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# Sub-decadal Volcanic Tsunamis Due to Submarine Trapdoor Faulting at Sumisu Caldera in the Izu–Bonin Arc

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## Key Points:

- Large tsunamis are generated by moderate-sized volcanic earthquakes at a submarine caldera.
- Tsunami and seismic data indicate that abrupt uplift of the submarine caldera by trapdoor faulting causes large tsunamis.
- Continuous magma supply into the submarine caldera induces submarine trapdoor faulting on a decadal timescale.

## 21 **Abstract**

22 The main cause of tsunamis is large subduction zone earthquakes with seismic magnitudes  $M_w >$   
23 7, but submarine volcanic processes can also generate tsunamis. At the submarine Sumisu  
24 caldera in the Izu–Bonin arc, moderate-sized earthquakes with  $M_w < 6$  occur almost once a  
25 decade and cause meter-scale tsunamis. The source mechanism of the volcanic earthquakes is  
26 poorly understood. Here we use tsunami and seismic data for the recent 2015 event to show that  
27 abrupt uplift of the submarine caldera, with a large brittle rupture of the ring fault system due to  
28 overpressure in its magma reservoir, caused the earthquake and tsunami. This submarine  
29 trapdoor faulting mechanism can efficiently generate tsunamis due to large vertical seafloor  
30 displacements, but it inefficiently radiates long-period seismic waves. Similar seismic radiation  
31 patterns and tsunami waveforms due to repeated earthquakes indicate that continuous magma  
32 supply into the caldera induces quasi-regular trapdoor faulting. This mechanism of tsunami  
33 generation by submarine trapdoor faulting underscores the need to monitor submarine calderas  
34 for robust assessment of tsunami hazards.

35

## 36 **Plain Language Summary**

37 Tsunamis are mainly caused by large submarine earthquakes, but submarine volcanic processes  
38 can also trigger tsunamis. Disproportionately large tsunami waves have been generated every  
39 decade by moderate-sized volcanic earthquakes at a submarine volcano with a caldera structure,  
40 called Sumisu caldera, in the Izu–Bonin arc, south of Japan. Despite the moderate earthquake  
41 size, the maximum wave heights of the tsunamis were about a meter, and their source  
42 mechanism has been controversial. In this study, we used tsunami and seismic data from a recent  
43 earthquake to show that the submarine caldera abruptly uplifts due to brittle rupture of its intra-

44 caldera fault system driven by overpressure of magma accumulating in its underlying magma  
45 reservoir and generates large tsunamis almost once a decade. The atypical source mechanism for  
46 tsunami generation suggests that it is important to monitor active submarine calderas for  
47 assessing tsunami hazards.

48

## 49 **1 Introduction**

50 Large earthquakes in subduction zones with seismic moment magnitudes  $M_w > 7$  are the  
51 main causes of tsunamis, but other submarine geophysical processes, such as volcanism or  
52 landslides, can also trigger tsunamis (Kanamori, 1972; Paris, 2015; Satake, 2015; Ward, 2001).  
53 Because the latter generally do not cause significant seismic ground motion, the difficulty in  
54 forecasting tsunamis results in increased tsunami risk to coastal societies (Grilli et al., 2019;  
55 Hunt et al., 2021; Tappin et al., 1999; Walter et al., 2019). Unusual tsunamis have been reported  
56 for earthquakes generated at Sumisu caldera (also known as Smith caldera), which is a  
57 submarine volcano with an 8 km  $\times$  10 km caldera structure in the Izu–Bonin arc (Figure 1)  
58 (Shukuno et al., 2006; Tani et al., 2008). At the caldera, volcanic earthquakes with moderate  
59 seismic magnitudes ( $M_w$  5.4–5.7) have occurred quasi-regularly in 1984, 1996, 2006, 2015, and  
60 2018 (Figure 1b; Table S1), which are known as Torishima earthquakes (Fukao et al., 2018;  
61 Kanamori et al., 1993; Satake & Kanamori, 1991). The earthquake on 2 May 2015 ( $M_w$  5.7)  
62 caused a disproportionately large tsunami with a maximum wave height of 1 m on Hachijojima  
63 Island, located 180 km north of the caldera (Figure 1c), although no ground shaking was felt on  
64 the island. The other four earthquakes also caused relatively large tsunamis with similar  
65 waveforms at many tide gauge stations (Figures 1d–e and S1). The five earthquakes were  
66 seismologically similar to each other, and all had a moment tensor with a large compensated-

67 linear-vector-dipole (CLVD) component and a dominant nearly vertical tension axis (Figure 1b),  
68 which is often called a vertical-T CLVD earthquake (Shuler, Ekström, et al., 2013; Shuler,  
69 Nettles, et al., 2013).

70         Since the 1984 earthquake, various models have been proposed for this atypical  
71 earthquake mechanism and tsunami generation. These include dip slip on a curved ring fault  
72 system of a caldera (Ekström, 1994), vertical opening of a shallow horizontal crack (Fukao et al.,  
73 2018), and volume change due to fluid injection at shallow depth (Kanamori et al., 1993; Satake  
74 & Kanamori, 1991). However, different interpretations can explain the moment tensors (Shuler,  
75 Ekström, et al., 2013), and no consensus on the earthquake mechanism has yet been reached,  
76 because of the inaccessibility of the submarine caldera. For the 2015 earthquake, the tsunami was  
77 recorded by high-quality ocean bottom pressure (OBP) gauges of a temporary array and recently  
78 deployed tsunami observation networks to the south of Japan (Figure 1a). The obtained tsunami  
79 waveform and regional seismic data provide an opportunity to determine the mechanisms  
80 responsible for these anomalous volcanic earthquakes.

81         The objective of this study is to determine the source mechanism of the volcanic  
82 earthquakes at Sumisu caldera. We initially conduct a preliminary analysis using only the  
83 tsunami waveform data to estimate the sea-surface disturbance due to the coseismic seafloor  
84 deformation. We then combine the tsunami and long-period seismic data to develop a source  
85 model that can quantitatively explain both datasets. Based on this model, we discuss the source  
86 mechanism of the earthquakes, possible causes of the efficient tsunami excitation and their sub-  
87 decadal recurrence, and implications for the submarine volcanism of Sumisu caldera.

88

## 89 **2 Data**

### 90 2.1 Tsunami data

91 We use tsunami data recorded by 24 OBP gauges (Figure 1a) of the array off Aogashima  
92 Island, the Dense Oceanfloor Network system for Earthquakes and Tsunamis (DONET) system,  
93 the Deep Sea Floor Observatory (DSFO) off Muroto Cape, and the Deep-ocean Assessment and  
94 Reporting of Tsunamis (DART) system. We manually check the data quality (i.e., data gaps,  
95 spikes, or repeated values) near the arrival times of the tsunami signals and remove tidal trends  
96 by fitting polynomial functions. Following Sandanbata, Watada, et al. (2021), we apply a two-  
97 pass second-order low-pass Butterworth filter to the tsunami waveforms. The cut-off frequencies  
98 are 0.0125, 0.0083, 0.0083, and 0.00667 Hz for stations from the array, DONET, DSFO, and  
99 DART, respectively, depending on the maximum depth along a source–station path.

100

### 101 2.2 Long-period seismic data

102 We use seismic data recorded by the BH channel (three components) of 36 regional  
103 stations (epicentral distance  $< 30^\circ$ ) of the F-net and Global Seismograph Network (GSN). The  
104 seismic stations are listed in Table S2. We remove the instrument response from the observed  
105 seismograms to obtain the displacement records and apply a one-pass fourth-order band-pass  
106 Butterworth filter with corner frequencies of 0.004 and 0.0167 Hz (band-pass period = 60–250 s)  
107 using the W-phase package (Duputel et al., 2012; Hayes et al., 2009; Kanamori & Rivera, 2008).

108

### 109 3 Preliminary analysis: Estimation of the initial sea-surface displacement

110 As a preliminary step for the source modeling of the 2015 earthquake, we estimate the  
 111 initial sea-surface displacement caused by the earthquake using a tsunami waveform inversion  
 112 method. To compute synthetic tsunami waveforms, we first assume 113 unit sources of sea-  
 113 surface displacement at 2-km intervals in a source area of 32 km × 32 km around Sumisu caldera  
 114 (Figure S2). Each unit source has a cosine-tapered shape (Hossen et al., 2015):

$$\eta^k(x, y) = 0.25 \times \left[ 1.0 + \cos \frac{\pi(x - x^k)}{L} \right] \times \left[ 1.0 + \cos \frac{\pi(y - y^k)}{L} \right], \quad (1)$$

$$(|x - x^k|, |y - y^k| \leq L)$$

115 where  $(x^k, y^k)$  is the central location in kilometers of the  $k$ th unit source ( $k = 1, 2, \dots, K$ ; here  $K$   
 116 = 113) with a source size of  $2L$  (i.e., 4.0 km). The rise time for each unit source is 10 s, given  
 117 that the earthquake source duration is 10 s as estimated by our moment tensor analysis (Text S1;  
 118 Table S3).

119 We then simulate tsunami propagation over the ocean from the assumed unit sources. To  
 120 compute a tsunami waveform with relatively long-period components at the most distant station  
 121 52404 (located ~1,400 km from the epicenter), we use a phase correction method developed for  
 122 long-period tsunamis (Ho et al., 2017). In this method, we first solve the linear long-wave  
 123 equations with the JAGURS code (Baba et al., 2015) and then correct the phase spectra to  
 124 incorporate the effects of the dispersion, the compressibility and the density stratification of  
 125 seawater, and the elasticity of the Earth. On the other hand, tsunami waveforms at the other  
 126 stations at shorter distances are dominated by shorter-period waves, which makes it inadequate to  
 127 use the linear long-wave equations. Hence, we use a different phase correction method that was  
 128 developed for short-period tsunamis (Sandarbata, Watada, et al., 2021). In this method, we solve

129 the linear Boussinesq equations (approximately including dispersion) by the JAGURS code and  
130 corrected the phase spectra to incorporate the accurate dispersion, the effects of seawater  
131 compressibility and density stratification, and the Earth's elasticity. The latter phase correction  
132 method incorporates variations in ray paths of highly dispersive short-period waves and enables  
133 us to compute short-period waveforms more accurately. In both cases, the computational time-  
134 step interval is 0.25 s. We use high-resolution bathymetric data (10 arcsec, ~300 m, grid spacing)  
135 processed from M7000 Digital Bathymetric Chart (M7022) for the area near Sumisu caldera and  
136 Aogashima Island, whereas we use JTOPO30 and GEBCO\_2014 (30 arcsec grid spacing) for the  
137 other regions. When the tsunami wavelength is comparable to or shorter than the water depth, the  
138 bottom pressure change becomes smaller and smoother than that just beneath the sea surface  
139 which is equivalent to the static water pressure of the wave height. To include this pressure  
140 reduction effect, we apply a spatial low-pass filter, often referred to as the Kajiura filter (Kajiura,  
141 1963), to the wave-height field output for every 5.0 s and obtain the OBP change at the stations  
142 (Chikasada, 2019). We also apply the low-pass Butterworth filter to the time series of the OBP  
143 change as used for the OBP data. Hereafter, the tsunami waveforms are OBP waveforms (in the  
144 [cm H<sub>2</sub>O] scale).

