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Observing posteruptive deflation of hydrothermal system using InSAR time series analysis: An application of ALOS-2/PALSAR-2 data on the 2015 phreatic eruption of Hakone volcano, Japan

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Key Points:

- Posteruptive deflation beneath the central cones of Hakone volcano was detected by radar interferometry after the 2015 phreatic eruption
- Our model inversion suggests that deflation of a hydrothermal system confined by a sealing layer beneath the volcano has been taking place
- The hydrothermal system deflation is likely attributable to rupture of the sealing layer and system depressurization due to the eruption

17 **Abstract**

18 From 29 June to 1 July, 2015, a phreatic eruption occurred in Owakudani, the largest fumarole
19 area in Hakone volcano, Japan. In this study, an interferometric synthetic aperture radar (InSAR)
20 time series analysis of the Advanced Land Observing Satellite-2 (ALOS-2)/Phased Array type L-
21 band Synthetic Aperture Radar-2 (PALSAR-2) data was performed to measure deformation after
22 the eruption. The results show that the central cones of the volcano have subsided since the
23 eruption and its deflation source is located beneath the previously estimated bell-shaped
24 conductor, which is considered as a sealing layer confining a pressurized hydrothermal reservoir.
25 Therefore, the InSAR results demonstrate the deflation of the hydrothermal system beneath the
26 volcano. One possible cause of this deflation is compaction due to a decrease in pore pressure
27 caused by rupture and fluid migration during and after the eruption.

28 **Plain Language Summary**

29 From 29 June to 1 July, 2015, an eruption occurred in Owakudani, the largest steaming area in
30 Hakone volcano, Japan. Our analysis using satellite radar demonstrates that the central part of
31 Hakone volcano has subsided since the eruption and that the deflation source is located in the
32 reservoir of hot water beneath the volcano. One possible cause of this deflation is compaction
33 due to a pressure drop produced by rupture and fluid migration during and after the eruption.

34

35 **1 Introduction**

36 Measurements of crustal deformation in volcanic regions play an important role in
37 volcano monitoring. With the recent development of synthetic aperture radar (SAR) technology,
38 post-eruptive deflation has been observed after phreatic eruptions in various volcanoes (e.g.,
39 Hamling et al., 2016; Himematsu et al., 2020; Narita & Murakami, 2018). Volcanic deflation,
40 which occurs at different temporal and spatial scales, is explained by various factors, such as
41 decreases in pore pressure resulting from fluid migration (e.g., Todesco et al., 2014; Wang et al.,
42 2019) and thermoelastic responses with cooling (e.g., Furuya, 2005; Wang & Aoki, 2019).
43 Constraining the source of post-eruptive deflation is important when evaluating the structure and
44 physical properties of hydrothermal systems beneath volcanoes and assessing the risk of future
45 phreatic eruptions and signals during volcanic unrest. However, the relationship between the
46 deflation source and the structure of the hydrothermal system based on pre-existing subsurface
47 surveys has not been sufficiently discussed in previous studies. Recent magnetotelluric surveys
48 have revealed the structure of the hydrothermal system beneath Hakone volcano, the focal point
49 of this study, providing an appropriate context within which to discuss this topic.

50 Hakone is a caldera volcano located approximately 100 km west of Tokyo, the capital of
51 Japan (Figure 1). This volcano has been active for more than 400 ky, and effusive eruptions of
52 andesitic magma in the past 40 ky have formed its central cones (e.g., Mts. Kamiyama and
53 Komagatake in Figure 1) (Geological Society of Japan, 2007). Since its latest magmatic eruption
54 (3 ka), several phreatic eruptions have occurred near Owakudani, the largest fumarole area of the
55 volcano, which was formed on the foot of the latest edifice (Kobayashi et al., 2006; Kobayashi,
56 2008; Tsuchiya et al., 2017). Since the beginning of the 21st century, volcanic unrest has
57 occurred every few years. The unrest that began in April 2015 was the largest in terms of
58 seismicity in the history of modern observation since 1960. The 2015 unrest culminated in a
59 small phreatic eruption on 29 June in Owakudani, which released 80–130 tons of ash and

60 ballistic clasts (Furukawa et al., 2015). Although the 2015 phreatic eruption was small in scale, a
61 dense network of instrumental observation sites detected detailed processes of earthquake
62 activity and crustal deformation during the unrest (e.g., Harada et al., 2018; Honda et al., 2018;
63 Yukutake et al., 2017).

64 The observation during the preeruptive unrest suggests a deep (>6 km) supply of fluid,
65 which was detected as an inflation of the volcanic edifice and a swarm of deep low-frequency
66 events, initiated in early April 2015 (Harada et al., 2018; Yukutake et al., 2019). Then shallow
67 (<6 km) pressurization of the hydrothermal system was implied from an earthquake swarm that
68 occurred beneath the central cones from the end of April, and abnormal steaming activity from a
69 steam production well (SPW) in Owakudani (500 m deep with a well mouth elevation of 1000
70 m) occurred in early May (Mannen et al., 2018; Yukutake et al., 2017). The area within 200 m
71 of the SPW showed local swelling, which was detected by an interferometric SAR (InSAR)
72 analysis of Advanced Land Observing Satellite-2 (ALOS-2)/Phased Array type L-band Synthetic
73 Aperture Radar-2 (PALSAR-2) data (Doke et al., 2018; Kobayashi et al., 2018). The phreatic
74 eruption occurred near the southern edge of the swelling area from 29 June to 1 July 2015
75 (Kobayashi et al., 2018). The InSAR analysis of ALOS-2/PALSAR-2 pairs before and after the
76 phreatic eruption has demonstrated surface displacements caused by the opening of an NW–SE-
77 trending crack formed deeper than 830 m above sea level and the closing of a sill beneath the
78 crack, approximately 225 m above sea level (Doke et al., 2018). Although InSAR has poor time
79 resolution, Honda et al. (2018) also estimated an NW–SE-trending crack from a rapid tilt change
80 over the course of 2 min starting at 07:33 JST on 29 June 2015. These lines of evidence indicate
81 that the phreatic eruption was triggered by hydrothermal fluids stored approximately 225 m
82 above sea level, which migrated toward the shallower part of the edifice through the crack during
83 the eruption. Since the 2015 phreatic eruption, fumarolic activity in Owakudani has been higher
84 than before (Mannen et al., 2021). This higher steam activity during and after the eruption
85 suggests the rupturing of the sealed and pressured hydrothermal system beneath the volcano
86 during the 2015 eruption, as indicated by general modeling of hydrothermal systems (e.g.,
87 Fournier, 1999; Stix & de Moor, 2018).

