudani valley (Seki et al., 2016). The AMT survey also revealed that thermal fluid is accumulating from a magma chamber at a depth of approximately 4 km,

which was estimated from a low velocity seismic zone (Matsubara et al., 2000) toward the shallow gas chamber. After 2011 when fumarolic activity level increased, significant deformation was no longer detected from InSAR due to its limitation of accuracy. To confirm whether this inflation has continued to the present, we conducted leveling survey in Jigokudani valley since 2015. As admittance to the valley is prohibited owing to the presence of volcanic gas as written above, we obtained a permission from the Ministry of the Environment and used gas masks and protective goggles to ensure safety while conducting the survey. The leveling surveys have been repeated every year and uplift or subsidence of several centimeters have been detected around active fumarolic areas of Hyakusho jigoku, Koya jigoku and the new fumarolic area (Fig. 1).

In the present study, we model and interpret vertical deformation during the period from 2016 to 2020 detected from leveling surveys. Then we investigate and discuss about temporal change in inflation/deflation based on obtained source and previous leveling data which have been accumulated every year since 2015.

2. Observation

Leveling survey in Jigokudani valley have been conducted every year since 2015 by University of Toyama. Leveling route in Jigokudani valley were set in 2015, but renewed in 2016 because some bench marks lost due to corrosion by volcanic gases. Location of bench marks are as shown in Fig. 1. We used Leica GFL-4S leveling staffs and Leica Sprinter 250M auto level. To avoid seasonal change in leveling data, leveling survey have been conducted in autumn (September or October) of every year. We assumed relative height of each bench marks and observation error with respect to BM. 1 from least square method of a net adjustment.

Change in relative height with respect to BM. 1 for each benchmark after 2016 is as shown in Fig. 2. Observation errors are less than 0.21 cm. In Koya jigoku and the new fumarolic area (BM. 7–11) once showed slight uplift during the period from 2016 to 2017 and turned continuous subsidence. In Hyakusho jigoku (BM. 14–20) have showed continuous subsidence. Subsidence rate of both areas is not constant but varying every year. Between these areas in Kajiya jigoku (especially BM. 12) have showed continuous uplift except the period from 2017 to 2018. Since BM. 2 showed anormal subsidence different with other nearby benchmarks probably due to collapse of concrete block where the bench mark is located, we excluded the data of this benchmark in the following analysis.

3. Analysis And Results

3.1. Deformation source and residual evaluation

Relative vertical deformation with respect to BM. 1 during the period from October 2016 to September 2020 is as shown in Fig. 2. Most bench marks showed subsidence up to 5.6 cm during the four-year period. BM. 12, locates at the center of the leveling route, showed uplift of 1.6 cm differently to the other

bench marks. This characteristic of vertical deformation indicates a closing crack – both side of the crack subside whereas right above the crack uplift. Therefore, we applied a dislocation source model (Okada, 1992) to the detected vertical deformation. We used weighted residual sum of square (WRSS) to evaluate residual which is defined as

$$WRSS = \sum_i \frac{U_i^{obs} - U_i^{cal}}{\sigma U_i^{obs}}, \quad (1)$$

where U_i^{obs} and U_i^{cal} are observed and calculated vertical displacement at BM. i with respect to BM. 1; and σU_i^{obs} is observation error at BM. i . Assuming a Poisson ratio of 0.25 and assuming surface as a flat topography (we ignored topographical effect because elevation difference within the leveling route is at most 26 m and can be approximated to be flat), we searched optimal combination of north-south and west-east location, depth, dip, strike, length, width and opening of the dislocation source model which minimize WRSS value by a grid search method. We set range and step of the grid for each parameter as shown in Table 1.

Table 1

Search range and step for the model parameters and their optimal values with uncertainties (square brackets). The origin of the horizontal coordinate is BM. 1 (137.597735°E, 36.58748187°N). The uncertainties are the 99% confidence intervals estimated from the F -test (Árnadóttir and Segall, 1994). The position is at the center of the top edge of the fault. the dip is clockwise from the horizontal, and the strike is clockwise from the north.

Parameter	Range	Step	Optimal value
N-S location	-800–0 m	25 m	-125 [-150, -100] m
E-W location	-800–0 m	25 m	-550 [-550, -525] m
Depth from the surface	0–500 m	25 m	50 [50, 50] m
Length	25–500 m	25 m	350 [250, 400] m
Width	25–500 m	25 m	100 [75, 175] m
Dip	0–90°	1°	61 [55, 65] °
Strike	N0–359°E	1°	N117 [107, 121] °E
Opening	-500–500 cm	1 cm	-344 [-472--215] cm

3.2. Result

The obtained optimal values are shown in Table 1; and location of the crack and comparison of observed and calculated vertical deformation is shown in Fig. 3. A crack with a length of 350 m, width of 100 m and a dip of 61° is located at a depth of 50 m near the Koya jigoku and the new fumarolic area where

highly activating recently. Its strike is N117°E. the closing of the crack of 344 cm yields volume decreases of 120,400 m³. Observed vertical deformation can be well explained by the obtained closing crack.