145       After computing the synthetic tsunami waveforms  $g_j^k(t)$  from the  $k$ th unit source to the  
146  $j$ th station ( $j = 1, 2, \dots, J$ ; here  $J = 24$ ), we solve a linear inverse problem to estimate the initial  
147 sea-surface displacement. Because the wave amplitudes of the near-field data (a few centimeters)  
148 are much larger than those of the regional-field data (a few millimeters), we normalize the  
149 observed and synthetic waveforms at the  $j$ th station by the weight  $w_j$ , following the method of  
150 Ho et al. (2017). The weight is the inverse root-mean-square (RMS) value of the observed  
151 waveform at each station:

$$\frac{1}{w_j} = \sqrt{\frac{\sum_{l=0}^{\gamma_j} \{d_j(t_l)\}^2}{\gamma_j}}, \quad (2)$$

152 where  $d_j(t_l)$  is the tsunami waveform data for the  $j$ th station and  $\gamma_j$  is the number of data points  
 153 used for the analysis. Using the normalized observed and synthetic waveform data, we solve the  
 154 following observation equation with the damped least-squares method (pp. 695–699 in Aki &  
 155 Richards, 1980):

$$\begin{bmatrix} \bar{\mathbf{d}} \\ \mathbf{0} \end{bmatrix} = \begin{bmatrix} \bar{\mathbf{g}} \\ \alpha \mathbf{I} \end{bmatrix} \mathbf{m}, \quad (3)$$

156 where  $\bar{\mathbf{d}} = [w_1 d_1(t) \quad \cdots \quad w_j d_j(t)]^T$  and  $\bar{\mathbf{g}} = \begin{bmatrix} w_1 g_1^1(t) & \cdots & w_1 g_1^K(t) \\ \vdots & \ddots & \vdots \\ w_j g_j^1(t) & \cdots & w_j g_j^K(t) \end{bmatrix}$  are the column vector

157 of the observed waveform data  $d_j(t)$  and the matrix of the synthetic waveform data  $g_j^k(t)$   
 158 weighted by  $w_j$  at the  $j$ th station (Equation 2), respectively, and  $\mathbf{m} = [m^1 \quad \cdots \quad m^K]^T$  is an  
 159 unknown column vector of the amplitude factors to be multiplied by the  $k$ th unit source,  $\mathbf{I}$  is the  
 160 identity matrix, and  $\alpha$  is the damping parameter used to obtain a smooth model. We assume  $\alpha =$   
 161 2.0 to achieve an appropriate trade-off between the waveform fit and the smoothness of the  
 162 solution (Figure S3).

163 Thus, we obtain an initial sea-surface displacement model, composed of a sea-surface  
 164 uplift of about 1 m over the caldera floor, with its uplift peak shifted northeastward relative to the  
 165 caldera center, and smaller subsidence outside of the caldera rim mainly on the northeastern side  
 166 (Figure 2a). This model reproduces the tsunami waveform data (Figure S4). To examine the  
 167 robustness of the exterior subsidence, we estimate the initial sea-surface uplift model, without  
 168 subsidence, by imposing a non-negative condition ( $\mathbf{m} \geq \mathbf{0}$ ) when solving Equation 3. The

169 obtained uplift model, containing only a larger northeastern uplift, cannot reproduce the tsunami  
170 first motions with initial downswing signals of the relatively near-field stations in the  
171 northeastern direction (A01–10; Figure 2b). This result suggests that, during the earthquake, the  
172 exterior of the caldera subsided at least on its northeastern side. Note that a previous study  
173 (Fukao et al., 2018) assumed a symmetrical caldera floor uplift model surrounded by peripheral  
174 subsidence to explain the tsunami waveforms at the array off Aogashima Island, but Sandanbata,  
175 Watada, et al. (2021) demonstrated that the model of Fukao et al. (2018) does not explain the  
176 tsunami arrival times at the stations of DONET, DSFO and DART. Our tsunami waveform  
177 inversion using all the OBP data with wider azimuthal coverage suggests that the uplift and the  
178 subsidence were localized on the northeastern side of the caldera.

179

## 180 **4 Source modeling of the 2015 earthquake: methodology**

### 181 4.1 Hypothetical earthquake source system

182 We next explore the source model of the 2015 earthquake by combining analyses of the  
183 tsunami and long-period seismic data. From the deformation pattern determined in the  
184 preliminary analysis (Section 3), we assume an earthquake source system composed of dip slip  
185 of an elliptical fault system and vertical deformation of a shallow horizontal crack beneath  
186 Sumisu caldera (Figure 3a). This assumption of the fault-crack composite system is inspired by  
187 previous caldera modeling studies that discussed interactive systems beneath calderas between a  
188 circular or elliptical fault, called *ring fault*, and a sill-like magma reservoir (e.g., Yun, 2007;  
189 Bathke et al., 2015; Liu et al., 2019; Galetto et al., 2019; Zheng et al., 2022). Most calderas are  
190 known to have pre-existing ring fault systems formed during caldera collapse in the past (e.g.,

191 Cole et al., 2005; Roche et al., 2000), where faulting events called *ring-faulting* sometimes take  
192 place in response to pressure change in an underlying magma reservoir (e.g., Ekström, 1994;  
193 Shuler, Ekström, et al., 2013; Contreras-Arratia & Neuberg, 2019; Sandanbata, Kanamori, et al.,  
194 2021). For example, at the subaerial caldera of Sierra Negra in the Galapagos Islands, seismic  
195 events characterized by vertical-T CLVD moment tensors occurred in such a sub-caldera  
196 interactive system, and caused large asymmetric uplifts of the caldera floor (e.g., Amelung et al.,  
197 2000; Chadwick et al., 2006; Jónsson, 2009) like what was estimated for the 2015 earthquake at  
198 Sumisu caldera in Section 3. Some previous studies (e.g., Yun, 2007; Zheng et al., 2022)  
199 explained geodetic data at Sierra Negra caldera by proposing source models that combine ring-  
200 faulting and deformation of its underlying horizontal crack; this inferred mechanism is especially  
201 referred to as *trapdoor faulting*. Given such successful examples of caldera modeling, the fault-  
202 crack composite system can be a good candidate for the earthquake source at Sumisu caldera.  
203 Caldera-floor cones, some of which were identified as young lava domes (Tani et al., 2008), are  
204 located along a line forming an elliptical shape on the floor of Sumisu caldera (Figure 1b); this  
205 also indicates that a ring fault system is connected to a shallow reservoir filled with magma (Cole  
206 et al., 2005).

207

## 208 4.2 Tsunami waveform inversion for fault-crack composite source models

209 We again use a tsunami waveform inversion method with the OBP data but this time to  
210 directly determine motions of the fault-crack composite system (i.e., dip-slip dislocations of the  
211 ring fault and tensile dislocations of the horizontal crack). The inversion procedure is as follows.

### 212 4.2.1 Source structure

213 To model the fault-crack composite system beneath Sumisu caldera, we assume reverse  
 214 slip for an inward-dipping ring fault and vertical deformation (opening or closing) for a  
 215 horizontal crack (Figures 3a). We consider reverse slip of the inward-dipping ring fault, because  
 216 vertical-T CLVD earthquakes accompanying a caldera floor uplift are expected for the  
 217 combination of the slip and dip directions of the ring-faulting (see Figure 9 in Shuler, Ekström, et  
 218 al., 2013, or Figure 1 in Sandanbata, Kanamori, et al., 2021). The ring fault is elliptical with its  
 219 center at (140.0454°E, 31.4816°N) and its major axis oriented N70°E, and its horizontal size is  
 220 3.0 km × 2.7 km on the seafloor. The ring fault may not be a full ring; the arc length is varied as  
 221 1/3, 2/3 and 1 (full ring), but the midpoint is fixed to the northeastern corner of the caldera  
 222 (Figures 3b–d). The ring fault extends with a uniform inward dip angle from the seafloor to the  
 223 edge of the elliptical horizontal crack. We try tens of source structures with three variable  
 224 geometric parameters: (a) the depth of the horizontal crack (3 or 6 km); (b) the dip angle of the  
 225 ring fault (70–90°); and (c) the arc length of the ring fault (1/3, 2/3, or full ring).

226 We discretize the source structures into triangular source elements. The ring fault is  
 227 divided into triangular elements with an arc angle of 22.5° along the circumference and 1 km  
 228 along the depth, and a trapezoid composed of two neighboring triangular elements with the same  
 229 dip and strike angles is regarded as a sub-fault. The horizontal crack is discretized by triangular  
 230 elements using the DistMesh code (Persson & Strang, 2004), and each element is regarded as a  
 231 sub-crack. Assuming the geometry of sub-faults and sub-cracks, we will determine dislocation  
 232 amounts of reverse slip at each sub-fault and opening (or closing) at each sub-crack, which are  
 233 denoted by  $\mathbf{s} = [s_1 \ \cdots \ s_{N_s}]^T$  and  $\boldsymbol{\delta} = [\delta_1 \ \cdots \ \delta_{N_\delta}]^T$ , respectively. Since the dislocations of  
 234 the ring fault and the horizontal crack should be consistent at their contacts, we impose a  
 235 kinematic condition that links the vertical component of the sub-fault slip at the ring fault bottom

236 to the sub-crack opening/closing at the crack edge adjacent to the sub-fault. The kinematic  
237 condition can be written as:

$$s_p \sin \Delta_p = \delta_q, \quad (4)$$

238 where  $\Delta_p$  is the dip angle of the  $p$ th sub-fault to which the  $q$ th sub-crack is adjacent.

#### 239 4.2.2 Computation of the tsunami Green's functions

240 We then compute synthetic tsunami waveforms, or Green's functions  $G_{ij}$ , relating the  
241 dislocation (i.e., reverse slip of the sub-fault and vertical opening of the sub-crack) of the  $i$ th  
242 source element ( $i = 1, 2, \dots, I$ ;  $I$  depends on the source structures) to the tsunami waveform at the  
243  $j$ th station. For this purpose, we reuse the synthetic tsunami waveforms  $g_j^k$  from unit sources of  
244 sea surface displacement  $\eta^k$ , which were computed in Section 3. By reusing  $g_j^k$ , we do not have  
245 to simulate tsunami propagation over the ocean as done in Section 3, which significantly reduces  
246 the computational cost and helps us to efficiently assess the inversions for tens of source  
247 structures, each of which consists of  $I > 50$  source elements. The computation of  $G_{ij}$  is  
248 performed with the following three steps.

249 First, we calculate the vertical seafloor displacements from 1 m reverse slips of sub-faults  
250 and 1 m opening of sub-cracks with the triangular dislocation (TD) method (Nikkhoo & Walter,  
251 2015) assuming a Poisson's ratio of 0.25 and a flat seafloor, and we convert the seafloor  
252 displacements into the vertical *sea-surface* displacements by applying the Kajiura filter (Kajiura,  
253 1963) assuming a water depth of 800 m; this filtering process is required because the resultant  
254 vertical sea-surface displacement becomes smaller and smoother than that at the seafloor when  
255 the horizontal scale of the seafloor displacement is comparable to or smaller than the water depth

256 (e.g., Saito & Furumura, 2013). We thus denote the vertical sea-surface displacement from the  
 257 *i*th source element  $h_i(x, y)$ .

258 Second, the computed sea-surface displacement  $h_i(x, y)$  is approximated by a linear  
 259 combination of the unit sources of sea-surface displacement  $\eta^k(x, y)$  (Equation 1; Figure S2):

$$h_i(x, y) \approx \sum_{k=1}^K m_i^k \eta^k(x, y), \quad (5)$$

260 where the amplitude factors  $m_i^k$  are obtained by a least-squares method.

261 Third, we obtain Green's functions relating the *i*th source element to the *j*th station by  
 262 superimposing the synthetic tsunami waveforms from the *k*th unit sources  $g_j^k(t)$  multiplied by  
 263 the amplitude factors  $m_i^k$ , as follows:

$$G_{ij}(t) = \sum_{k=1}^K m_i^k g_j^k(t). \quad (6)$$

#### 264 4.2.3 Inverse problem

265 Finally, we solve the observation equation with the kinematic condition (Equation 4) by  
 266 the damped least-squares method:

$$\begin{bmatrix} \bar{\mathbf{d}} \\ \mathbf{0} \\ \mathbf{0} \end{bmatrix} = \begin{bmatrix} \bar{\mathbf{G}} \\ \mathbf{K} \\ \beta \mathbf{I} \end{bmatrix} \begin{bmatrix} \mathbf{s} \\ \boldsymbol{\delta} \end{bmatrix}, \quad (7)$$

267 where  $\bar{\mathbf{d}}$  is the column vector of the observed tsunami waveforms  $d_j$  normalized by  $w_j$  at the *j*th

268 station (Equation 2), and  $\bar{\mathbf{G}} = \begin{bmatrix} w_1 G_{11}(t) & \cdots & w_1 G_{1I}(t) \\ \vdots & \ddots & \vdots \\ w_J G_{1J} & \cdots & w_J G_{IJ}(t) \end{bmatrix}$  is the matrix of the Green's functions

269  $G_{ij}$  normalized by  $w_j$ .  $\mathbf{s}$  is an unknown column vector of reverse slip amounts for sub-faults of

270 the ring fault, for which we impose the non-zero condition ( $\mathbf{s} \geq \mathbf{0}$ ), and  $\boldsymbol{\delta}$  is an unknown column

271 vector of opening amounts for sub-cracks of the horizontal crack, for which we allow either

272 positive (opening) or negative (closing) values. The linear equation of  $\mathbf{K} \begin{bmatrix} \mathbf{S} \\ \boldsymbol{\delta} \end{bmatrix} = \mathbf{0}$  represents the  
 273 kinematic condition of Equation 4.  $\beta$  is the damping parameter for smoothing, which we set at  
 274 0.3, by balancing the waveform fit and the smoothness of the motion (Figure S5). The inversion  
 275 time windows include several wave crests and troughs. Thus, we determine motions of the fault-  
 276 crack composite systems and obtain source models based on the tsunami data.