88 Regarding the location of Hakone volcano, there are residential areas within 1 km of
89 Owakudani, the possible eruption center, so even a small-scale eruption would cause significant
90 damage. Although forecasting phreatic eruptions is known to be challenging, it may be possible
91 to monitor the hydrothermal system located in the shallow regions of the volcano using InSAR.
92 In this study, we performed an InSAR time series analysis of the ALOS-2/PALSAR-2 data to
93 clarify the surface velocities after the 2015 phreatic eruption of Hakone volcano. Applying the
94 inversion technique to the surface velocities, we modeled the deflation sources, and the cause of
95 this deflation is discussed here.

96 **2 Data and Methods**

97 The PALSAR-2 is a multi-mode and right- and left-looking SAR sensor aboard the
98 ALOS-2 launched by the Japan Aerospace Exploration Agency (JAXA) (Rosenqvist et al.,
99 2014). Its wavelength is 23.8 cm (L-band). The datasets selected for this study are path 126
100 (ascending orbit, right-looking) and path 18 (descending orbit, right-looking), which include
101 observations of Hakone volcano. These paths have the largest number of observation data of any
102 ascending or descending orbit, respectively, from 2 July 2015 to 1 April 2021, which is the
103 period after the phreatic eruption. Thus, it is expected that many interference pairs can be

104 obtained, allowing for greater precision in the analysis. Paths 126 and 18 represent observations
105 from the west and east sides of the sky, respectively, and their off-nadir angles are 38.7° and
106 38.9° , respectively. The data extracted for this study are given in Table S1. InSAR time series
107 analysis based on the small baseline subset (SBAS) method (Berardino et al., 2002) was used to
108 remove noise, such as atmospheric effects. For the SBAS-InSAR time series analysis,
109 interference pairs, whose time intervals are within 365 days, were extracted for each path. Path
110 126 has 21 extracted scenes and 74 pairs, whereas path 18 has 24 extracted scenes and 85 pairs.
111 The time–baseline plots are shown in Figure S1.

112 ENVI SARscape software was used for the SBAS-InSAR time series analysis. The
113 analysis area was cut out from the original data to focus on Hakone volcano and reduce the
114 analysis time (Figure 1). The data were averaged over 11 by 14 looks in the range and azimuth
115 directions, respectively (corresponding to an area of approximately 25 m by 25 m), to improve
116 the signal-to-noise ratio. The influence of the topography in initial interferograms was removed
117 using ellipsoidal height, generated from a 10-m digital elevation model (DEM) released by the
118 Geospatial Information Authority of Japan and Earth Gravitational Model 2008 geoid heights
119 (Pavlis et al., 2012). An adaptive filter (Goldstein and Werner, 1998) was used to reduce the
120 noise, and the interferograms were unwrapped by the minimum-cost flow approach (Costantini,
121 1998) with a 0.25 coherence threshold. For the removal of orbital residuals, 150 points of ground
122 control point were set as good coherence points in the area, except at the central cones of Hakone
123 volcano, in which significant displacements were observed, and a polynomial surface was
124 assumed. For the inversion of the SBAS-InSAR time series analysis (Berardino et al., 2002), a
125 linear displacement model was used. Atmospheric effects were estimated by applying a spatial
126 low-pass filter with a cutoff of 1,200 m and a temporal high-pass filter with a cutoff of 365 days.
127 Finally, the estimated surface velocities were geocoded to the geographic coordinates in WGS-
128 84, and surface velocity maps were obtained with a resolution of 25 m by 25 m. Moreover,
129 Quasi-eastward and quasi-upward components were calculated by 2.5-D analysis (Fujiwara et al.,
130 2000).

131 **3 Results**

132 Figures 2(a) and (b) show surface velocity maps after the 2015 phreatic eruption
133 estimated by the SBAS-InSAR time series analysis. The velocities are indicated in the line-of-
134 sight (LOS) directions, and positive and negative values indicate velocities toward and away
135 from the satellite, respectively. An area of 2 km in diameter, located at the central cones of the
136 volcano, shows subsidence in the quasi-upward component, and its velocity is below -10 mm/yr
137 (Figure 2 (d)). Since the atmospheric conditions in the study area are varied locally, the effects
138 may not have been fully eliminated by the analysis. However, the observed velocity is
139 significantly greater than the component correlated with topography, suggesting subsidence at
140 the central cones.

141 Figure 3 shows the time variation of displacements at the selected locations A and B in
142 Figure 2. Location A was selected in the Sengokuhara area (Figure 1), located on the caldera
143 floor far from the central cones of the volcano, and location B was selected near the central
144 cones. Although location A did not show any significant displacement, location B was displaced
145 in the negative LOS direction (away from the satellite) during the analysis period, except for
146 2019 at Path 126. These results show that the central cones (location B) had significantly
147 subsided with respect to location A. The vertical velocity at location B is approximately -18.3

148 mm/yr (Figure 2(d)). The displacement pattern in 2019 might have been affected by volcanic
149 unrest.