4. Discussion

The obtained crack is striking parallel to the line of Mikurigaike and Midorigaike lakes, which are old explosion craters. Around Jigokudani valley, phreatic eruptions have repeatedly occurred for the last 40,000 years (Harayama et al., 2000). The compress stress field in WNW-ESE around this region have been continue for at least 40,000 years, creating explosion craters such as Mikurigaike and Midorigaike ponds by repeated phreatic eruptions. The current maximum compressive stress field in the region of Hida Mountains, including Tateyama volcano, is WNW-ESE (Mikumo et al., 1988). This direction is corresponding to crack striking direction, and crack closing direction is orthogonal direction of the compressive stress field. This compressive field might create a crack striking in the direction of WNW-ESE and the crack might be filled with volcanic fluid or gas. The crack is now closing due to recent active fumarole activities.

The closing amount of the obtained crack, 344 cm, might be said to be very large. This might be caused because our analytical model is too simple which is based on an elastic model in a homogeneous half space. Nevertheless, the opening/closing rate of the crack is not necessarily too large. The average rate of closing is less than 0.3 cm/day. There is an example of shallow crack opening of nearly 200 cm/day which occurred at Sakurajima volcano on August 15, 2015 (Hotta et al., 2016) and closing rate of the Jigokudani crack is much less than opening rate of the Sakurajima crack.

During the previous period from 2007 to 2010, a deformation source was found at a depth of 50 m from InSAR (Kobayashi, 2018). The obtained deformation source was interpreted to be corresponding to the gas chamber which was found from AMT at similar depth and location (Seki et al., 2016). The obtained crack from leveling data is approximately similar position of the gas chamber. The location of the crack is also similar to a low-density zone found from Bouguer anomaly (Kusumoto et al., 2021) which might be also corresponding to the gas chamber filled with volcanic fluid or gas. Therefore, the crack might be corresponding to the gas chamber, which is closing due to emission of fluids or gases caused by current violent fumarolic activities.

We applied the obtained crack to previous vertical deformation of one-year periods to investigate temporal change in opening of the crack. Cumulative opening during the period from 2015 to 2020 is as shown in Fig. 4(a). The data of every one-year periods can be explained within the difference within approximately 1 cm by the estimated opening/closing (Fig. 4(b)). The crack opened (i.e., inflated) 47 cm during the period from 2015 to 2016. Opening of the crack stopped during the next one-year period from 2016 to 2017. Then the crack started closing between 2017 and 2018. The crack has continued closing (i.e., deflation) since then although the rate of closing varies from 14 to 190 cm/year. This deflation might be caused by increase in fumarole activity due to a new crater formation at Yahata jigoku (northwest of BM. 17 and 18; Fig. 1) during the period from 2017 to 2018, and thus emission of volcanic fluid or gas

may have increased since then. As a result, the crack, which may be corresponding to the shallow gas chamber and inflated from 2007 until 2017, turned deflation.

5. Conclusions

From leveling survey in Jigokudani valley which have been conducted every year since 2015, uplift/subsidence up to 3 cm per year was detected. A crack was identified at a depth of 50 m from the surface near Koya jigoku and the new fumarolic area where fumarolic activity is increasing. The crack might be corresponding to the shallow gas chamber. Due to emission of volcanic gas or fluid by violent fumarolic activity, the gas chamber started deflation between 2017 and 2018 when a new crater was formed and have continued until at least 2020, causing increase in activity level.

Abbreviations

InSAR: Interferometric Synthetic Aperture Radar; AMT: audio-frequency magnetotelluric; WRSS: residual sum of square

Declarations

Competing/Conflict of interests

Not applicable.

Availability of data and materials

The datasets supporting the conclusions of this article are included within the article.

Availability of data and materials

Not applicable.

Funding

This study was supported by the Ministry of Education, Culture, Sports, Science and Technology of Japan, under its Earthquake and Volcano Hazards Observation and Research Program.

Author's contributions

KH contributed to the study conception and design; acquisition, analysis and interpretation of the data; and drafted the manuscript. SK contributed to the study conception and design; acquisition and analysis of data; and helped to draft the manuscript with critical revisions. HT and YH participated in the acquisition and analysis of data and helped to draft the manuscript. All authors read and approved the final manuscript.

Acknowledgements

Some figures in this paper are prepared using genetic mapping tools (Wessel et al., 2013). Many students and/or graduate students of University of Toyama have joined and helped leveling surveys in Jigokudani valley. We are grateful to the Ministry of the Environment and Toyama Prefecture for allowing the installation of benchmarks.