277 To evaluate the model performance, we calculate the normalized root-mean-square  
 278 (NRMS) misfit of the tsunami waveforms, which we term the tsunami waveform misfit:

$$\rho^t = \sqrt{\sum_j \|\mathbf{c}_j^t - \mathbf{d}_j^t\|^2 / \sum_j \|\mathbf{c}_j^t\|^2}, \quad (8)$$

279 where  $\mathbf{c}_j^t$  and  $\mathbf{d}_j^t$  are the column vectors of the synthetic and observed tsunami waveforms of the  
 280 model in inversion time window at the  $j$ th station, respectively.  $\|\cdot\|$  denotes the L2 norm.

281

### 282 4.3 Computation of the long-period seismic waveforms

283 For validation of the fault-crack composite source model inverted from the tsunami data,  
 284 we compute long-period seismic waveforms for the model and compare them with the long-  
 285 period seismic data. Because the wavelength of seismic data we use is much longer than the size  
 286 of the caldera, the seismic source can be modeled by a point-source moment tensor. The total  
 287 moment tensor  $\mathbf{M}$  of the source model is calculated as:

$$\mathbf{M} = \mathbf{M}_{RF} + \mathbf{M}_{HC} = \sum \mathbf{m}_{RF}^p + \sum \mathbf{m}_{HC}^q, \quad (9)$$

288 where  $\mathbf{M}_{RF}$  and  $\mathbf{M}_{HC}$  are the moment tensors of the ring fault and horizontal crack, respectively,  
 289 and  $\mathbf{m}_{RF}^p$  and  $\mathbf{m}_{HC}^q$  are the moment tensors of the  $p$ th sub-fault slip and the  $q$ th sub-crack opening

290 or closure, respectively (Figure S6a). The coordinate system is  $(r, \theta, \phi)$  for [up, south, east].  $\mathbf{m}_{RF}^p$   
 291 is computed from the reverse slip amount and strike, dip, and rake ( $90^\circ$ ) angles of the  $p$ th sub-  
 292 fault (Box 4.4 in Aki & Richards, 1980). The seismic moment is computed as  $\mu s_p A_p$ , where  $s_p$   
 293 and  $A_p$  are the reverse slip amount and area of the  $p$ th sub-fault, and  $\mu$  is the rigidity, or Lamé's  
 294 constant.  $\mathbf{m}_{HC}^q$  is calculated as:

$$\mathbf{m}_{HC}^q = \begin{bmatrix} M_{rr} & M_{\theta r} & M_{\phi r} \\ M_{r\theta} & M_{\theta\theta} & M_{\phi\theta} \\ M_{r\phi} & M_{\theta\phi} & M_{\phi\phi} \end{bmatrix} = \delta_q \times A_q \times \begin{bmatrix} \lambda + 2\mu & 0 & 0 \\ 0 & \lambda & 0 \\ 0 & 0 & \lambda \end{bmatrix}, \quad (10)$$

295 where  $\delta_q$  and  $A_q$  are the opening amount and area of the  $q$ th sub-crack, respectively (Kawakatsu  
 296 & Yamamoto, 2015). Lamé's constants  $\lambda$  and  $\mu$  are assumed to be 29.90 and 31.85 GPa,  
 297 respectively, based on the P- and S-wave velocities ( $V_p = 6.0$  km/s and  $V_s = 3.5$  km/s) and the  
 298 density ( $\rho_0 = 2.6 \times 10^3$  kg/m<sup>3</sup>) in the shallowest layer of the Earth model (Figure S6b). The  
 299 scalar seismic moment of the moment tensor is  $M_0 = \sqrt{\sum_{ij} M_{ij} M_{ij}} / 2$  (pp. 166–167 in Dahlen &  
 300 Tromp, 1998; Silver & Jordan, 1982), and the moment magnitude is  $M_w =$   
 301  $\frac{2}{3} (\log_{10} M_0 - 9.10)$ , with  $M_0$  in the [N m] scale (Hanks & Kanamori, 1979; Kanamori, 1977).

302 By assuming the moment tensor (Equation 9), we compute the long-period (60–250 s)  
 303 seismic waveforms with the W-phase package (Duputel et al., 2012; Hayes et al., 2009;  
 304 Kanamori & Rivera, 2008). We compute the Green's functions of the seismic waveforms for the  
 305 one-dimensional crustal velocity model for Japan (Figure S6b) using the wavenumber integration  
 306 method (Herrmann, 2013). We fix the centroid location at a depth of 1.5 km below the seafloor  
 307 in the center of Sumisu caldera (140.053°E, 31.485°N). The half duration of the source time  
 308 function and the centroid time shift relative to the origin time reported by the Global CMT  
 309 (GCMT) catalogue (Ekström et al., 2012; Table S1) are assumed to be 5 s, based on our moment

310 tensor analysis (Table S3). We apply the same filter as for the seismic data (see Section 2.2) to  
311 the synthetic waveforms.

312 To evaluate the model performance, we calculate the NRMS misfit of the long-period  
313 seismic waveforms, which we term the seismic waveform misfit:

$$\rho^s = \sqrt{\sum_j \|\mathbf{c}_j^s - \mathbf{d}_j^s\|^2 / \sum_j \|\mathbf{c}_j^s\|^2}, \quad (11)$$

314 where  $\mathbf{c}_j^s$  and  $\mathbf{d}_j^s$  are the column vectors of the synthetic and observed seismic records at the  $j$ th  
315 channels, respectively. We set the time window to include the P, S, and surface waves.

316

## 317 **5 Source modeling of the 2015 earthquake: Results**

318 By the tsunami waveform inversion, we obtain tens of fault-crack composite source  
319 models for the 2015 earthquake with different combinations of the three geometric source  
320 parameters (i.e., the depth of the horizontal crack, the dip angle and arc length of the ring fault).  
321 As an example, Figure 4a shows the result when the horizontal crack is at a 3 km depth and the  
322 ring fault has a dip angle of  $85.0^\circ$  and a 2/3-ring arc length. This model shows that the ring fault  
323 has nonzero slips at all depths that are consistent with the horizontal crack motions at the bottom  
324 (Figure 4b). The nonzero slips at all the depths are obtained for most models with the horizontal  
325 crack at a depth of 3 km. By contrast, if we assume that the horizontal crack is at a depth of 6  
326 km, the ring fault has a zone with zero slip in the middle depth of the ring fault (Figure S7),  
327 which we consider unrealistic for the fault system. Hence, we suggest that the horizontal crack is  
328 at a shallower depth and hereafter show models with a horizontal crack at the depth of 3 km.

329 Figure 5 shows the tsunami NRMS misfit for the models with the crack at 3-km depth.  
330 The misfit varies only slightly as a function of the dip angle and the arc length of the ring fault.  
331 Figure 6 shows that the source model with a 2/3-ring arc length (shown in Figure 4a) reproduces  
332 the observed tsunami data well. Similarly, models with a full or 1/3-ring arc length yield good  
333 waveform fits (Figures S8 and S9). These indicate that the tsunami waveform data provide little  
334 constraint on the ring-fault parameters. However, we emphasize that, irrespective of the assumed  
335 ring-fault arc length (2/3, full, or 1/3-ring), the obtained source models are expected to similarly  
336 cause larger sea-surface uplifts over the northeastern part of the caldera but much smaller over  
337 the southwestern part (see Figures 6a, S8b, and S9b). This implies that the ring-faulting occurred  
338 mainly around the northeastern side but was minor (if any) on the southwestern side.

339 To further constrain the model, we use the long-period seismic data. In contrast to the  
340 tsunami data, the seismic data are useful to constrain the ring-fault parameters. In Figure 5, we  
341 plot the seismic NRMS misfit as a function of the dip angle and the arc length of the ring fault.  
342 First, the seismic waveform misfit strongly depends on the ring-fault dip angle. Figure 7  
343 compares fault-crack motions, moment tensors, and synthetic seismograms of three models with  
344 different dip angles (but similarly with a 2/3-ring arc length), showing that the amplitudes of  
345 seismic waveforms are significantly different despite similar slip amounts and  $M_w$  determined by  
346 the tsunami waveform inversion. This is because the ring-faulting at such a shallow depth  
347 becomes less efficient in radiating long-period seismic waves as the dip angle becomes closer to  
348 the vertical (Sandarbata, Kanamori, et al., 2021). From the seismic NRMS misfits (Figure 5), we  
349 determine optimal dip angles to be 85.0°, 85.5°, and 83.5 for 2/3, full, and 1/3-ring arc lengths,  
350 respectively. Note that if we assume a smaller rigidity for the shallow source depth, the optimal  
351 dip angles become smaller (see Text S2).

352           Among the three models with the optimal dip angles, the 2/3-ring arc-length model  
353 yields the smallest seismic NRMS misfit of 0.425 (Figure 5; 0.465 and 0.480, for the full and  
354 1/3-ring arc lengths, respectively); this model is shown in Figure 4a. Figure 8 shows the moment  
355 tensors and synthetic seismograms for the 2/3-ring arc-length model, which overall explain the  
356 observed seismic waveforms. For comparison, we show in Figures S10 and S11 the cases for the  
357 full and 1/3-ring arc-length models with the optimal dip angles. The preference of the 2/3-ring  
358 arc-length model over the other two models can be seen in the better phase fits of the horizontal  
359 components at some stations (e.g., BHE channel of KZS, YMZ, and TYS, and BHN channel of  
360 AMM in Figures 8d, S10d, and S11d). As shown in Sandanbata, Kanamori, et al. (2021), the  
361 seismic radiation pattern of the ring-faulting is sensitive to the ring-fault arc length, and the side  
362 on which the ring fault is placed, because of the geometrical cancelation of double-couple  
363 components of the moment tensor (see Figure 2 of Sandanbata, Kanamori, et al., 2021, for  
364 example). This property causes differences in seismic waveforms of the three arc-length models,  
365 which helps us to select the 2/3-ring arc-length model as the most preferable model.

366           In summary, based on the tsunami and seismic analyses above, we consider the model  
367 shown in Figure 4a as our best-fit source model for the 2015 earthquake. This model has a  
368 horizontal crack at the depth of 3 km and a ring fault with an inward dip angle of  $85^\circ$  along a  
369 2/3-ring arc length, on both of which large dislocations are determined. The ring fault has a  
370 maximum reverse slip of 6.8 m on its northeastern side. The vertical opening of the horizontal  
371 crack is a maximum of 2.7 m on its eastern side, whereas its closure is 5.0 m on its southwestern  
372 side. The net volume increase of the horizontal crack calculated with the model is  $1.26 \times 10^7 \text{ m}^3$ .  
373 Figure 4c shows the subsurface displacements due to the combination of the ring-faulting and the  
374 crack deformation, calculated by the TD method, which represents the asymmetric motion of the

375 caldera block. The maximum upward displacement is about 4 m on the inner side of the  
376 northeastern ring fault, while the maximum downward displacement is about 2 m on the  
377 southwestern upper wall of the horizontal crack.

378 The vertical sea-surface displacement caused by the best-fit source model (Figure 6a)  
379 presents uplift twice as large as and more localized than our preliminary analysis estimated  
380 (Figure 2a), but explains equally well the tsunami waveform data at all the OBP gauges (Figure  
381 6b). Note that in the preliminary analysis, the main uplift was estimated in a relatively broader  
382 area (Figure 2a) because of no constraint from the source structure, possibly leading to the  
383 underestimation of the amplitude.

