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

3

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9

10 **Abstract**

11 We installed and operated a low-cost groundwater level observation system at  
12 intermittent hot spring wells in order to monitor volcanic strain signals from the active  
13 Meakan-dake volcano in eastern Hokkaido, Japan. Data are sampled at 1 Hz and are  
14 transmitted to the data center in real time. Evaluation of the water level time series with  
15 theoretical predictive tidal strain and coseismic static strain changes has suggested that  
16 the wells penetrate to the artesian aquifer and act as a volumetric strain sensor. An active  
17 earthquake swarm with more than 400 events occurred at the shallower part of the  
18 volcano from January 9 to 11, 2008. Three independent wells recorded pre- to co-swarm  
19 groundwater drops simultaneously, which represented a decrease in volumetric strain.  
20 The total volumetric strain change during the three active days was estimated to be from  
21 6 to  $7 \times 10^{-7}$ . The observed data, including changes in volumetric strain, absence of  
22 deformation in the GPS coordinates, and activation of deep low-frequency earthquakes,  
23 might imply possible deflation of a source deeper than 10 km, and these preceding  
24 deeper activities might induce an earthquake swarm in a shallower part of the

25 Meakan-dake volcano.

26

## 27 **1. Introduction**

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

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

43 Geothermal fields and hot springs are located on and near the volcanic edifice. Prior to  
44 2004, the average temperature of active fumaroles in the summit crater (Fig. 1) had been  
45 approximately 400°C (Fig. 2b). However, a decrease in temperature was observed over  
46 the last decade, and recent data gathered during the spring of 2008 indicated that the  
47 temperature was less than 100°C (Fig. 2b).

48 Crustal deformation associated with volcanic activity can be used to investigate the

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

58

## 59 **2. Groundwater level observation**

60 Several studies have shown that, under proper conditions, artesian groundwater acts as  
61 a volumetric strain sensor (Wakita, 1975, Roeloffs, 1988, Quilty and Roeloffs, 1997,  
62 Matsumoto et al., 2002, 2003, Akita and Matsumoto, 2004, Itaba et al., 2010, Shibata et  
63 al., 2010, Gahalaut et al., 2010). The suggested volcanic strain signals might also be  
64 observed as groundwater level changes. In order to monitor volcanic unrest signals  
65 using groundwater level data, we used three preexisting intermittent hot spring water  
66 wells, AK1, AK3, and AK4, which are situated approximately 8 km NNE from the  
67 volcano summit (Fig. 1). The parameters of each well are listed in Table 1 (Kawamori et  
68 al., 1987). Well AK1 had a borehole depth of 1,061 m with a strainer located at a depth  
69 of between 518 and 1,061 m, whereas wells AK3 and AK4 had shallower boreholes (92  
70 and 57 m) with strainers located at depths of between 24 and 55 m and between 41 and  
71 57 m, respectively. These facts indicate that AK1 and AK3-4 penetrate different aquifers.  
72 In order to measure the groundwater levels, in April of 2006, we installed a water

73 pressure measurement sensor (Druck PTX1830) approximately 5 m below the water  
74 surface. The hydraulic heads from the ground surface are 1 m for AK1 and 0.5 m for  
75 AK3 and AK4. The sensor resolution is less than 1 mm. A barometric pressure sensor  
76 was also deployed at the same location in order to eliminate barometric pressure effects  
77 on the water levels. The obtained data are converted to digital signals using a 24-bit AD  
78 converter at a sampling rate of 1 Hz and are transmitted in real time to the data center at  
79 Hokkaido University via IP protocol. A precise time calibration is accomplished by  
80 on-site GPS receivers every two hours. All data are stored in a crustal deformation  
81 database system (Yamaguchi et al., 2010) and are distributed to concerned institutions in  
82 pseudo-real time.

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

97 BAYTAP-G software. The strain sensitivities to the M2 tidal constituent,  $W_s$ , were  
98 calculated as follows:

$$99 \quad W_s = T_w/T_t,$$

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

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

111

### 112 **3. Volcanic earthquake swarm and groundwater level changes**

113 An earthquake swarm began at 17:00 on January 9, 2008. Note that we hereinafter use  
114 Japan Standard Time (JST) (GMT+9). The number of earthquakes increased until 12:00  
115 January 10 and then decreased until 23:00 January 10. The hypocenters of the volcanic  
116 earthquakes determined by the Sapporo district Meteorological Observatory (SMO) of  
117 the JMA volcano observation network were concentrated just under the summit crater at  
118 an elevation of 0 to 0.5 km (Fig. 3). The maximum number of hourly earthquakes  
119 exceeded 40, and the total number of earthquakes over a three-day period was 624.  
120 None of the earthquakes were felt because the maximum magnitude was less than 0.5.

121 Webcams installed by the JMA and other institutes did not capture any anomalous  
122 activity, such as smoke escaping from active vents. Moreover, the GPS stations operated  
123 by the JMA did not detect any signals during this swarm (Fig. 4).