References

1. Árnadóttir T, Segall P (1994) The 1989 Loma Prieta earthquake imaged from inversion of geodetic data. *Journal of Geophysical Research*, 99(B11):21835-21855, doi:[10.1029/94JB01256](https://doi.org/10.1029/94JB01256).
2. Harayama S, Takahashi Y, Nakano S, Kariya Y, Komazawa M (2000) Geology of the Tateyama District. Geological Survey of Japan, 218.
3. Hotta K, Iguchi M, Tameguri T (2016) Rapid crack intrusion into Sakurajima volcano on August 15, 2015, as detected by multi-parameter ground deformation observations. *Earth, Planets and Space*, 68, 68, doi:[10.1186/s40623-016-0450-0](https://doi.org/10.1186/s40623-016-0450-0).
4. Japan Meteorological Agency (2013) Japan Meteorological Agency, Midagahara, National Catalogue of the Active Volcanoes in Japan (fourth ed.), 1502.
5. Kobayashi T (1980) The recent deposits of phreatic explosions in Tateyama volcano. *Bulletin of the Volcanological Society of Japan*, 25 (4), 297 (in Japanese).
6. Kobayashi T (2018) Locally distributed ground deformation in an area of potential phreatic eruption, Midagahara volcano, Japan, detected by single-look-based InSAR time series analysis. *Journal of Volcanology and Geothermal Research*, 357, 15, 213-223, doi:[10.1016/j.jvolgeores.2018.04.023](https://doi.org/10.1016/j.jvolgeores.2018.04.023).
7. Kusumoto S, Takahashi H, Higashinaka M, Hayakawa Y (2021) Estimation of near-surface porosity distribution using Bouguer anomaly. *Butsuri Tansa*, 74, 30-35 (in Japanese with English abstract).
8. Matsubara M, Hirata N, Sakai S, Kawasaki I (2000) A low velocity zone beneath the Hida Mountains derived from dense array observation and tomographic method. *Earth, Planets and Space*, 52, 143-154, doi:[10.1186/BF03351623](https://doi.org/10.1186/BF03351623).
9. Mikumo T, Wada H, Koizumi M (1988) Seismotectonics of the Hida region, central Honshu, Japan. *Tectonophysics*, 147 (1), 95-119, doi:[10.1016/0040-1951\(88\)90150-3](https://doi.org/10.1016/0040-1951(88)90150-3).
10. Nakano S, Itoh J (1998) Eruption of Tateyama Volcano. *Bulletin of the Volcanological Society of Japan*, 43, 123-126 (in Japanese).
11. Okada Y (1992) Internal deformation due to shear and tensile faults in a half-space, *Bulletin of Seismological Society of America*, 82, 1018-1040.
12. Seki K, Kanda W, Tanbo T, Ohba T, Ogawa Y, Takakura S, Nogami K, Ushioda M, Suzuki A, Saito Z, Matsunaga Y (2016) Resistivity structure and geochemistry of the Jigokudani Valley hydrothermal system, Mt. Tateyama, Japan. *Journal of Volcanology and Geothermal Research*, 325, 1, 15-26, doi:[10.1016/j.jvolgeores.2016.06.010](https://doi.org/10.1016/j.jvolgeores.2016.06.010).

13. Wessel P, Smith WHF, Scharroo R, Luis JF, Wobbe F (2013) Generic mapping tools: improved version released. EOS Transactions American Geophysical Union, 94, 409-410, doi:[10.1002/2013EO450001](https://doi.org/10.1002/2013EO450001).

Figures

Figure 1

(Upper left) Location map of Tateyama volcano (solid triangle). (Lower right) an enlarged map around Jigokudani valley (north area of the map). Open circles are remained old leveling bench marks set in 2015 and solid circles are new leveling bench marks renewed in 2016. Ellipses with gray dashed line represents fumarolic areas.

Figure 2

Vertical displacement of each bench mark with respect to BM. 1 during the periods of 2016–2017, 2016–2018, 2016–2019 and 2016–2020. Error bars are 1σ .

Figure 3

Location of the obtained dislocation source (rectangle) and a comparison of the observed (black vector) and calculated (white vector) vertical displacement with respect to BM. 1 (the solid star). Error ellipses are 1σ . The thick black line of the rectangle represents the top of the obtained dislocation source.

(a)

(b)

Figure 4

(a) Cumulative opening of the crack during the period from 2015 to 2020. Cumulative opening is calculated from volume changes of one-year periods (2015–2016, 2016–2017, 2017–2018, 2018–2019 and 2019–2020). Error bars are 99% confidence interval estimated from the F-test. (b) Comparison of observed and calculated vertical displacements with respect to BM. 1. Error bars are 1σ .

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- [ga.png](#)