384 Figure 9 compares the contributions of the ring fault and the horizontal crack to tsunamis  
385 at representative stations. Tsunami waveforms from the two parts are more different at shorter  
386 distances (see A01–A04), indicating the importance of near-field tsunami observations to  
387 distinguish the two sources. We note that if we perform the tsunami waveform inversion by  
388 assuming only either the ring fault or the horizontal crack, the waveform fit clearly deteriorates  
389 (Figures S12 and S13), demonstrating that the fault-crack composite source model is an  
390 appropriate model for the earthquake.

391 The moment tensor of the best-fit source model (Figure 8a) with a large isotropic  
392 component consists of the ring fault (Figure 8b) and the horizontal crack (Figure 8c)  
393 components. This model explains well the long-period seismic data at most stations, as shown in  
394 Figure 8d. Although slight waveform discrepancies are seen in several records (e.g., BHE  
395 channel of KZS, YMZ, and TYS, and BHN channel of AMM), they can be substantially reduced  
396 by performing the source modeling with slight modifications of dip angles in parts of the ring  
397 fault (see Text S3, Figures S14 and S15).

398 To consider contributions to long-period seismic waves from each of source parts, we  
399 show in Figure 10 long-period seismograms computed for the three partial moment tensors from  
400 our best-fit source model: (a) the ring fault only ( $\mathbf{M}_{RF}$ :  $M_w$  6.11); (b) the horizontal crack only  
401 ( $\mathbf{M}_{HC}$ :  $M_w$  5.91); and (c) the ring fault only, but without  $M_{r\theta}$  and  $M_{r\phi}$  (i.e.,  $M_{rr}$ ,  $M_{\theta\theta}$ ,  $M_{\phi\phi}$ , and  
402  $M_{\theta\phi}$  of  $\mathbf{M}_{RF}$ :  $M_w$  5.71). The seismic magnitude of  $\mathbf{M}_{HC}$  is comparable to that of  $\mathbf{M}_{RF}$ , but the  
403 seismic amplitudes from  $\mathbf{M}_{HC}$  are much smaller than those from  $\mathbf{M}_{RF}$  (compare Figures 10a and  
404 10b). Additionally, synthetic seismograms from  $\mathbf{M}_{RF}$  change little even after excluding the two  
405 moment tensor elements ( $M_{r\theta}$  and  $M_{r\phi}$ ; compare Figures 10a and 10c), showing the very small  
406 contribution by the two elements. These highlight the very small long-period seismic excitations  
407 from the horizontal crack and the two elements ( $M_{r\theta}$  and  $M_{r\phi}$ ) of the ring fault that occur at  
408 shallow depths near the free-traction seafloor surface (pp. 180–183 of Dahlen & Tromp, 1998;  
409 Fukao et al., 2018; Sandanbata, Kanamori, et al., 2021). Thus, despite the seismic magnitude  $M_w$   
410 6.16 of  $\mathbf{M}_{HC} + \mathbf{M}_{RF}$  (a seismic moment  $M_0 = 2.16 \times 10^{18}$  Nm; Figure 8a), only the limited part  
411 of the ring-faulting  $\mathbf{M}_{RF}$ , excluding the two elements, that corresponds to  $M_w$  5.71 ( $M_0 = 0.46 \times$   
412  $10^{18}$  Nm; equivalent to 22% of the total seismic moment; Figure 10c), contributes the long-  
413 period seismic radiation of the fault-crack composite source model. We note that the four  
414 moment tensor elements of the ring fault contributing to the seismic waves constitute a vertical-T  
415 CLVD-type moment tensor (Figure 10c), which agrees with the solution reported in the GCMT  
416 catalog (Ekström et al., 2012) (Figure 1b).

417

## 418 **6 Discussion**

### 419 6.1 Submarine trapdoor faulting at Sumisu caldera

420 We have shown that the fault-crack composite source model (Figure 4a) explains  
421 quantitatively both the tsunami and long-period seismic data of the 2015 earthquake at Sumisu  
422 caldera. This source model strongly suggests the *trapdoor faulting* mechanism of the earthquake  
423 at the submarine caldera (Figure 11), like that found at the subaerial Sierra Negra caldera. As  
424 introduced briefly in Section 4.1, trapdoor faulting events have been observed geodetically  
425 several times at Sierra Negra caldera (e.g., Amelung et al., 2000; Chadwick et al., 2006; Jónsson,  
426 2009). Based on geodetic data, many previous studies showed that the trapdoor faulting takes  
427 place in the interaction between sudden rupture of the intra-caldera ring fault and deformation of  
428 its underlying sill-like magma reservoir, and suggested that it is driven by high magma pressure  
429 within the reservoir (Amelung et al., 2000; Yun, 2007; Jónsson, 2009; Gregg et al., 2018).  
430 Recently, Zheng et al. (2022) numerically solved the mechanical interaction between the ring  
431 fault and the crack-like reservoir with magma pressure change effect, and proposed a trapdoor  
432 faulting model by fitting the geodetical data for the 2005 event of Sierra Negra caldera. Their  
433 mechanical model predicted that the trapdoor faulting caused large reverse slip of a part of an  
434 inward-dipping ring fault and asymmetric deformation of the crack-like reservoir (see Figure 2b  
435 in Zheng et al., 2022). Although our kinematic source model of the earthquake at Sumisu caldera  
436 does not consider the mechanical interaction or magma pressure change effect, the fault-crack  
437 motion patterns shown in our model (Figure 4a) are similar to those of the trapdoor faulting  
438 predicted by the mechanical model of Zheng et al.

439 In addition to the model similarities, trapdoor faulting events at Sierra Negra caldera  
440 share many similar features with the Sumisu caldera earthquake. First, trapdoor faulting events at

441 Sierra Negra occurred with vertical-T CLVD earthquakes of  $M_w \sim 5$  (Shuler, Ekström, et al.,  
442 2013; Sandanbata, Kanamori, et al., 2021) and caused meter-scale asymmetrical caldera floor  
443 uplifts (Amelung et al., 2000; Chadwick et al., 2006; Jónsson, 2009). Second, the deformation  
444 during a trapdoor faulting in 2005 at Sierra Negra recorded by a Global Positioning System  
445 sensor near the southern intra-caldera fault occurred within 10 s (Chadwick et al., 2006; Jónsson,  
446 2009), which is comparable to the rupture duration (10 s: the half duration of 5 s) estimated for  
447 the earthquakes at Sumisu caldera by our moment tensor analysis (Text S1; Table S3). Third,  
448 during the 2005 trapdoor faulting at Sierra Negra, the northern caldera floor, opposite from the  
449 southern fault with the largest slip, subsided by a few centimeters, which was attributed to the  
450 pressure drop of the inner magma reservoir (Jónsson, 2009; Zheng et al., 2022). This feature can  
451 be expected similarly from our model with closure of the crack in the southwestern part of  
452 Sumisu caldera.

453 Therefore, similarly to interpretations for trapdoor faulting at Sierra Negra caldera in  
454 previous studies (e.g., Amelung et al., 2000; Jónsson, 2009; Zheng et al., 2022), we suggest that  
455 submarine trapdoor faulting at Sumisu caldera, driven by overpressure of magma accumulating  
456 in the horizontal crack, or a sill-like reservoir, caused the 2015 earthquake and tsunami (Figure  
457 11). We speculate that continuous magma supply into the crack gradually increases the shear  
458 stress on the pre-existing ring fault system in the interseismic process, until it reaches a critical  
459 value for initiation of brittle rupture of the ring fault. Once the trapdoor faulting process initiates  
460 with the ring-faulting, the top surface of the horizontal crack moves vertically upward. The  
461 consequent increase in the reservoir volume depressurizes the inner magma, possibly causing the  
462 closure of the southwestern part of the crack, as shown by Zheng et al. (2022). Note that Zheng  
463 et al. suggested that the reservoir filled with compressible magma increases its inner volume

464 during the trapdoor faulting. Hence, our model containing a net volume increase of  $1.26 \times 10^7 \text{ m}^3$   
465 implies that the magma beneath the caldera is compressible. Due to the volume increase and  
466 depressurization of the inner magma, the trapdoor faulting may not lead to an immediate  
467 submarine eruption at the caldera (Amelung et al., 2000). Our finding of submarine trapdoor  
468 faulting, following the previous observations at the subaerial Sierra Negra caldera, indicates that  
469 this volcanic phenomenon might be more common at calderas than previously thought.

470

## 471 6.2 Efficient tsunami generation mechanism

472 Trapdoor faulting produces an unusually large fault slip as compared with ordinary  
473 tectonic earthquakes and can generate a large tsunami despite its moderate earthquake magnitude  
474 when it occurs under water. For the 2015 earthquake ( $M_w$  5.7 in the GCMT catalog), our best-fit  
475 source model has a maximum slip of 6.8 m along the ring fault (Figure 4a). In contrast, the  
476 empirical scaling law (Wells & Coppersmith, 1994) predicts that tectonic earthquakes with the  
477 same moment magnitude have a maximum slip of only 0.17 m. The subaerial trapdoor faulting in  
478 2005 at Sierra Negra caldera also caused a large slip of  $\sim 2$  m along the intra-caldera fault, despite  
479 its small seismic body-wave magnitude of 4.6 (Jónsson, 2009; Zheng et al., 2022). These  
480 disproportionately large slips might be possible because the fault system connected to the  
481 reservoir can effectively cause slip. Additionally, atypical source properties of trapdoor faulting  
482 such as the shallow source depth, the localized stress increase due to magma overpressure, and/or  
483 the fault–magma interaction during rupture, possibly contribute to large slips.

484 Submarine trapdoor faulting is efficient in generating tsunamis, even for the relatively  
485 low seismic magnitude of the earthquakes, due to its shallow and complex source structure.

486 Firstly, trapdoor faulting occurring above a shallow magma reservoir at a depth of <3 km more  
487 efficiently deforms the seafloor than tectonic earthquakes that typically occur at a depth of >10  
488 km (Ward, 1982). Secondly, the combination of reverse slip along the ring fault and vertical  
489 motion of the horizontal crack localizes the coseismic uplift on a small area within the circular  
490 ring fault (Figures 6a and 9a–b). As such, trapdoor faulting can generate larger tsunamis than  
491 ordinary seismic faults of an equivalent fault size. However, at such shallow depths, the vertical  
492 motion of the horizontal crack and the two moment tensor elements,  $M_{r\theta}$  and  $M_{r\phi}$ , of the ring  
493 fault are inefficient in radiating long-period seismic waves (Fukao et al., 2018; Sandanbata,  
494 Kanamori, et al., 2021), as shown earlier in Section 5. Additionally, the curved geometry of the  
495 ring fault also reduces long-period seismic amplitudes by the geometrical cancelation of the  
496 double-couple components (Ekström, 1994; Shuler, Ekström, et al., 2013; Sandanbata,  
497 Kanamori, et al., 2021).

498

### 499 6.3 Quasi-regular recurrence of submarine trapdoor faulting

500 We suggest that continuous magma supply below Sumisu caldera causes submarine  
501 trapdoor faulting almost every decade. By additional moment tensor analysis using long-period  
502 seismic data (Text S3), we estimate the *resolvable moment tensor*  $\mathbf{M}_{res}$  for the four earthquakes,  
503 which was studied in Sandanbata, Kanamori, et al. (2021) to constrain the ring fault geometry.  
504 The resolvable moment tensors characterized by the null-axis direction and the ratio of the  
505 vertical-CLVD component ( $k_{CLVD}$ ), which was introduced in Sandanbata, Kanamori et al. (2021)  
506 and is explained in Text S1, are similar for the 1996, 2006, and 2015 earthquakes (Figures 12a–  
507 c). These similarities indicate that, at the times of the earthquakes, trapdoor faulting occurred  
508 along almost the same ring fault segment of the source model for the 2015 earthquake (Figure

509 4a). This interpretation is supported by their similar tsunami waveforms recorded at tide gauges  
510 (Figures 1d–e and S1). The overall recurrence interval of  $\sim 10$  yr may correspond to the time  
511 required to accumulate enough magma overpressure within the reservoir to rupture the ring fault  
512 (Cabaniss et al., 2020; Gregg et al., 2018). On the other hand, the resolvable moment tensor for  
513 the 2018 earthquake, which occurred only three years after the 2015 earthquake, contains a more  
514 dominant double-couple component (i.e., smaller  $k_{CLVD}$ ) and has a smaller moment magnitude  
515  $M_w$  (Figure 12d), suggesting that the trapdoor faulting in 2018 caused a rupture along a ring fault  
516 segment with a shorter arc length than those for the other events. This may explain the smaller  
517 tsunami associated with the 2018 earthquake (Figures 1d–e and S1). Some complexities linked to  
518 source geometries, frictional properties along the ring fault, or magma supply rate may cause  
519 variations in the size, the ring-fault length, and the recurrence interval of trapdoor faulting. For  
520 seismic waveform comparison, we show the results of moment tensor analyses for the four  
521 events in Figures S16–19.