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

143 Changes at the three wells appeared to begin before earthquake swarm occurrence. A  
144 differential rate of water level change at AK1 indicated that the water table fall started at

145 20:00 January 8 (Fig. 6), which is approximately 21 hours prior to earthquake swarm  
146 initiation (Fig. 6). This clearly indicates that tensional dilatation had progressed at the  
147 AK wells without showing earthquake activity. The earthquake swarm began at almost  
148 the maximum water table drop during the period of interest. All of the water levels  
149 decreased and did not recover until at least 20 January. The amplitudes of the total water  
150 decrease at AK1, AK3, and AK4 were approximately 25 cm, 3 cm, and 4 cm,  
151 respectively. The sensitivity coefficient difference (AK1 is 5.8 times larger than AK4) is  
152 consistent with that of the water level change values. In fact, the volumetric strain  
153 values calculated using the estimated sensitivity coefficients was of approximately the  
154 same order (Table 1).

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

163

#### 164 **4. Discussion**

165 The observed data strongly suggested that water level changes were related to the  
166 volcanic unrest of the Meakan-dake volcano. However, the biased location of the wells  
167 did not allow us to estimate the deformation source parameters of the strain event. The  
168 JMA have operated a continuous GPS network in this volcano for some time (Fig. 1).

169 Baseline length changes for a month including an earthquake swarm period suggested  
170 that this network can detect a displacement signal of more than a few centimeters (Fig.  
171 4). We assumed detection resolutions of 1 cm and 2 cm for the baseline and vertical  
172 components, respectively. No significant displacement signals exceeding the above  
173 resolutions were observed before, during, or after the swarm, which provides a strong  
174 constraint for deformation source modeling.

175 We used water level and GPS data to estimate the depth and volume change of the  
176 deformation source. A buried point source, the Mogi model (Mogi, 1958), was assumed  
177 for modeling. The lack of GPS displacement for all of the baselines suggested that point  
178 source location estimation based on these data would be impossible. The epicenters of  
179 both the shallower earthquake swarm (Fig. 3) and the deep low-frequency earthquakes  
180 (DLEs) were concentrated just beneath the summit crater. Wherefore, we fixed the  
181 horizontal location of a point source to the summit crater a priori. The depth and volume  
182 change were valuable for modeling. The displacement and strain field was computed  
183 using Okada's (1992) formula, and the Poisson ratio and Lamé's constant were set to  
184 0.25 and  $\mu = \lambda$ , respectively.

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

193 shallowest source deflation.

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

202 On the other hand, the rms of the AK1 volumetric strain indicates an asymmetric  
203 distribution (Fig. 7c). The left- and right-hand segments are due to the deflation and  
204 inflation of the point source, respectively. Small, broad rms segments appear in the  
205 left-upper side. This rms distribution indicates that deflation is preferable to inflation.  
206 The local rms minimum appearing in right-lower side might not be correct because of  
207 the inconsistency with the rms maps of GPS baselines and vertical data. However, these  
208 three rms maps do not provide the optimal parameters because no common minimum  
209 spot was identified. Proper weighting for joint data treatment is difficult due to  
210 differences in data quality. Nevertheless, comparison of the three rms distribution maps  
211 may provide a clue for searching for reasonable parameters. For example, a source at a  
212 depth of greater than 10 km with a deflation of  $0.01 \text{ km}^3$  generates a smaller rms than a  
213 shallower depth. No signal at TES station was also consistent with above assumption.  
214 These considerations with respect to the rms maps suggest that the observed data might  
215 be explained well by the possibility of a deeper source having a deflation volume of  
216 approximately  $0.01 \text{ km}^3$ . A strain observation array with a proper station distribution is

217 required in order to clarify this problem numerically.

218 Takahashi and Miyamura (2009) found that the activity of DLEs in the Meakan-dake  
219 volcano is the second highest among Japanese quaternary volcanoes. Source mechanism  
220 studies of DLEs have suggested possible crack openings caused by fluid (Nakamichi et  
221 al., 2003). Activation of DLEs prior to eruption or magmatic unrest had been reported at  
222 several volcanoes (White, 1996, Nakamichi et al., 2003), and DLE activations without  
223 successively eruption have also been reported (Nichols et al., 2011). In the  
224 Meakan-dake volcano, more than 800 DLE events were recorded during the decade  
225 before the 2008 earthquake swarm. The epicenters and DLEs were concentrated just  
226 beneath the summit crater at depths of 20 km and 25 km, respectively (Takahashi and  
227 Miyamura, 2009). These findings imply the possible presence of fluid and/or magma in  
228 the DLE hypocenter region. The cumulative number of DLEs and shallow volcanic  
229 earthquakes (SVEs) as determined by the JMA during the earthquake swarm is shown in  
230 Fig. 8. An increase in the number of DLEs started the night of January 8 at a depth of  
231 between 15 and 20 km nearly simultaneously with the water table decrease at the AK  
232 wells.

233 The observed groundwater level and GPS data suggest a possible interaction between  
234 deeper deflation and the shallow earthquake swarm. The rapid response of shallower  
235 seismic activity to DLEs activations were observed during the Mt. Pinatubo (White,  
236 1996) and Mt. Iwate (Nakamichi et al., 2003) unrests. In the Meakan-dake volcano, a  
237 delay of only one day of shallower activity posteriori to the initiation of strain signals  
238 implied that a possible upward volatile migration generated the swarm. However,  
239 observed data that indicating no eruption, no change in smoke amount and active vent  
240 temperature did not seem to support this idea (Fig. 2).