150 Significant displacement was detected near Owakudani, and this area was evaluated as
151 location C. Location C showed the maximum velocity in the negative LOS direction on path 18
152 with a velocity of approximately -43.5 mm/yr (Figures 2(b) and 3(b)). However, the equivalent
153 displacement was not detected on path 126 (Figure 3(a)). This velocity was considered to be due
154 to a landslide because it shows the local displacement near Owakudani and is located on a slope
155 steeply inclined toward the northwest (the negative LOS direction on path 18). Assuming that the
156 displacement is in the inclination direction of the slope, the velocity is estimated to be 51.9
157 mm/yr. Moreover, a seasonal pattern was observed at Location C (Figure 3(b)), suggesting that
158 the landslide displacement was accelerated by precipitation and other factors.

159 Model inversion was conducted to explain the surface velocity distributions obtained
160 from the SBAS-InSAR time series analysis (see Text S1 and Figures S2-5). Two deflation source
161 models were used: a point pressure source model (Mogi, 1958) and a rectangular sill model
162 (tensile fault model by Okada, 1985) in a semi-infinite elastic crust. The optimal parameters for
163 each model are given in Table 1 with their standard errors. Moreover, the root mean square
164 (RMS) and Akaike's information criterion (AIC) values for each model are also given in Table 1.
165 The point source deflation model, which had a volume change rate of -5.96×10^4 m³/yr, was
166 estimated beneath the central cones of Hakone volcano at an altitude of 211.0 m above sea level.
167 Additionally, the rectangular sill deflation model with a long side along the NW–SE direction
168 was estimated at 95.0 m above sea level, and its opening rate was -0.111 m/yr (closing). The
169 volume change rate of the sill deflation model was calculated to be -6.54×10^4 m³/yr. Although
170 the RMS and AIC values for the sill deflation model are slightly smaller than those for the point
171 source deflation model, both models can explain the patterns of the surface velocities (Figure
172 S2).

173 **4 Discussion and Conclusion**

174 Recent magnetotelluric surveys of Hakone volcano have reported the existence of a bell-
175 shaped conductor (<10 Ω m) beneath the central cones of the volcano (Mannen et al., 2019; Seki
176 et al., 2020; Yoshimura et al., 2018). Similar bell-shaped conductors have been detected in other
177 volcanoes (e.g., Komori et al., 2013; Nurhasan et al., 2006; Usui et al., 2017) and interpreted as
178 impermeable layers that contain smectite, a very conductive altered mineral formed by
179 hydrothermal activity (e.g., Lévy et al., 2018; Pellerin et al., 1996). Moreover, these
180 impermeable layers are considered to be sealing layers that confine pressurized hydrothermal
181 systems beneath volcanoes, which can cause phreatic eruptions (e.g., Stix & de Moor, 2018).
182 Based on a controlled-source audio-frequency magnetotellurics (CSAMT) survey and geological
183 analysis, Mannen et al. (2019) indicated that a portion just beneath the bell-shaped conductor
184 forms a vapor–liquid coexisting hydrothermal system. The area surrounded by the bell-shaped
185 conductor in a wider range of resistivity structure estimated by Yoshimura et al. (2018) agrees
186 well with the subsidence area (Figure 2(d)). Moreover, Seki et al. (2021) showed that the bottom
187 of the bell-shaped conductor beneath the central cones of Hakone volcano is approximately 600–
188 700 m above sea level so that the post-eruptive deflation source is located beneath the bell-shaped
189 conductor (about 100–200 m above sea level; Figure 4). Therefore, the results of this study
190 demonstrate that deflation has been occurring in the hydrothermal system beneath the volcano.

191 Based on the heat flux of 20 MW before the 2015 phreatic eruption in Owakudani
 192 (Mannen et al., 2018), the release rate for water vapor is estimated to be 2.8×10^8 kg/yr (1 atm,
 193 100 °C). Alternatively, the deflation rates (5.96×10^4 – 6.54×10^4 m³/yr) for the models in this
 194 study can be converted to water loss rates of 4.1×10^7 – 4.5×10^7 kg/yr, assuming the water
 195 density (690 kg/m³) at the boiling point (311 °C) for the pore pressure at the given depth (10
 196 MPa). This means even preruptive water release at Owakudani was at least 6–7 times larger
 197 than the water loss of the hydrothermal system implied from our InSAR time series analysis.
 198 After the eruption, the release of water vapor can be considered to be several times greater than
 199 the preruptive release. Therefore, the posteruptive deflation source was not regarded as the
 200 principal source of posteruptive fumarole activity, and the hydrothermal fluids are supplied from
 201 a deeper part.

202 So what is the cause of the posteruptive deflation in Hakone volcano? One possible cause
 203 of posteruptive deflation is compaction due to a decrease in pore pressure (Todesco et al., 2014;
 204 Wang et al., 2019). Because the behavior of crustal deformations during the 2015 phreatic
 205 eruption suggests fluid migration from the hydrothermal reservoir to a shallower edifice (Doke et
 206 al., 2018), the preruptive pore pressure could have been released during and after the migration
 207 (Figure 4). Moreover, in the shallow part of Owakudani, a posteruptive enlargement of the high-
 208 resistivity zone ($>10 \Omega\text{m}$) was detected (Mannen et al., 2019). This result suggests a phase
 209 change from water to vapor within the shallowest part of the hydrothermal system due to a
 210 pressure decrease after the phreatic eruption. An effect of compaction, which depends on the
 211 rheologies of subsurface rocks, can continue for a long time after a pressure drop. Todesco et al.
 212 (2014) described the process of compaction Δh with the following equation:

$$\Delta h = h_0 \frac{P_c A^{-1} t^b}{1 - \phi_0 + P_c A^{-1} t^b} \quad (1)$$

213 where h_0 is the initial thickness of the compacting layer, ϕ_0 is the porosity, P_c is the pressure
 214 change, and t is the elapsed time in days. Additionally, A and b are empirically derived
 215 parameters that express the rheological properties of the compacting layer: A is a scalar
 216 associated with the magnitude of creep compaction, and b is related to the apparent viscosity of
 217 the system (Todesco et al., 2014). The initial thickness h_0 was set to 500 m, considering the
 218 structure beneath the bell-shaped conductor where the posteruptive deflation source is located
 219 (Seki et al., 2021; Figure 4), and the porosity ϕ_0 was set to 0.1 as a typical value used for
 220 simulations of hydrothermal systems (e.g., Tanaka et al., 2018). The other parameters were
 221 estimated by fitting, assuming that the LOS displacements were entirely in the vertical direction.
 222 The values of the parameters with error ranges in parentheses are $P_c = 0.91$ (0.70–1.11) MPa, $A =$
 223 $596,514$ (483,720–777,888) MPa·day ^{b} , and $b = 0.64$ (0.61–0.67), which are similar to the values
 224 estimated in Campi Flegrei (Todesco et al., 2014). The obtained curves (dashed lines in Figure 3)
 225 fit well with the pattern of subsidence after the 2015 phreatic eruption. Although the validity of
 226 these parameters remains to be verified, the results indicate that compaction due to a decrease in
 227 pore pressure is a plausible process to explain subsidence at the ground surface.

228 Another possible cause of deflation is a thermoelastic response with cooling (e.g.,
 229 Furuya, 2005; Wang and Aoki, 2019). However, most examples of thermoelastic responses are
 230 related to the cooling of intruded magma bodies. Narita et al. (2019) demonstrated that the
 231 temperature change in the thermoelastic response expected from the posteruptive deflation after
 232 the 2014 phreatic eruption of Ontake volcano, Japan, was too large for the shallow part (500 m in

233 depth) of the volcano. They concluded that the thermoelastic response is not a major factor
 234 contributing to deflation in Ontake volcano. The 2015 phreatic eruption of Hakone volcano was
 235 very small in scale, and significant temperature changes were unlikely to have happened in the
 236 coexisting vapor–liquid hydrothermal system, where the temperature change was buffered by the
 237 release of latent heat due to the condensation of water vapor (e.g., Ingebritsen et al., 2006).
 238 Therefore, the thermoelastic process is unlikely to be a major factor in the deflation of Hakone
 239 volcano.

240 The continuing deflation process means that the sealing ability has not been restored yet
 241 since the 2015 phreatic eruption of Hakone volcano. If compaction continues according to
 242 Equation (1), subsidence of approximately 5 mm/yr is predicted even 100 years after the
 243 eruption. However, if the sealing ability is restored as a result of mineral crystallization or other
 244 factors and the pressure starts to increase, this deflation will terminate shortly. Therefore, it is
 245 important to monitor the displacement at the ground surface to assess the pressure conditions of
 246 the hydrothermal system and the risk of future phreatic eruptions.

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 252 are available on Zenodo (<https://doi.org/10.5281/zenodo.5014834>).

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409 **Figure 1.** Index map of Hakone volcano. The base map is a false-color image captured by
410 ALOS/AVNIR-2 on 10 November 2006, and the red tones indicate vegetated areas. The areas
411 enclosed by the rectangles indicate the analysis areas in this study.

412 **Figure 2.** Distribution of LOS velocities estimated from SBAS-InSAR time series analysis of
413 ALOS-2/PALSAR-2 data; (a) path 126, (b) path 18, and (c) quasi-eastward and (d) quasi-
414 upward components. The contour lines represent intervals of 100 m in height. The red circles
415 represent locations mentioned in the text and Figure 3. The yellow circles (E) show the location
416 of the 2015 eruption center. The red dashed line shows the area surrounded by the bell-shaped
417 conductor at the height of 0 m (Yoshimura et al., 2018).

418 **Figure 3.** Time variation of the displacements at locations A–C in Figure 2 for (a) path 126 and
419 (b) path 18. Locations A and B were selected on the caldera floor and the central cones of
420 Hakone volcano, respectively. Location C is the site that shows the maximum velocity away
421 from the satellite along the LOS in path 18. Positive and negative values indicate displacements
422 toward and away from the satellite, respectively. Dashed lines are the lines of best fit assuming
423 that compaction due to the pore pressure decreases (see text).

424 **Figure 4.** Schematic illustration of the shallow hydrothermal system beneath the central cones of
425 Hakone volcano. The subsurface model is based on the conductivity structure and interpretation
426 shown in Figure 4 of Seki et al. (2021), previous deformation sources proposed by Doke et al.
427 (2018), and the results of the present study. During the 2015 phreatic eruption, the sealing layer
428 was ruptured, and pressurized hydrothermal fluids migrated toward the shallower edifice.
429 Post-eruptive deflation might be caused by a pore pressure decrease in the hydrothermal reservoir
430 due to fluid migration.

431 **Table 1.** Estimated Model Parameters.

432

Figure 1.