522 The topography of Sumisu caldera also reflects the longer-term recurrence of trapdoor  
523 faulting. Our source model predicts that the submarine trapdoor faulting in 2015 uplifted the  
524 northeastern part of the caldera floor but caused little deformation in its southwestern part  
525 (Figure 12e). Along a SW–NE profile across the caldera (A–B in Figure 12e), coseismic vertical  
526 displacement with an offset of about 4 m correlates with the caldera floor topography, which  
527 slopes upward from the SW to NE with an altitude offset of  $\sim 150$  m (Figure 12f). A similar  
528 correlation was found at Sierra Negra caldera (Amelung et al., 2000), where trapdoor faulting  
529 has occurred repeatedly due to continuous magma input. This suggests that magma supply has  
530 been continuous at Sumisu caldera, thereby causing submarine trapdoor faulting repeatedly and  
531 forming the slope of the caldera floor. Since an explosive submarine eruption in 1916 (Japan

532 Meteorological Agency, 2013), no clear evidence of eruptions has been found at Sumisu caldera  
533 and the relationship between trapdoor faulting and eruptions is still unclear.

534

#### 535 6.4 Mechanisms of volcanic tsunami generation

536 Various mechanisms have been proposed to generate volcanic tsunamis: submarine  
537 explosions, pyroclastic flows, flank failures, caldera collapses, volcanic earthquakes  
538 accompanying eruptions, and interactions of ocean waves with atmospheric waves from volcanic  
539 explosions (Paris, 2015; Paris et al., 2014). The submarine trapdoor faulting mechanism  
540 identified in this study may be categorized as a volcanic earthquake mechanism, but is  
541 characterized by large-amplitude tsunamis without significant seismic radiation and by quasi-  
542 regular recurrence. This mechanism may also explain unusual tsunamis with similar  
543 characteristics generated near volcanic islands in the Kermadec arc, north of New Zealand  
544 (Gusman et al., 2020). These volcanic tsunamis due to submarine trapdoor faulting suggest that  
545 continuous monitoring of submarine calderas is necessary to reliably assess tsunami hazards.

546

### 547 **7 Conclusions**

548 By using remotely observed tsunami and long-period seismic data for the 2015  
549 earthquake at Sumisu caldera, we constructed a fault-crack composite source model of  
550 submarine trapdoor faulting, which can quantitatively explain both datasets. The combined  
551 waveform analyses also allow us to constrain the magma reservoir depth and the ring fault  
552 geometry. Based on the model, we show that the atypical source properties, or large slip on a  
553 shallow and complex structure, contributed to meter-scale tsunami generation despite the

554 moderate seismic magnitude. The sub-decadal recurrence of trapdoor faulting with similar  
555 tsunamis and seismic characters suggests that continuous magma supply into the submarine  
556 caldera has been taking place. Further investigations of the submarine caldera using *in situ*  
557 geophysical instruments, such as hydrophones, seismometers, pressure sensors, and ship-borne  
558 surveys will be useful for understanding the volcanism, including the magma accumulation  
559 process. This may lead to improved predictions of future submarine trapdoor faulting and/or  
560 eruptions.

561

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572

## 573 **Open Research**

574 The earthquake data are from the Global CMT catalog (Ekström et al., 2012;  
575 <https://www.globalcmt.org/>). Tide gauge data are available on request from the Japan

576 Meteorological Agency (<https://www.jma.go.jp/jma/indexe.html>) and Hydrographic and  
577 Oceanographic Department, Japan Coast Guard  
578 ([https://www1.kaiho.mlit.go.jp/TIDE/gauge/index\\_eng.php](https://www1.kaiho.mlit.go.jp/TIDE/gauge/index_eng.php)) upon requests. Bathymetric data of  
579 M7000 Digital Bathymetric Chart and JTOPO30 are available from the Japan Hydrographic  
580 Association ([https://www.jha.or.jp/shop/index.php?main\\_page=index](https://www.jha.or.jp/shop/index.php?main_page=index)) and GEBCO\_2014 Grid  
581 is available from GEBCO Compilation Group (Weatherall et al., 2015;  
582 [https://www.gebco.net/data\\_and\\_products/gridded\\_bathymetry\\_data/gebco\\_30\\_second\\_grid/](https://www.gebco.net/data_and_products/gridded_bathymetry_data/gebco_30_second_grid/)).  
583 Ocean bottom pressure data of the array off Aogashima Island (Fukao et al., 2019) and the Deep  
584 Sea Floor Observatory off Muroto Cape (Momma et al., 1997) are available from the Japan  
585 Agency for Marine-Earth Science and Technology (<http://p21.jamstec.go.jp/top/>; under  
586 construction at the time of publication), DONET data are available from National Research  
587 Institute for Earth Science and Disaster Resilience (National Research Institute for Earth Science  
588 and Disaster Resilience, 2019a; <https://www.seafloor.bosai.go.jp/>), and DART data is available  
589 from National Oceanic and Atmospheric Administration (National Oceanic and Atmospheric  
590 Administration, 2005; <https://nctr.pmel.noaa.gov/Dart/>). F-net seismic data of F-net are available  
591 from the NIED (National Research Institute for Earth Science and Disaster Resilience, 2019b;  
592 <https://www.fnet.bosai.go.jp/top.php?LANG=en>), and Global Seismograph Network data are  
593 available through the IRIS Wilber 3 system (<https://ds.iris.edu/wilber3/>) or IRIS Web Services  
594 (<https://service.iris.edu/>), including the IU seismic network (GSN; Albuquerque, 1988). The  
595 source models presented in this paper are detailed in Data Set S1.

596

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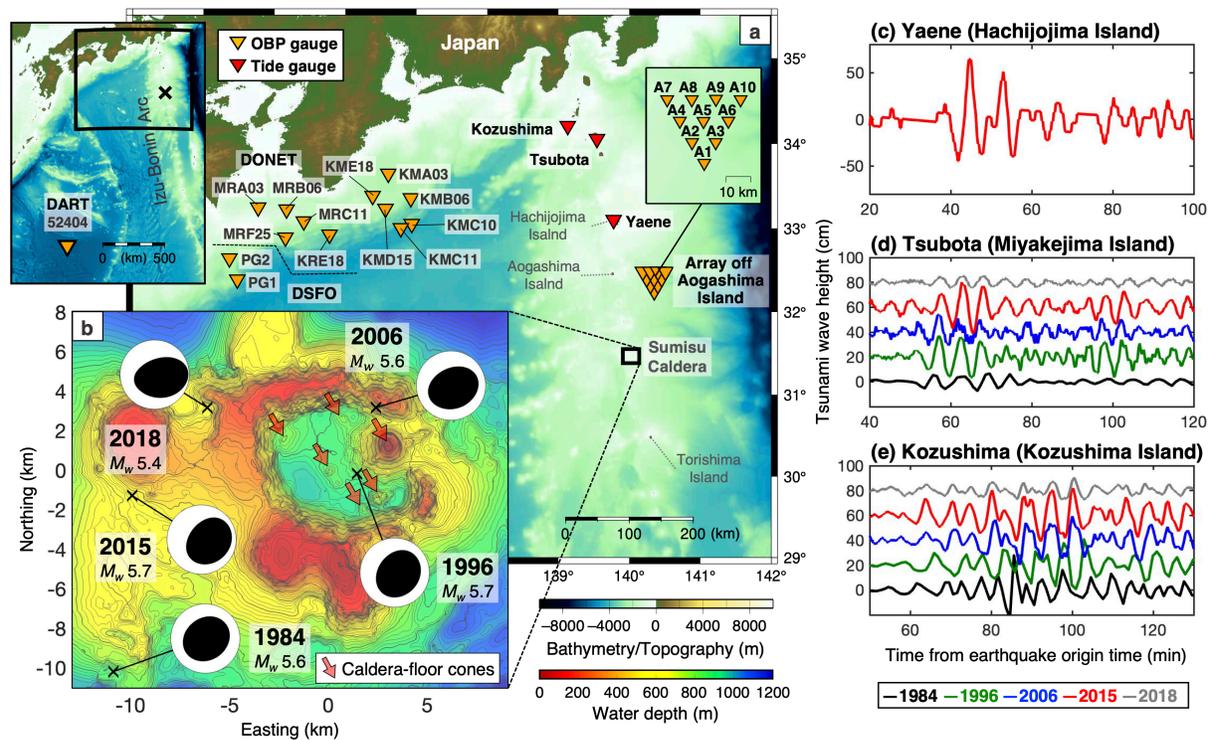
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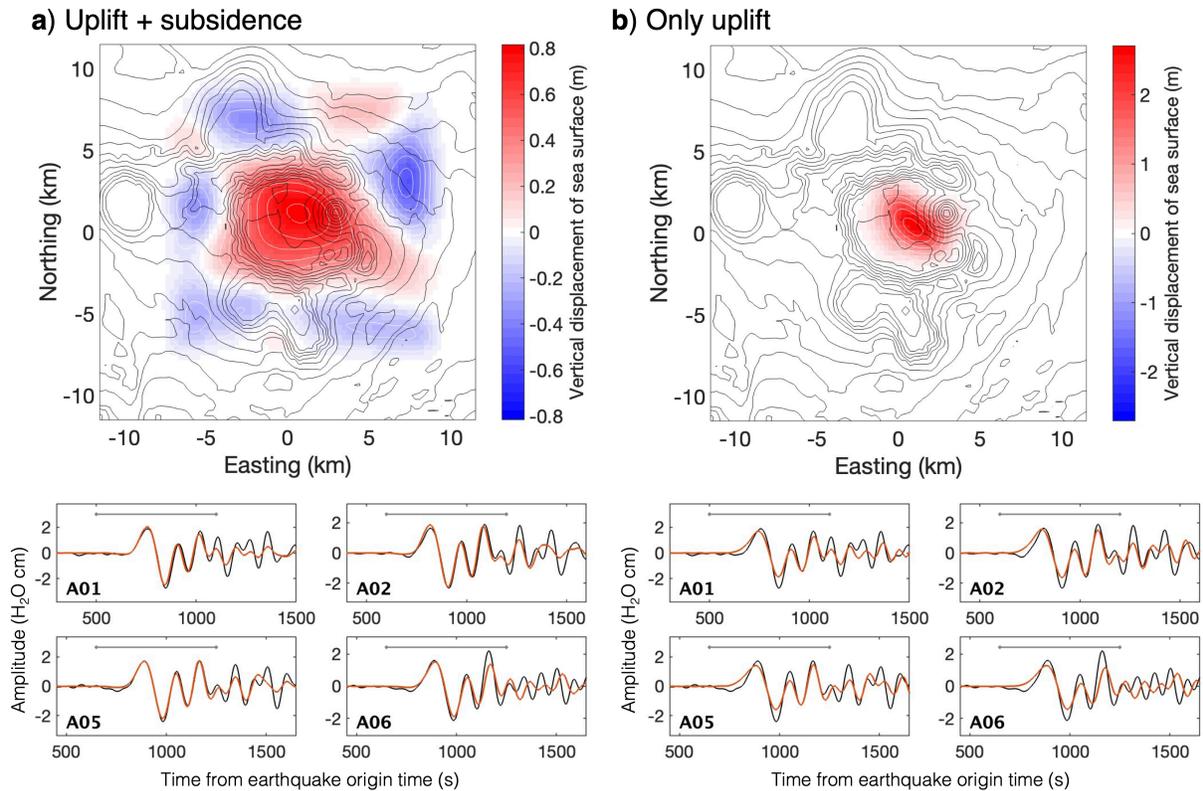
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- 795
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797

798 **Figure 1.** Anomalous tsunamis due to volcanic earthquakes at Sumisu caldera. (a) Map showing  
 799 the locations of Sumisu caldera, ocean bottom pressure gauges (orange triangles), and  
 800 representative tide gauges (red triangles). (b) Repeating earthquakes near Sumisu caldera  
 801 reported by the GCMT catalog (Ekström et al., 2012). The focal mechanisms are shown by  
 802 projection of the lower focal hemisphere. Arrows point to cones on the caldera floor, some of  
 803 which were identified as lava domes (Tani et al., 2008). (c) Tsunami waveform from the 2015  
 804 earthquake recorded by the tide gauge at Yaene (Hachijojima Island). (d–e) Tsunami waveforms  
 805 at Tsubota (Miyakejima Island) and Kozushima (Kozushima Island) from the repeating  
 806 earthquakes. Baselines for different events are shifted by multiples of 20 cm. Tsunami  
 807 waveforms at other tide gauge stations are shown in Figure S1.