241 Self-potential surveys suggested a possible permeable layer at around sea level  
242 (Matsushima et al., 1994, Zlotnicki and Nishida, 2003). Volcanic gases, e.g., H<sub>2</sub>S, SO<sub>4</sub>,  
243 and CO<sub>2</sub>, have high water solubility (National Astronomical Observatory of Japan,  
244 2010). If we accept the hypothesis that upward volatile migration occurred as the water  
245 table descended, then the lack of surface phenomena might suggest that the aquifer  
246 acted as a barrier due to the dissolution of ascending volcanic volatiles in water.  
247 Chemical component analysis of hot spring water 2 km west of the summit crater  
248 reveals very higher concentration of H<sub>2</sub>S to be 34.99 mg per liter and of SO<sub>4</sub> to be 1,615  
249 mg per liter, respectively (Geological Survey of Hokkaido, 1980). This also implies  
250 possible volcanic gas dissolution in the shallower aquifer. Continuous chemical  
251 component analysis of hot spring water may provide clues to help clarify the interaction  
252 between the shallower aquifer and volcanic volatile migration.

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

265 zone.

266

## 267 **5. Conclusion**

268 We have started groundwater level observations at intermittent hot spring wells near  
269 the active Meakan-dake volcano using a low-cost system. Simultaneous lowering of the  
270 water level prior to a volcanic earthquake swarm was recorded at three independent  
271 wells. The total volumetric strain changes associated with an earthquake swarm was 6 to  
272  $7 \times 10^{-7}$ . Proper point source (Mogi model) parameters were sought using water level and  
273 GPS data. Although optimal parameters were not defined because of an insufficient data  
274 set, several assumption and residual distribution maps suggest a possible deflation  
275 source at a greater depth ( $>10$  km) with a volume change of approximately  $0.01 \text{ km}^3$ .  
276 Synchronization in space and time between DLE activation and possible deflation  
277 source activity was recognized. Although the timeline of deeper activities and a  
278 shallower earthquake swarm might imply that the earthquake swarm was triggered by  
279 upward migrating volatile, no physical model or observation data were presented. The  
280 observation data of the present study clearly demonstrate low-cost groundwater level  
281 observation at existing wells can record volumetric strain with high precision, on the  
282 order of  $10^{-7}$ . The proposed monitoring system can be easily expanded because of the  
283 numerous unused hot spring wells that exist near active volcanoes.

284

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298

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385

386 **Figure captions**

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

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

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

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

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

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

409 swarm are indicated by dotted and dashed lines, respectively.

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

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

416 Fig. 9 Schematic diagram of the volcanic unrest during January 2008. DLE: deep,  
417 low-frequency earthquake, SVE: shallow volcanic earthquake. Note that no  
418 earthquakes were observed between the deep and shallow active zones during the  
419 swarm period.

**Table**[Click here to download Table: Table.pdf](#)

Table 1 Parameters of observation wells.

ID	Location (Lat, Lon, Height)	Depth (m)	Strainer depth (m)	Geology along strainer	Volumetric strain coefficient (mm/10 <sup>-8</sup> strain)	Water level change (cm)	Volumetric strain change (microstrain)
AK1	N43.4309 E144.0995 H432m	1061	518.1-1005.8: Casing	Miocene volcanic rocks	3.42	-19.2	-0.56
AK3	N43.4306 E144.0847 H420m	91.8	24.0-68.0: Casing Below 68.0: Bare	Pliocene-Quaternary volcanic rocks	(0.38-0.50)	-2.8	-
AK4	N43.4303 E144.0846 H420m	54.7	41-54.7: Casing	Pliocene-Quaternary volcanic rocks	0.60	-4.4	-0.74

Coefficient of AK3 is deduced from swarm-related water change comparing to AK1 and AK4.