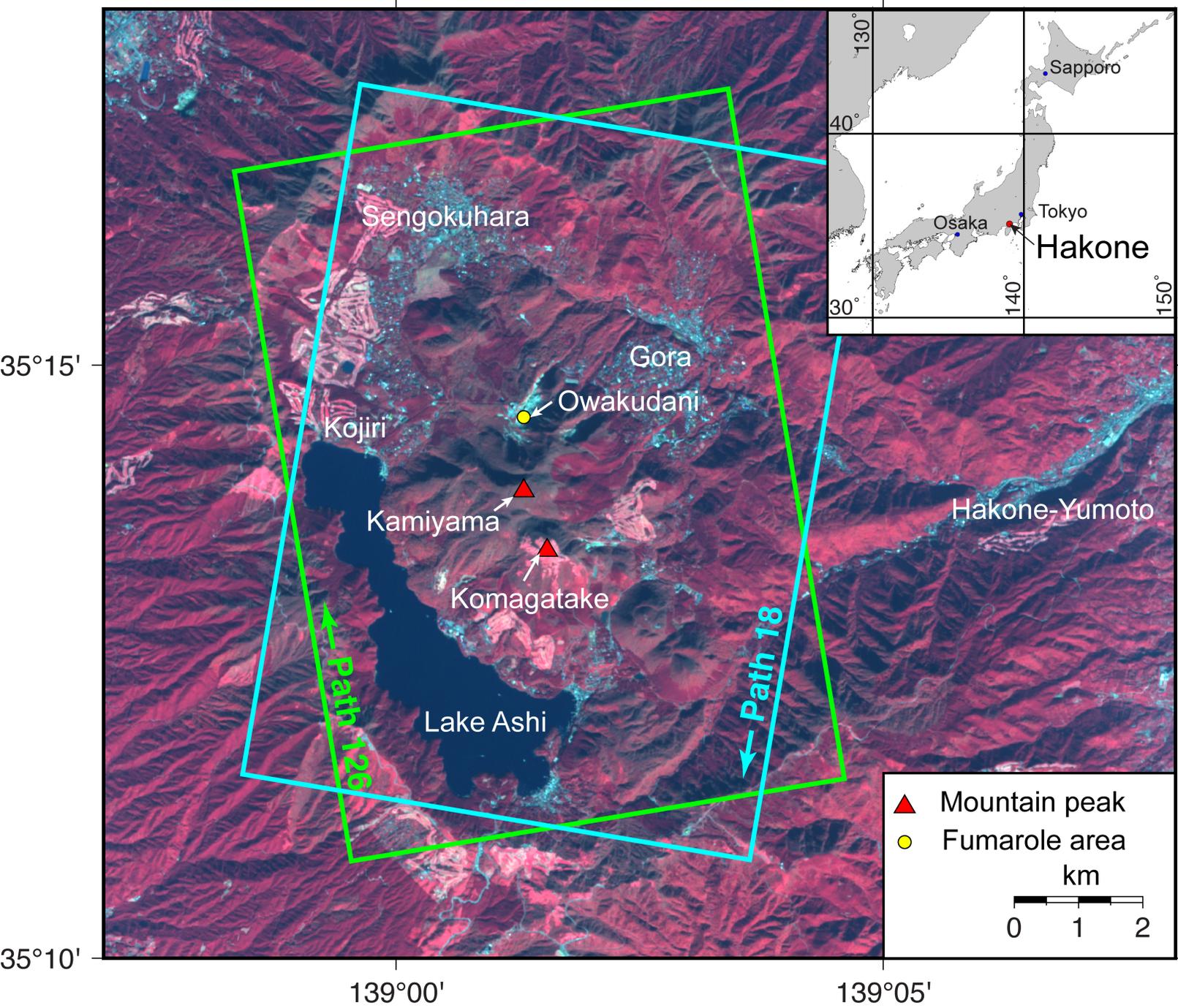


Figure 2.