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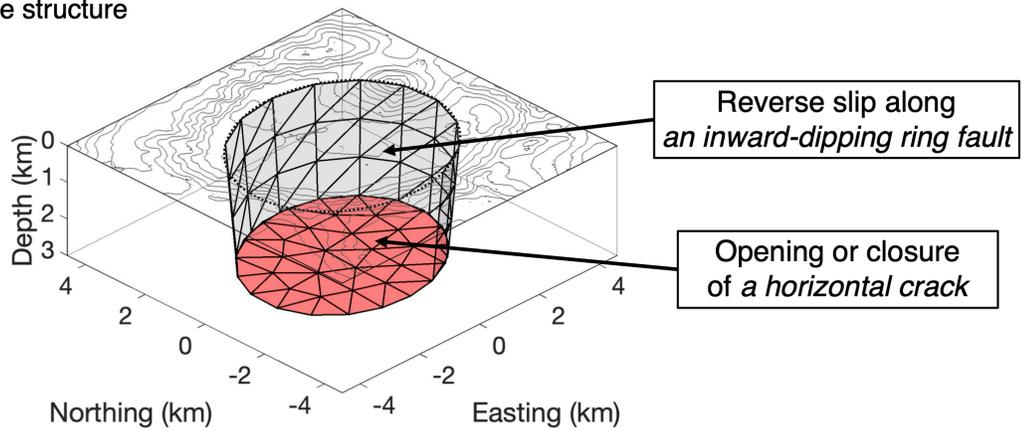


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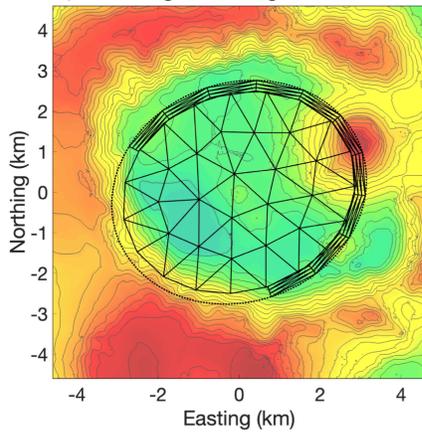
810 **Figure 2.** Preliminary initial sea-surface displacement models. Models with (a) both uplift and  
 811 subsidence and (b) only uplift. (Top panel) Red and blue colors represent uplift and subsidence,  
 812 respectively. Bathymetric contours at 100 m intervals. (Bottom panels) Comparison of the  
 813 observed (black) and synthetic (red) tsunami waveforms at representative ocean bottom pressure  
 814 gauges. The gray line represents the time interval used for the inversion.

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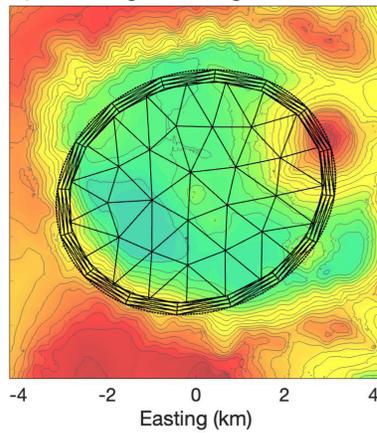
**a) Source structure**



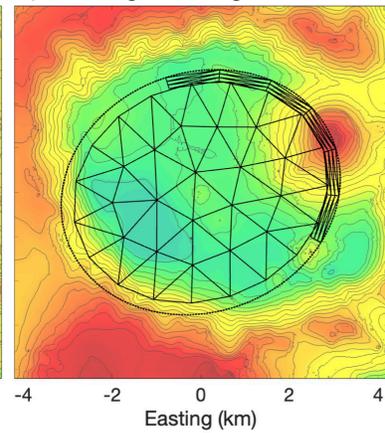
**b) 2/3-ring arc length**



**c) Full-ring arc length**



**d) 1/3-ring arc length**

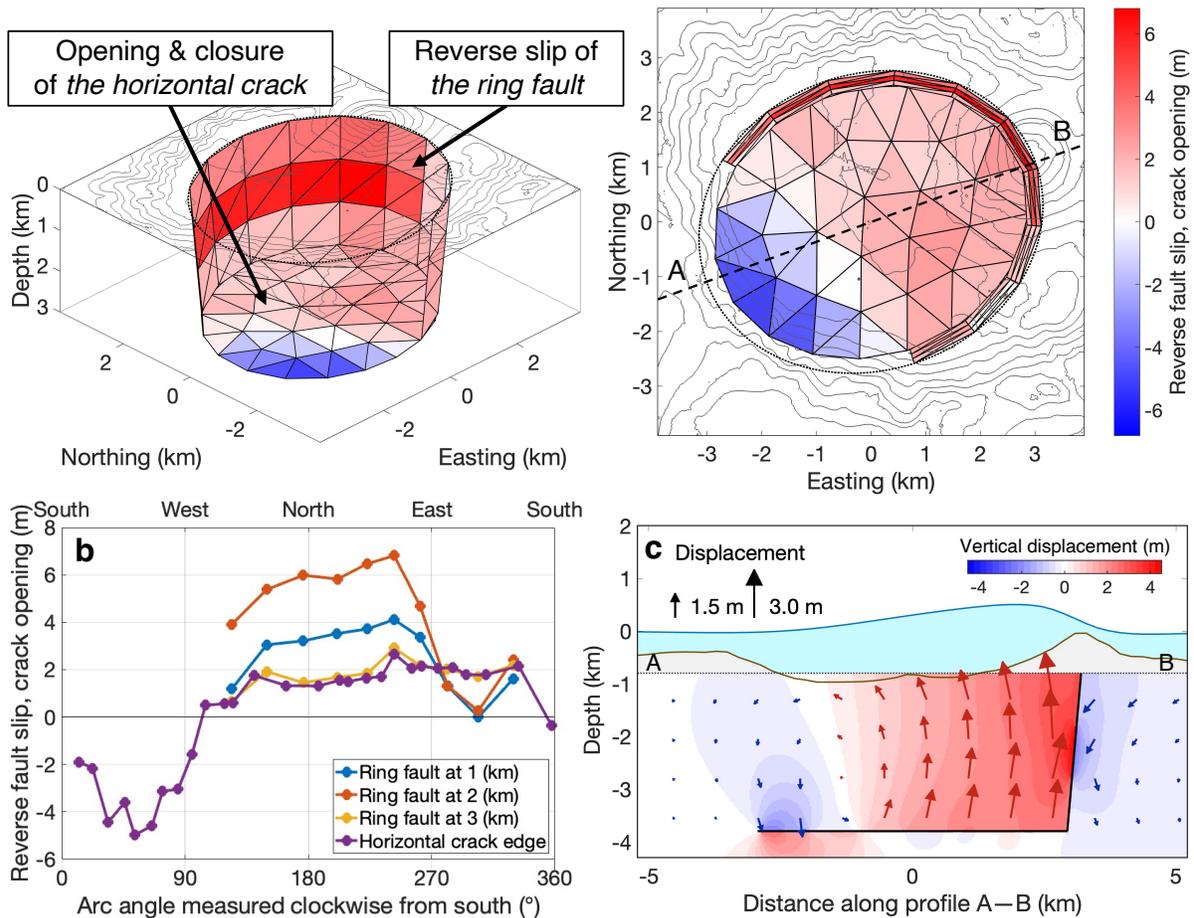


816

817 **Figure 3.** Fault-crack composite system assumed for the source modeling. (a) Example of the  
 818 source structure assumed in this study. (b–d) Three cases of the ring-fault arc length assumed in  
 819 the source modeling: (b) 2/3 ring, (c) full ring, and (d) 1/3 ring arc lengths.

820

**a) Best-fit model (Crack depth, Arc length, Dip angle) = (3.0 km, 2/3-ring, 85.0°)**

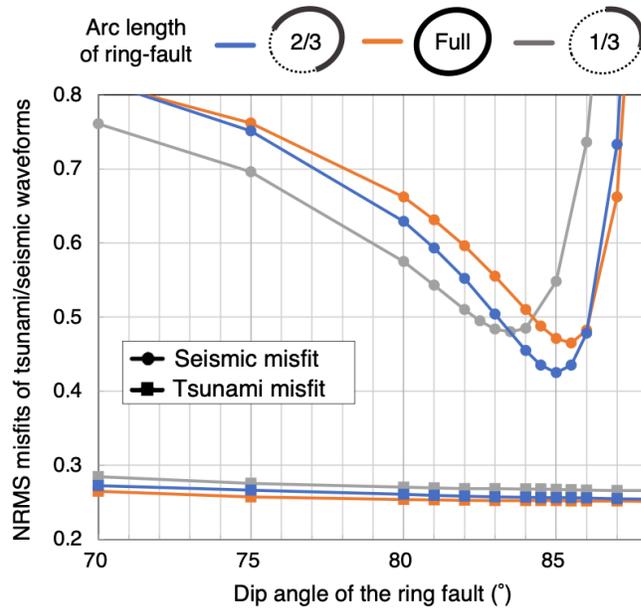


821

822 **Figure 4.** Best-fit source model for the 2015 earthquake. (a) Motions (dislocations) of the fault-  
 823 crack composite system viewed from the southwest (left panel) and above (right panel). The  
 824 horizontal crack is at a depth of 3 km, and the ring fault along two-thirds of the arc of the caldera  
 825 rim has a uniform dip angle of 85°. The red color on the ring fault represents reverse slip. Red  
 826 and blue colors on the horizontal crack represent vertical opening and closure, respectively. (b)  
 827 Amounts of reverse slip at sub-faults of the ring fault and opening or closing of sub-cracks on the  
 828 horizontal crack edge. The arc angle shown in the horizontal axis is measured clockwise from  
 829 south (black dot in the right panel of a). Circles in b are plotted at arc angles of centroids of the  
 830 sub-faults and sub-cracks. Note that the ring fault displacement at the bottom (3 km) is in

831 approximate agreement with that of the adjacent crack, because of the kinematic condition  
832 (Equation 4). (c) Displacement of the caldera computed with the model along the A–B profile  
833 shown in **a** (right panel). The red and blue colors indicate upward and downward displacements,  
834 respectively. We assume that the bathymetry is flat for the computation. Note that the seafloor  
835 and sea-surface displacements are exaggerated.