Figure

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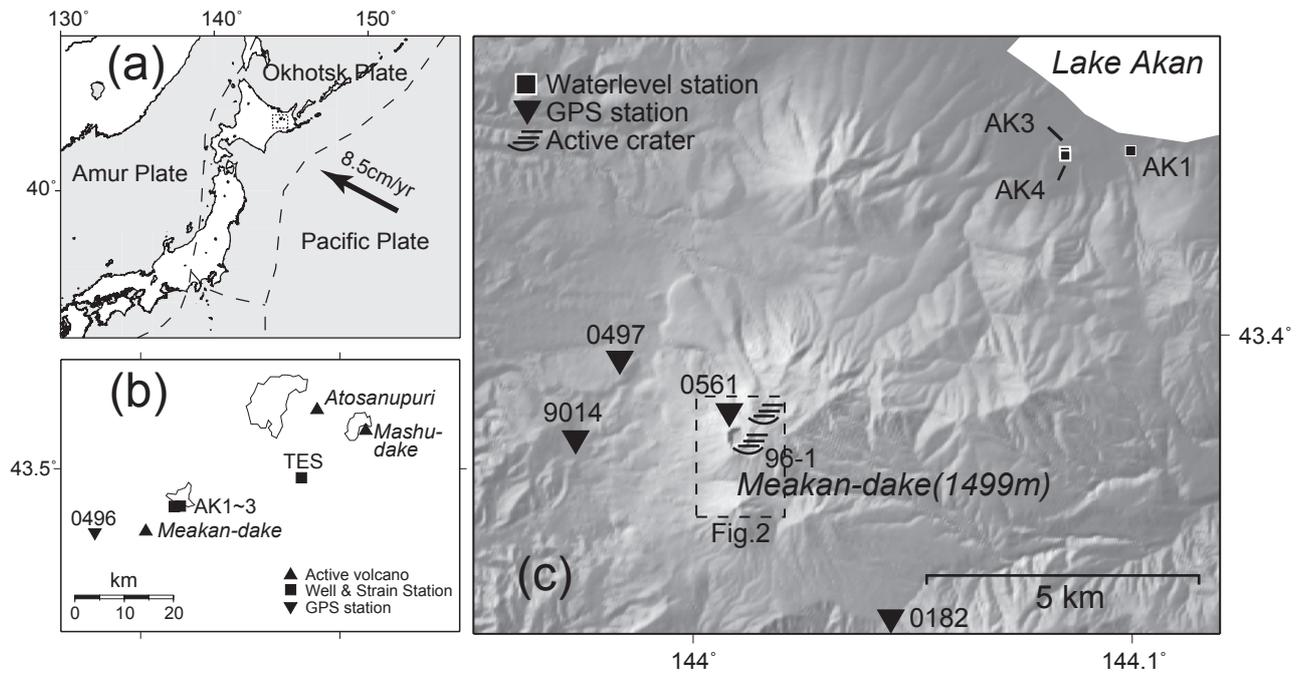
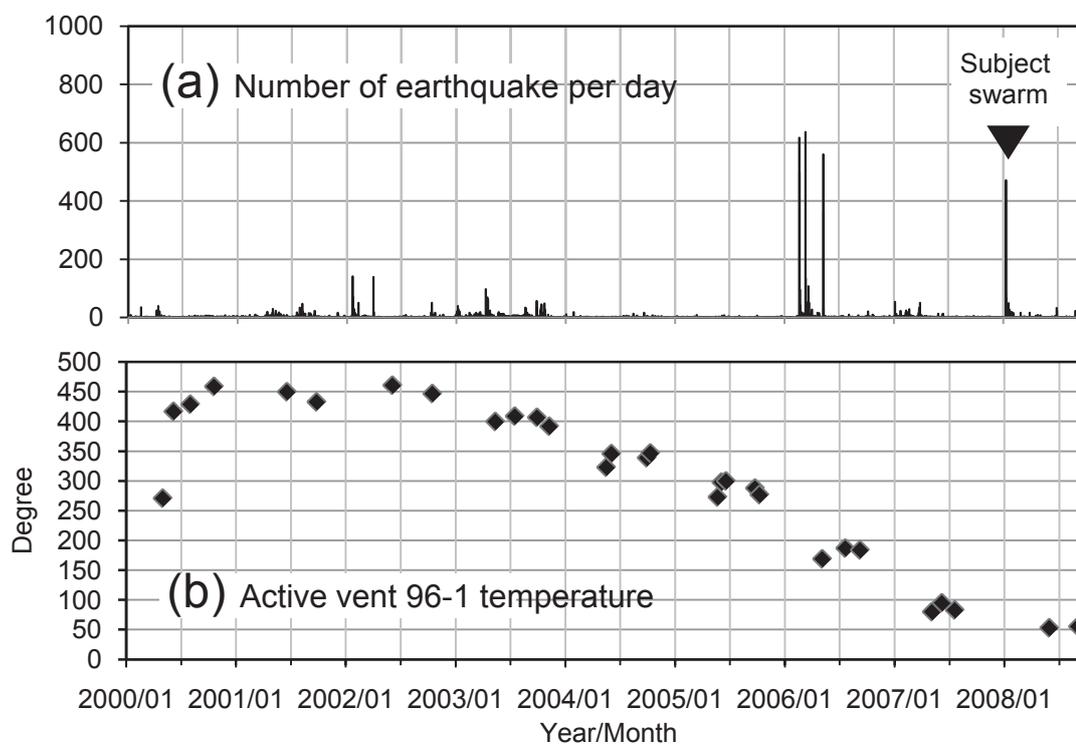