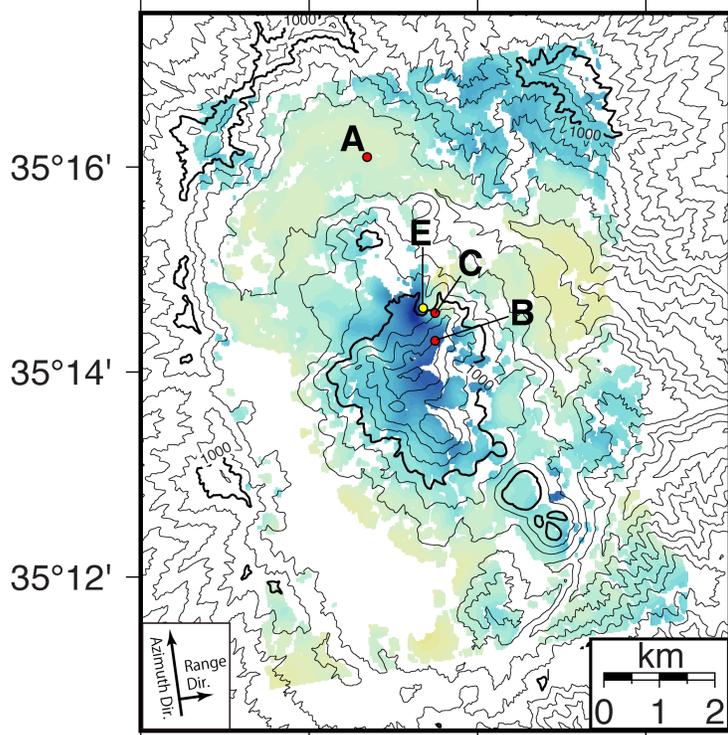
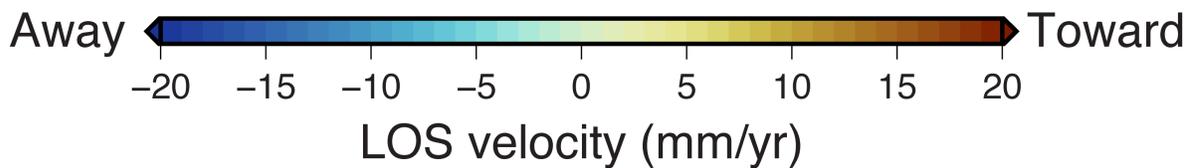
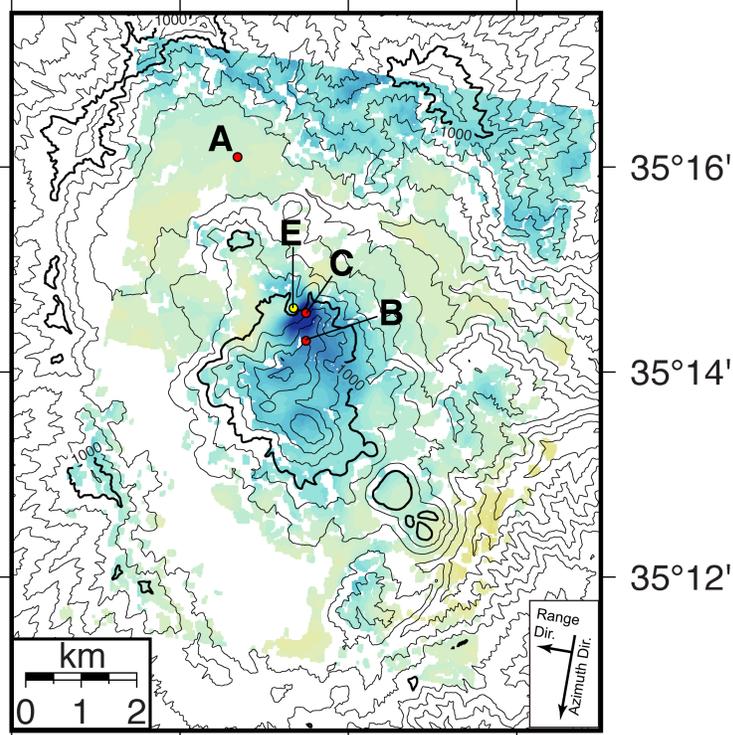
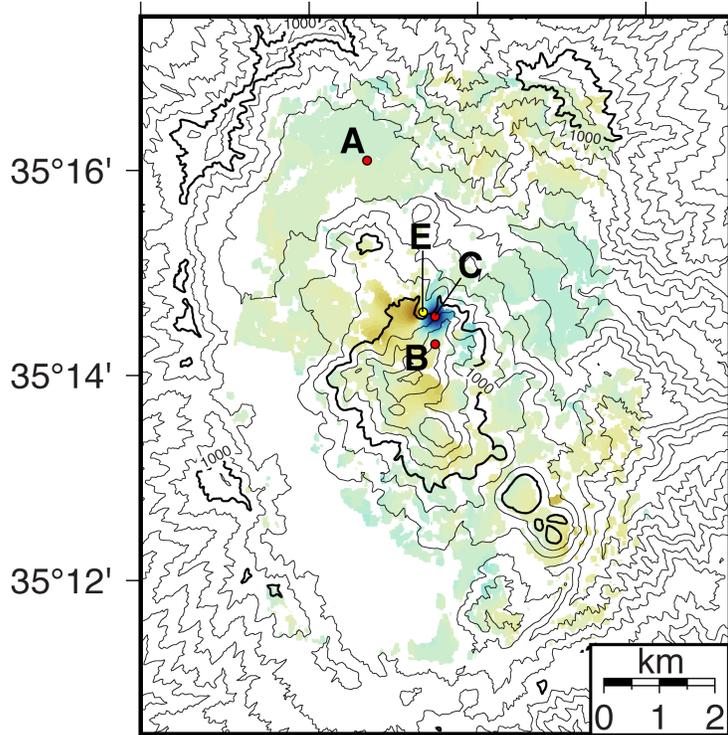
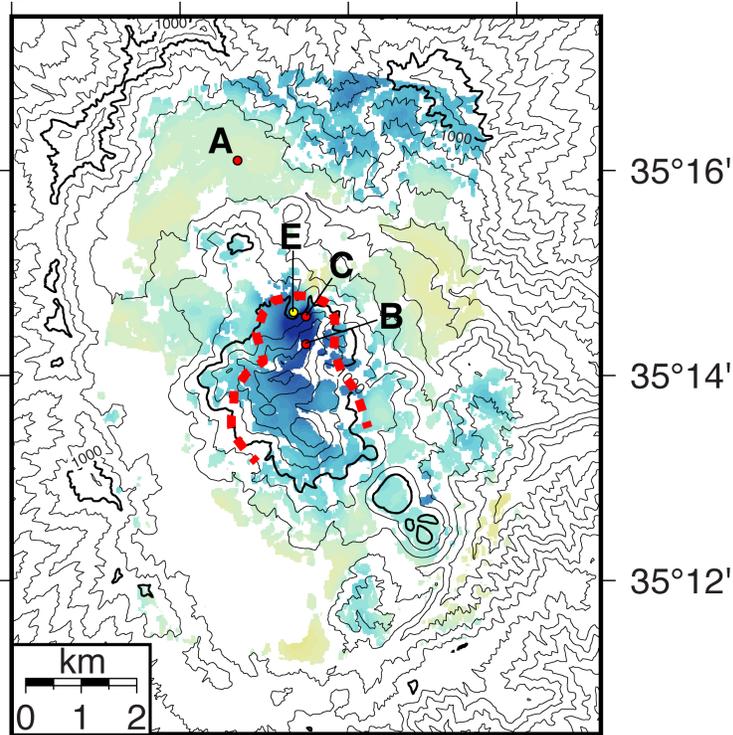
(a) Path 126**(b) Path 18****(c) Quasi-EW****(d) Quasi-UD**

Figure 3.