836

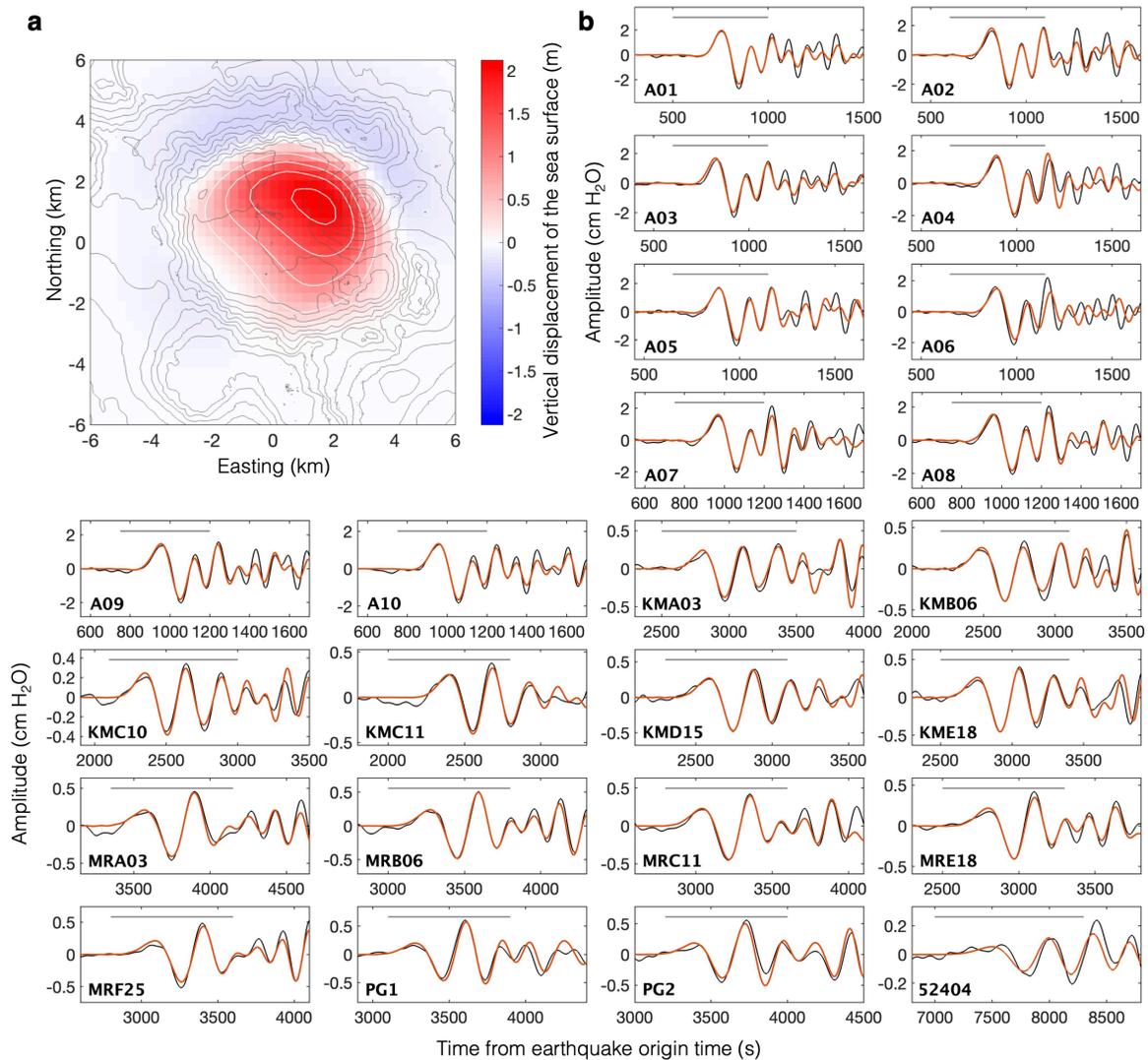


837

838 **Figure 5.** Comparison of the tsunami and seismic waveform misfits (Equations 8 and 11,  
 839 respectively) for source models with different ring-fault dip angles and arc lengths. All the  
 840 models shown here have the horizontal crack at a depth of 3 km.

841

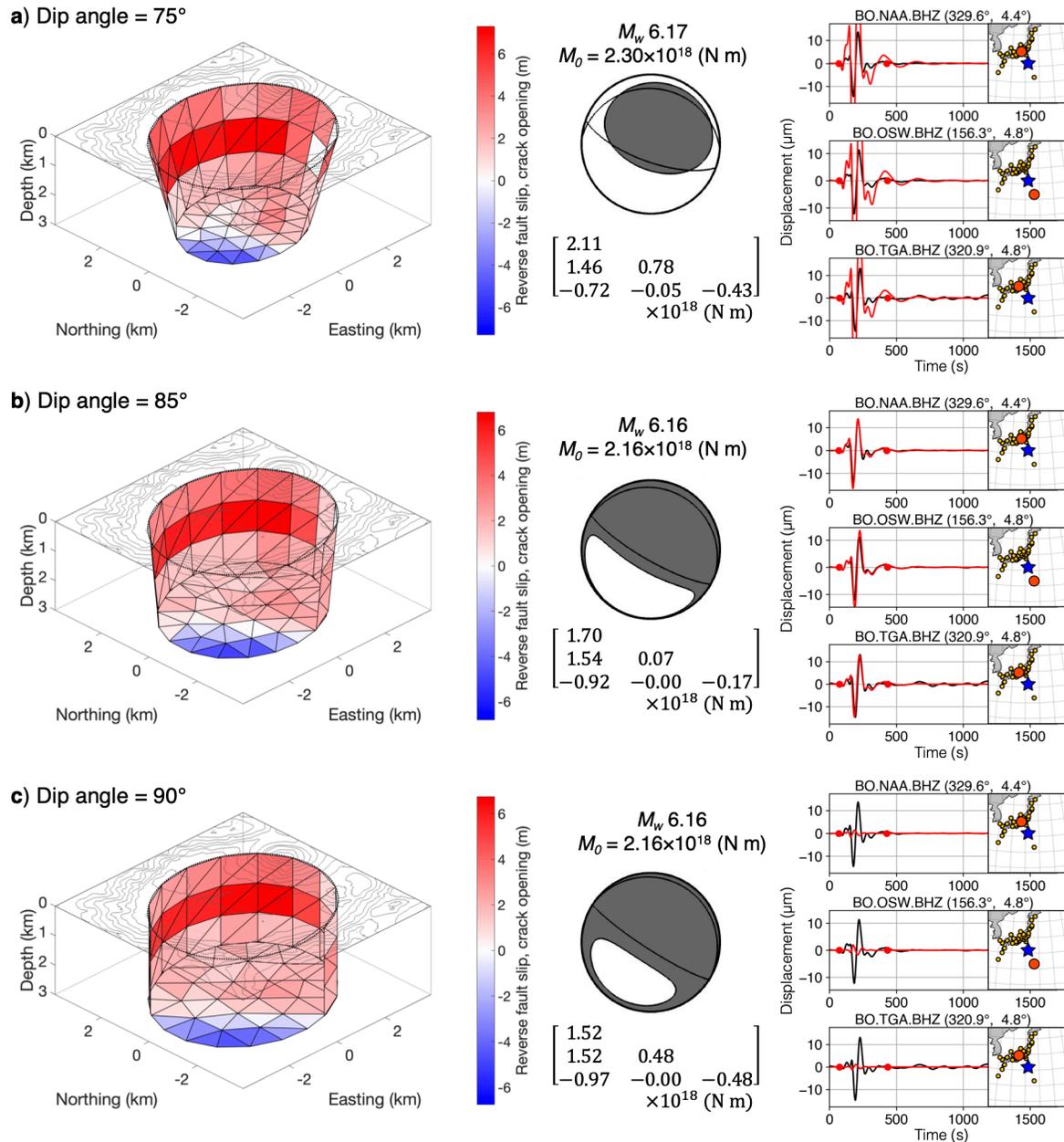
**Best-fit model (Crack depth, Arc length, Dip angle) = (3.0 km, 2/3-ring, 85.0°)**



842

843 **Figure 6.** Tsunami waveforms from the best-fit source model (Figure 4a). (a) Vertical  
 844 displacement of sea surface caused by the model. Red and blue colors represent uplift and  
 845 subsidence, respectively, with white contour lines plotted every 0.5 m. Note that the color scale  
 846 in this figure is different from that in Figure 2a. (b) Comparison of the observed (black) and  
 847 synthetic (red) tsunami waveforms from the model at the ocean bottom pressure gauges. The  
 848 gray line represents the time interval used for the inversion.

849



850

851 **Figure 7.** Long-period seismic data analyses from source models with the ring-fault dip angles  
 852 of (a) 75°, (b) 85°, and (c) 90°. (Left) Motions of the fault-crack composite system inverted from  
 853 the tsunami data. (Middle) Moment tensors of the model. The focal mechanisms are shown as  
 854 projections of the lower focal hemisphere, and the orientation of the best double-couple solution  
 855 is shown as thin lines. (Right) Comparison of the observed (black) and synthetic (red)

856 seismograms (period = 60–250 s) at representative stations. In each inset figure, a large red circle  
857 and blue star represent the station and earthquake centroid, respectively. The network name,  
858 station name, record component, station azimuth, and epicentral distance are given on the top of  
859 each panel. Note that the amplitudes of the synthetic waveforms decrease as the ring-fault dip  
860 angle increases.

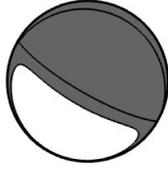
861

**Best-fit model (Crack depth, Arc length, Dip angle) = (3.0 km, 2/3-ring, 85.0°)**

**a) Model ( $M_{RF} + M_{HC}$ )**

$$M_w 6.16$$

$$M_0 = 2.16 \times 10^{18} \text{ (N m)}$$

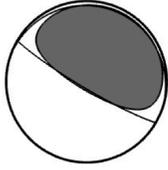


$$\begin{bmatrix} 1.70 & & \\ 1.54 & 0.07 & \\ -0.92 & -0.00 & 0.17 \end{bmatrix} \times 10^{18} \text{ (N m)}$$

**b) Ring fault ( $M_{RF}$ )**

$$M_w 6.11$$

$$M_0 = 1.85 \times 10^{18} \text{ (N m)}$$

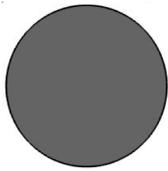


$$\begin{bmatrix} 0.52 & & \\ 1.54 & -0.31 & \\ -0.92 & -0.00 & -0.21 \end{bmatrix} \times 10^{18} \text{ (N m)}$$