Fig. 1

# Figure

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## Fig. 2

Figure

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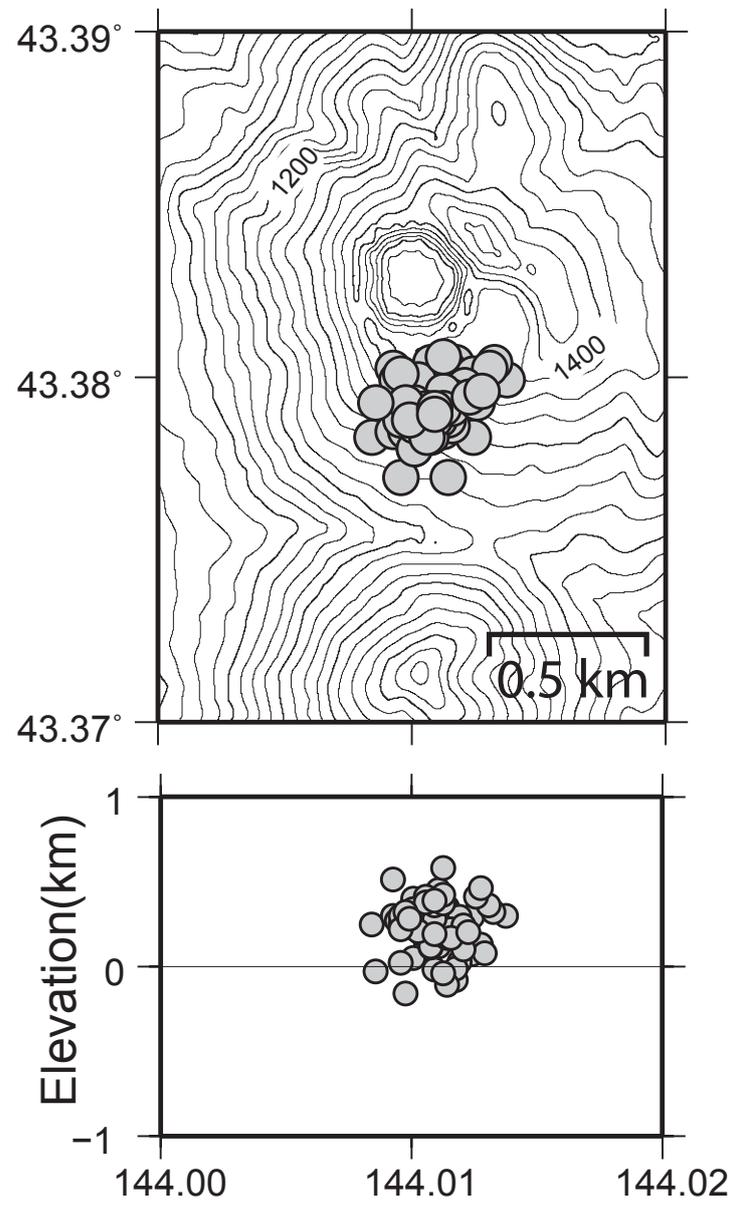


Fig. 3

Figure

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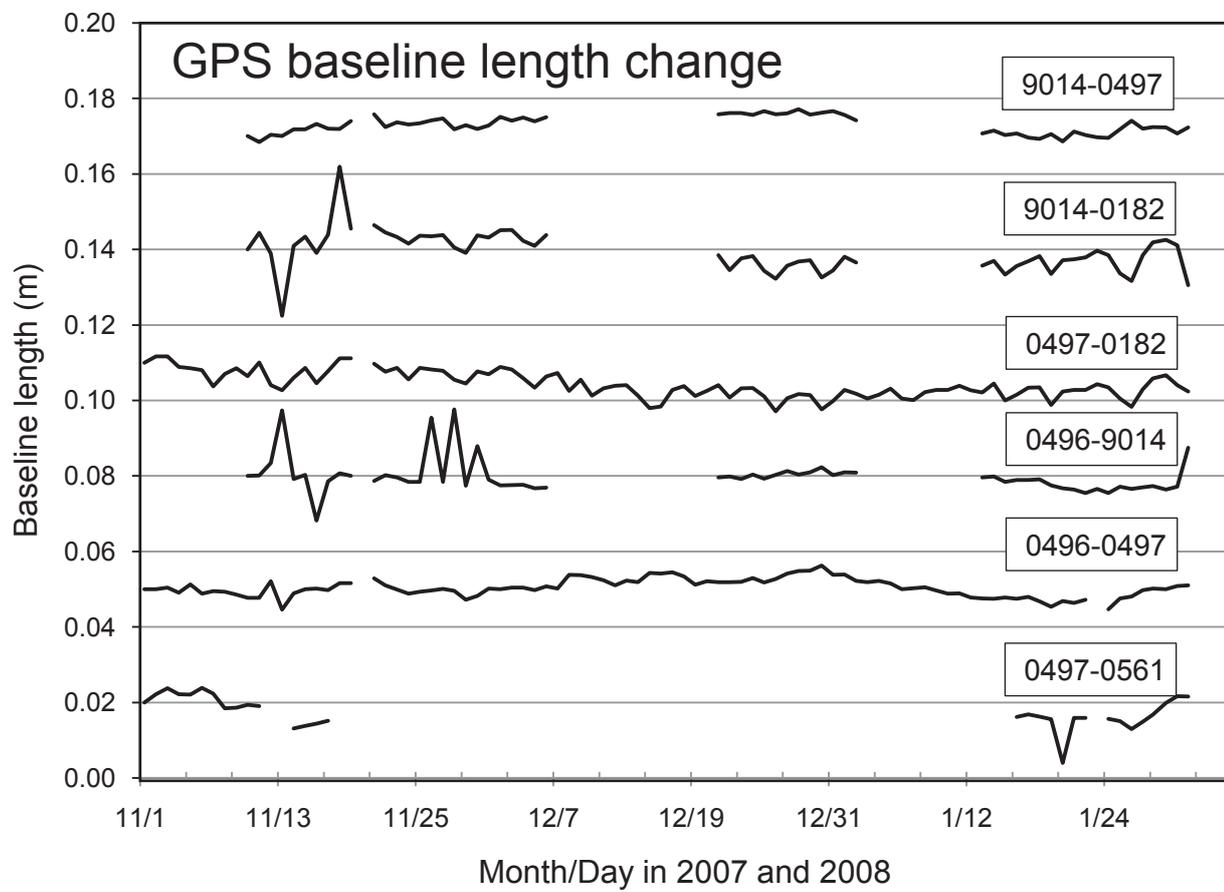