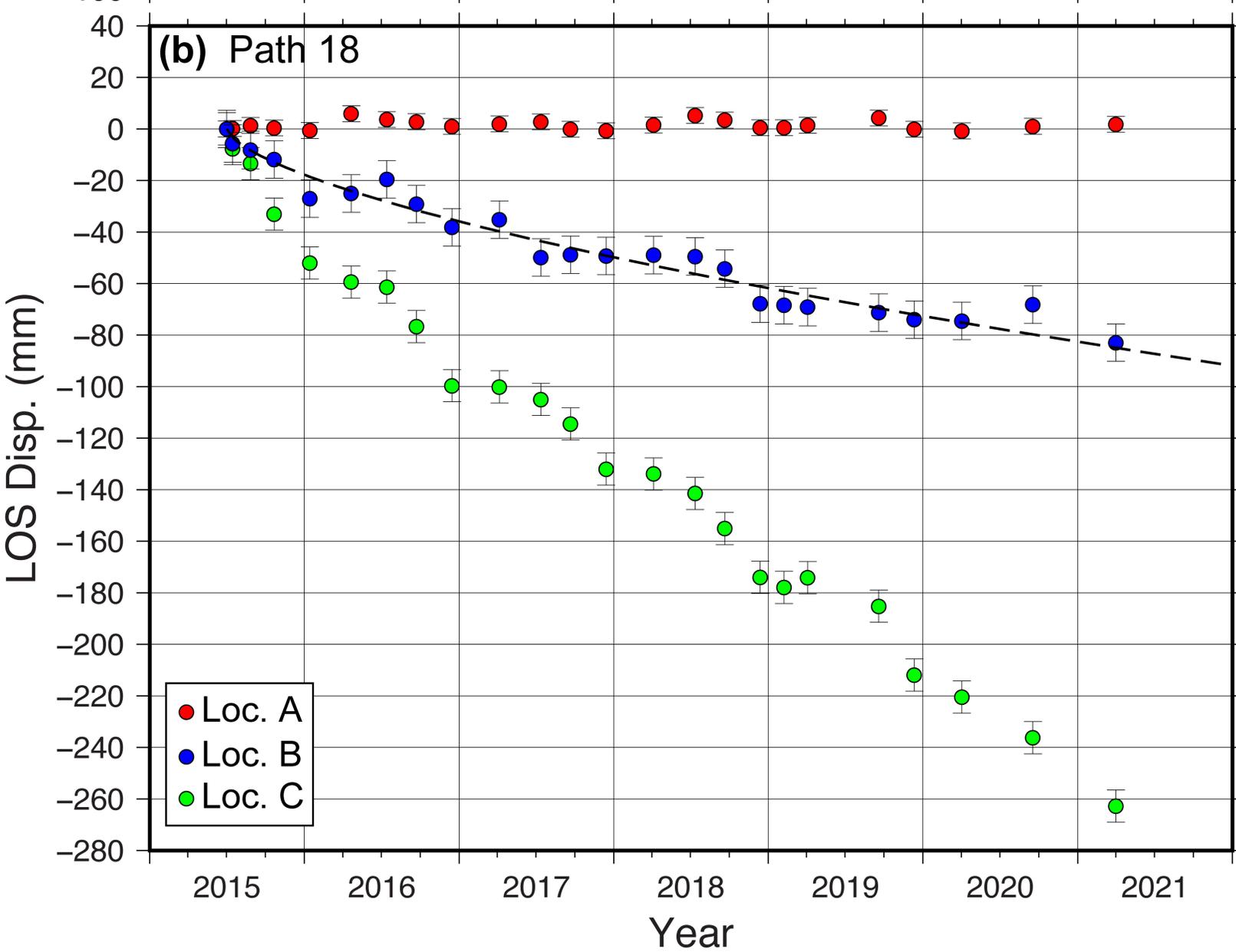
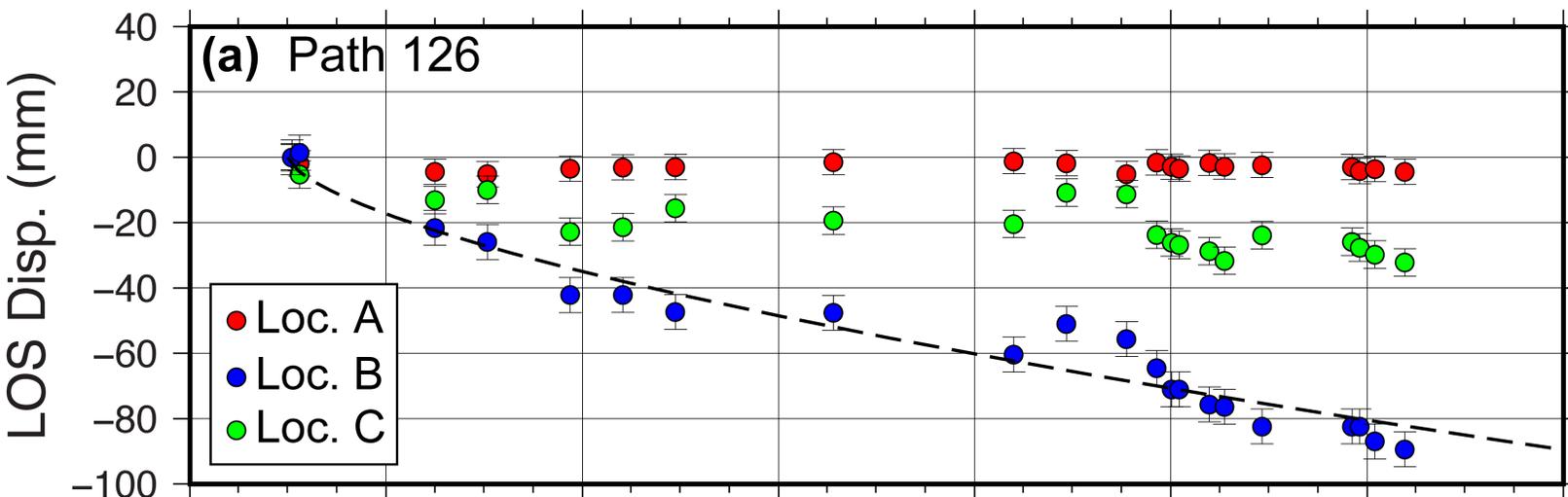


Figure 4.

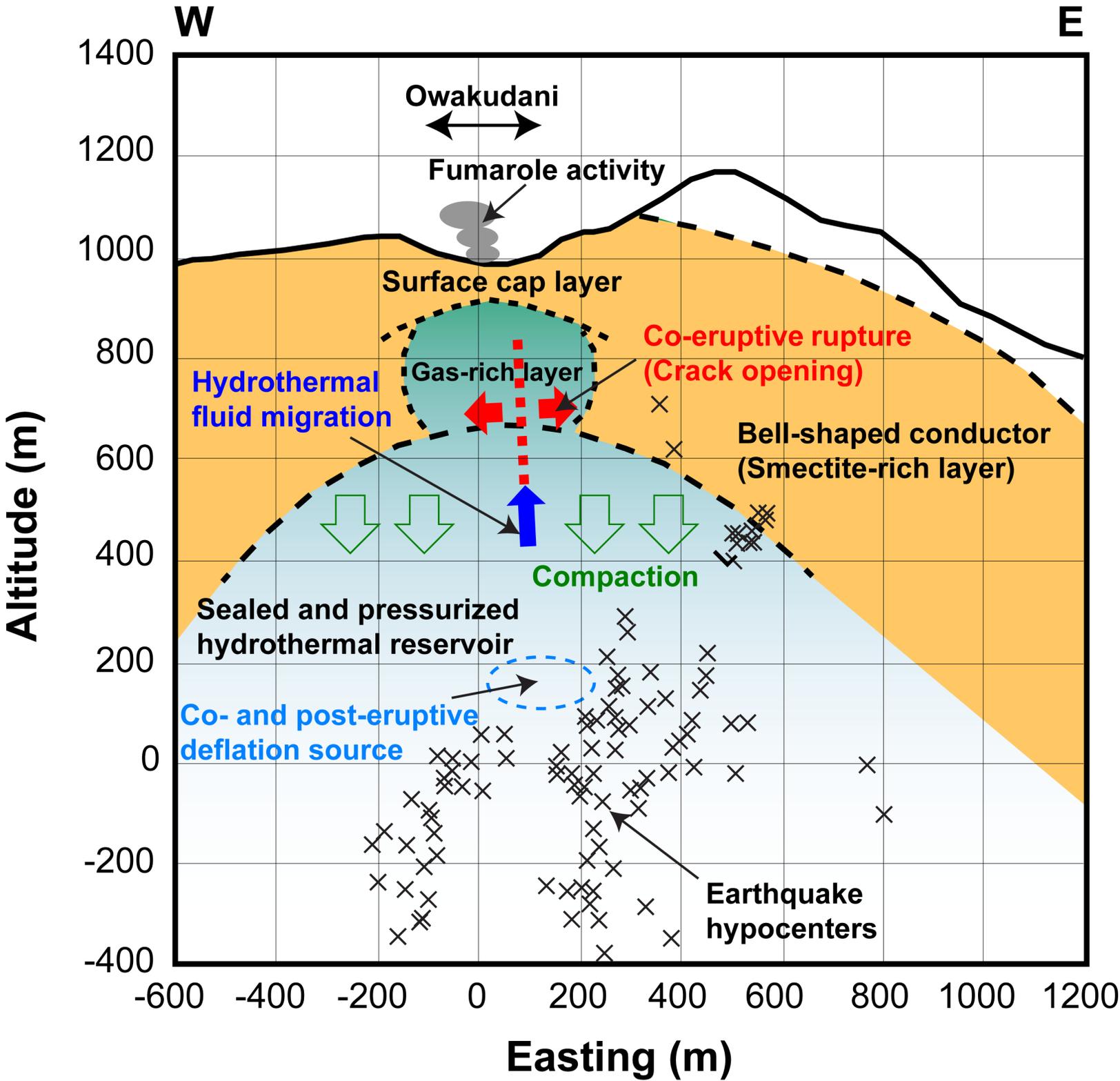


Table 1. *Estimated Model Parameters.*

	Model A [Point source deflation]	Model B [Sill deflation]
Longitude (°) ^a	139.0242 (0.0007)	139.0289 (0.0005) ^b
Latitude (°) ^a	35.2372 (0.0006)	35.2250 (0.0006) ^b
Altitude (m) ^c	211.0 (64.7)	95.0 (42.9)
Volume change rate (m ³ /yr)	-5.96×10^4 (2.76×10^4)	-6.54×10^4 (5.78×10^3) ^d
Length (m)	–	2392.2 (94.0)
Width (m)	–	246.2 (15.4)
Strike (°)	–	339.1 (1.2)
Opening rate (m/yr)	–	–0.111 (0.005)
RMS Path 126 (mm/yr)	2.525	2.305
RMS Path 18 (mm/yr)	2.358	2.255
RMS Total (mm/yr)	2.444	2.280
AIC	3662	3574

Note: Standard errors are given in parentheses.

^a The longitude and latitude are given in WGS-84 coordinates.

^b The coordinates for Model B indicate the southernmost point of the sill model.

^c The altitude is the height above sea level, corrected from the originally estimated ellipsoidal height.

^d The volume change rate for Model B was calculated from the length, width, and opening of the sill model.