Fig. 4

Figure

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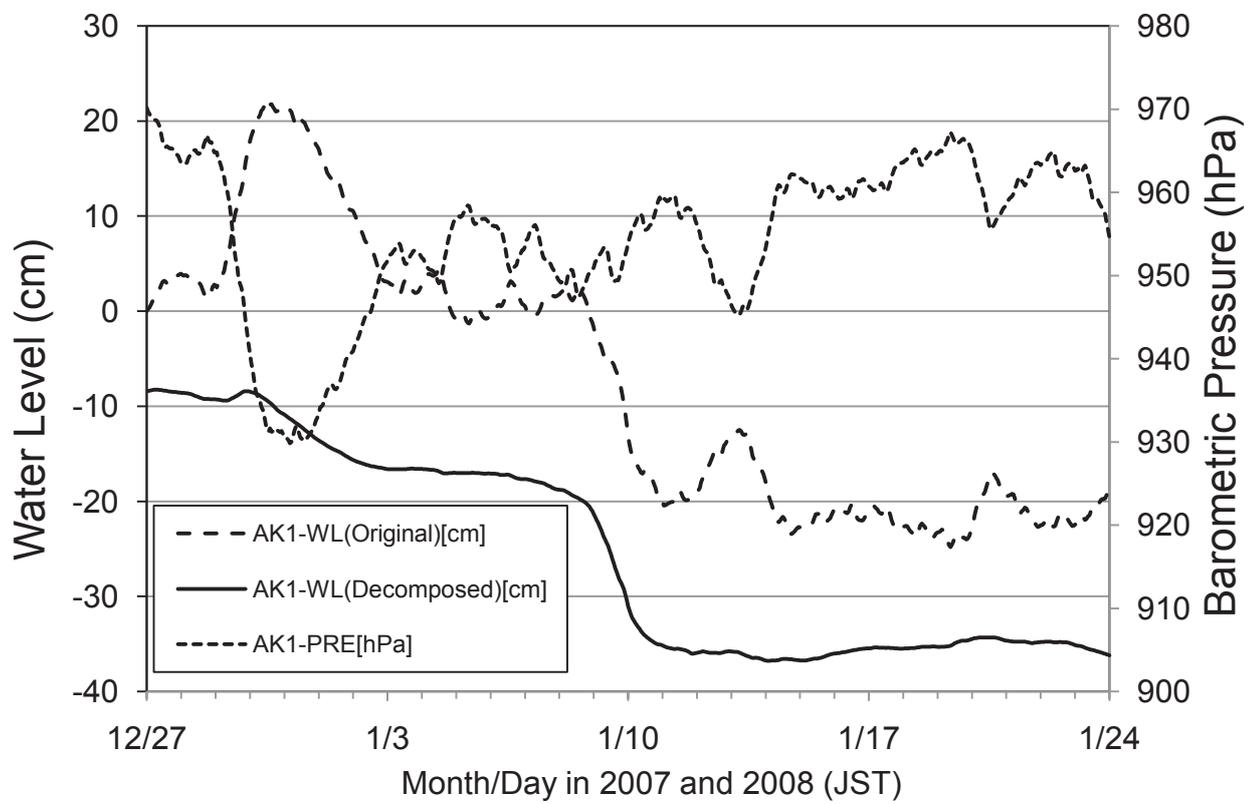


Fig. 5

Figure

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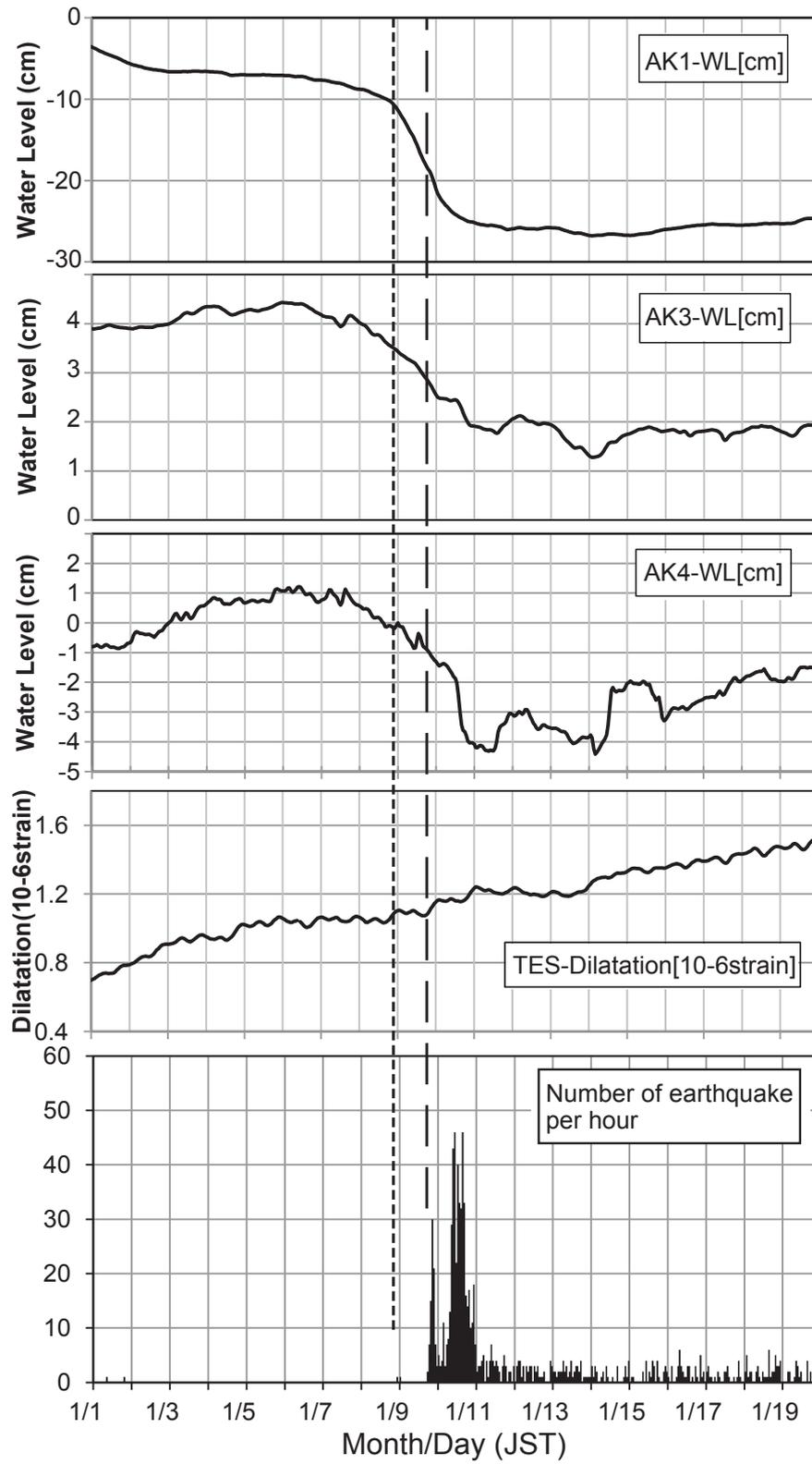


Fig. 6

Figure

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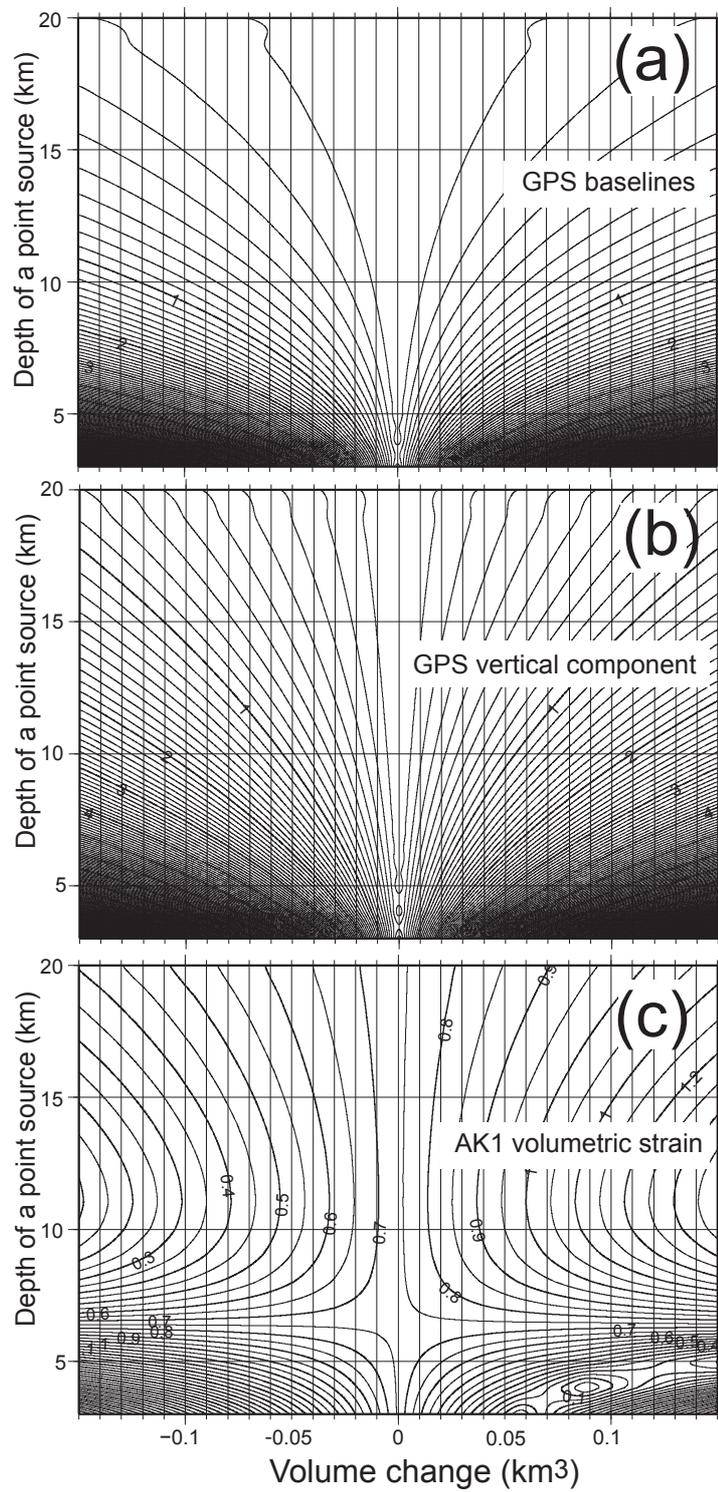
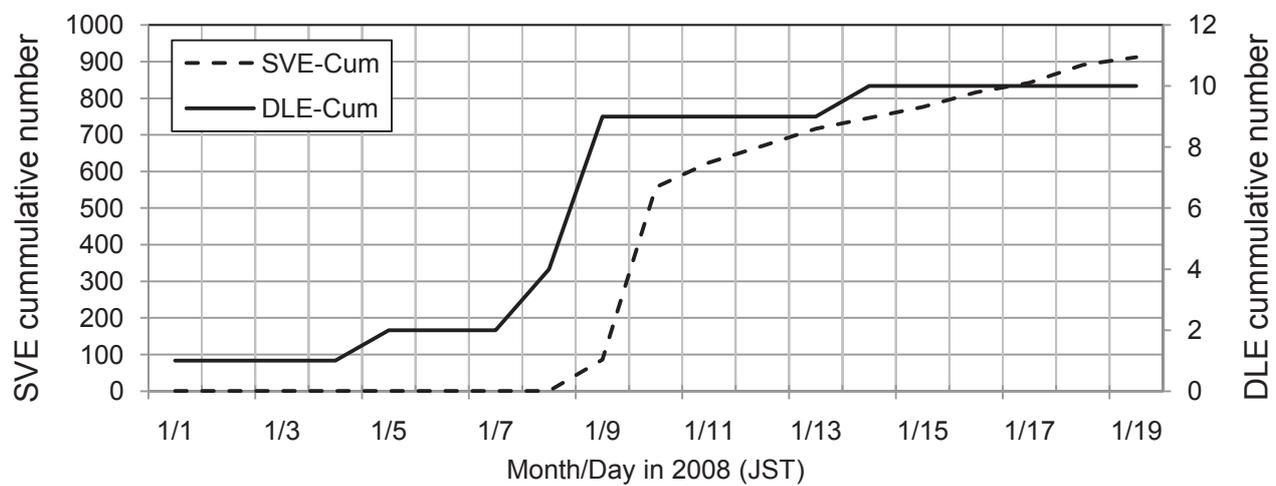


Fig. 7

# Figure

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## Fig. 8

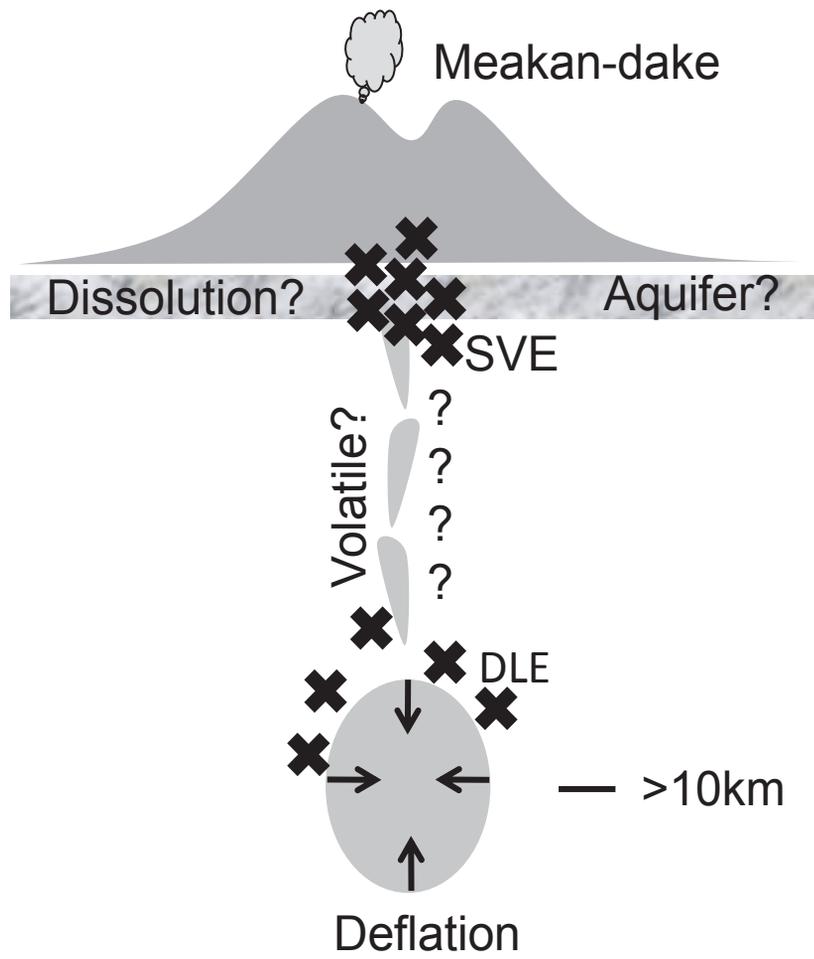


Fig. 9