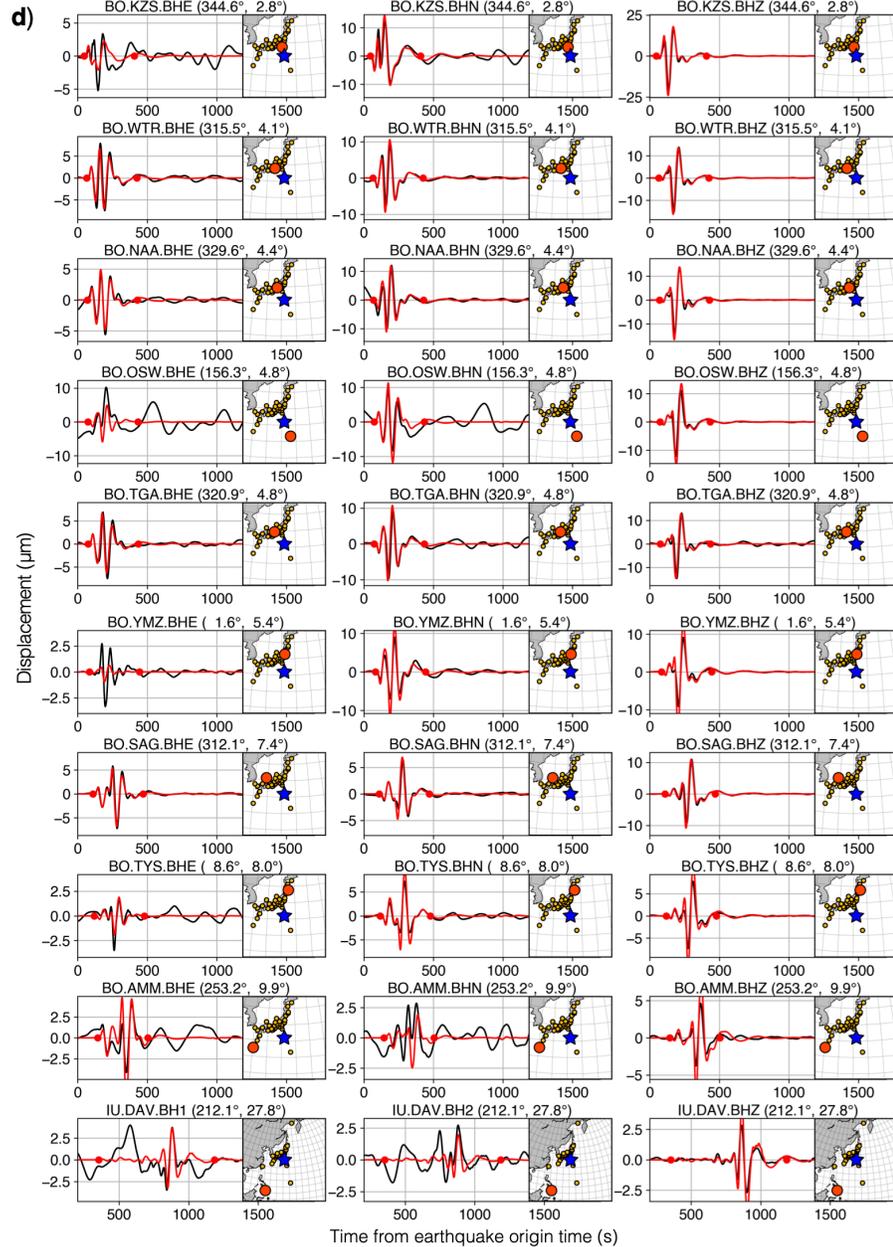
**c) Horizontal crack ( $M_{HC}$ )**

$$M_w 5.91$$

$$M_0 = 0.91 \times 10^{18} \text{ (N m)}$$



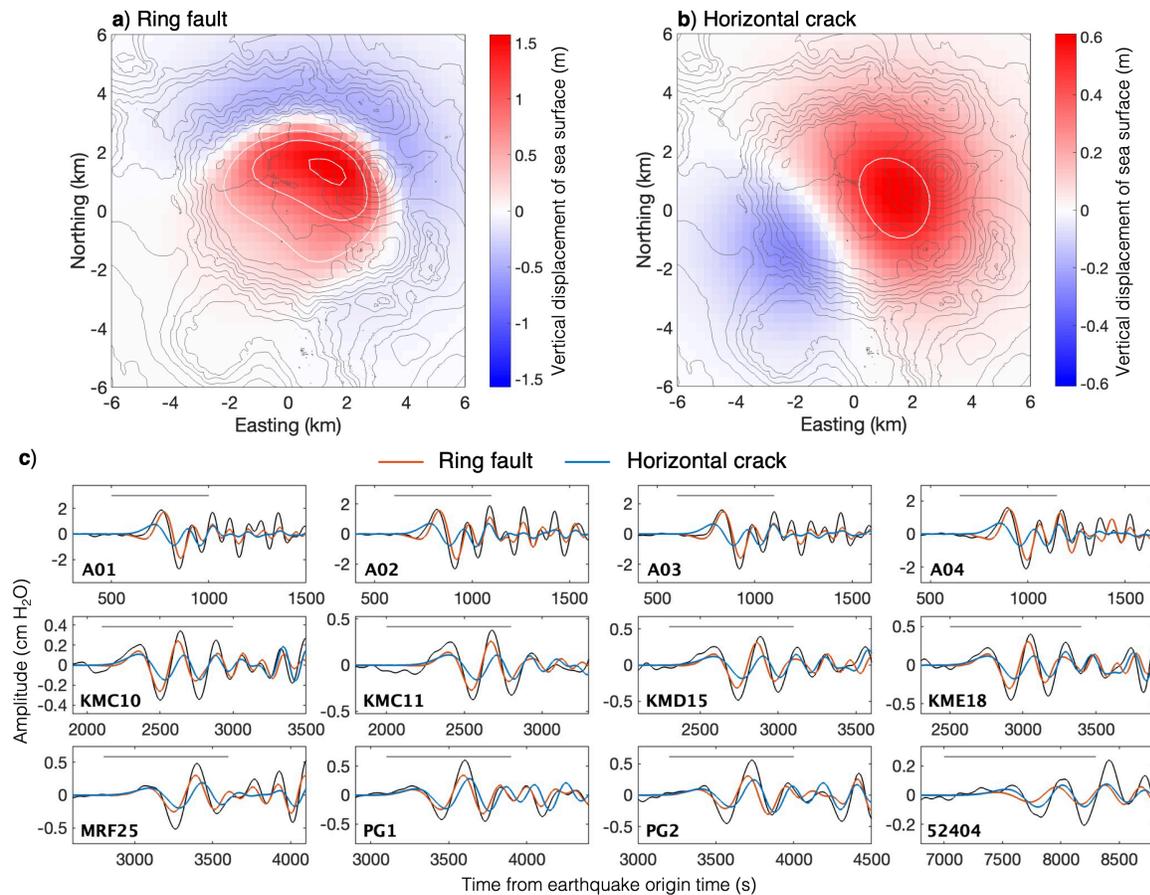
$$\begin{bmatrix} 1.18 & & \\ 0.00 & 0.38 & \\ 0.00 & 0.00 & 0.38 \end{bmatrix} \times 10^{18} \text{ (N m)}$$



862

863 **Figure 8.** Long-period seismic data analyses from the best-fit source model (Figure 4a). (a)  
 864 Moment tensors of the model. (b–c) Partial moment tensors of (b) the ring fault and (c) the  
 865 horizontal crack. The focal mechanisms are shown as projections of the lower focal hemisphere,  
 866 and the orientation of the best double-couple solution is shown as thin lines. (d) Comparison of

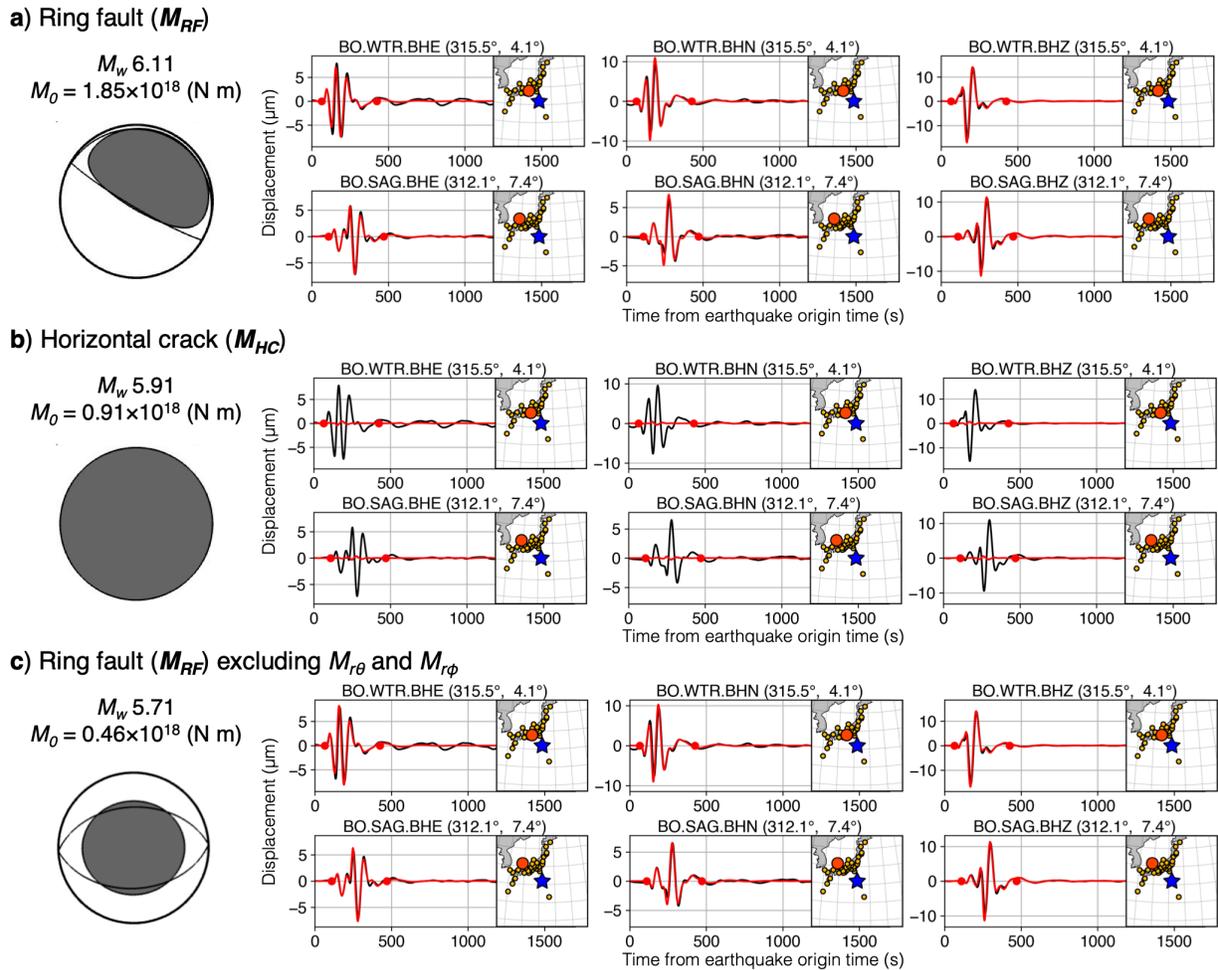
867 the observed (black) and synthetic (red) seismograms (period = 60–250 s), computed with the  
868 moment tensor shown in **a** at representative stations. The data interval used to calculate the  
869 waveform misfit is delimited by the red dots. See the caption for the right panel of Figure 7.  
870



871

872 **Figure 9.** Partial contributions of the ring fault and the horizontal crack of the best-fit source  
 873 model (Figure 4a) to the tsunami waveforms. (a–b) Vertical sea-surface displacements caused by  
 874 (a) the ring fault and (b) the horizontal crack. Red and blue colors represent uplift and  
 875 subsidence, respectively, with white contour lines plotted every 0.5 m. (c) Comparison of the  
 876 synthetic tsunami waveforms from the ring fault (red) and the horizontal crack (blue), with the  
 877 observed (black) waveforms at representative OBP gauges. The gray line represents the time  
 878 interval used for the inversion.

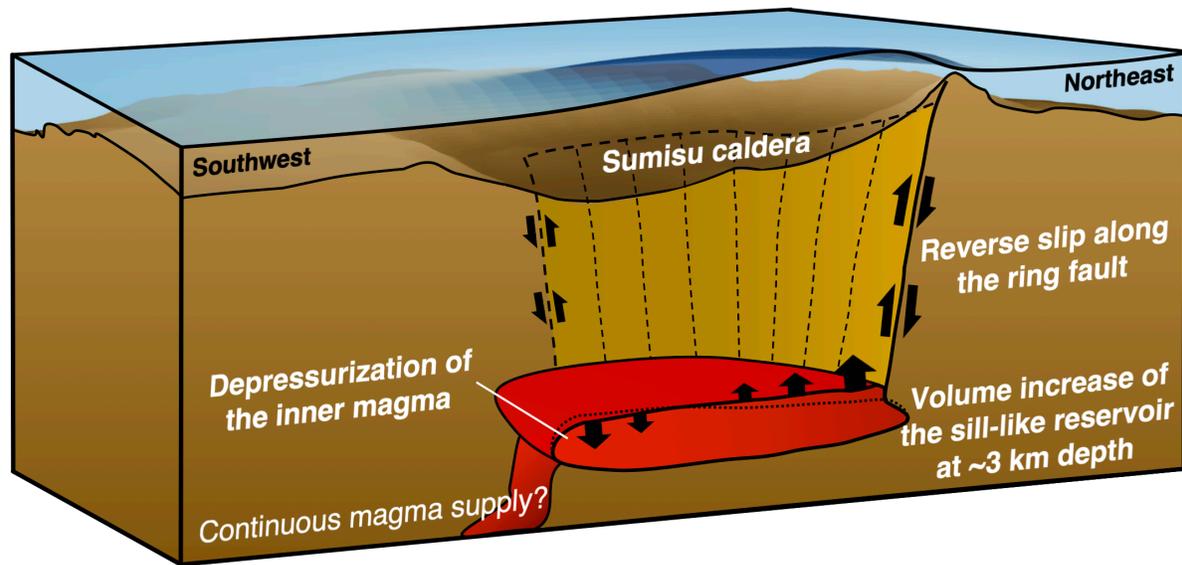
879



880

881 **Figure 10.** Contributions of the best-fit source model (Figure 4a) to the long-period seismic  
 882 waves. Synthetic seismograms (red curves) from the moment tensors of (a) the ring fault  $M_{RF}$ ,  
 883 (b) and horizontal crack  $M_{HC}$ , and (c) the ring fault, but excluding the two elements  $M_{r\theta}$  and  
 884  $M_{r\phi}$  (i.e.,  $M_{rr}$ ,  $M_{\theta\theta}$ ,  $M_{\phi\phi}$ , and  $M_{\theta\phi}$  of  $M_{RF}$ ). Note that the synthetic seismic waveforms from  
 885 the horizontal crack (b) are much smaller than those from the ring fault (a), and that the  
 886 waveforms from the ring fault do not change although  $M_{r\theta}$  and  $M_{r\phi}$  are removed (compare the  
 887 synthetic waveforms in a and c).

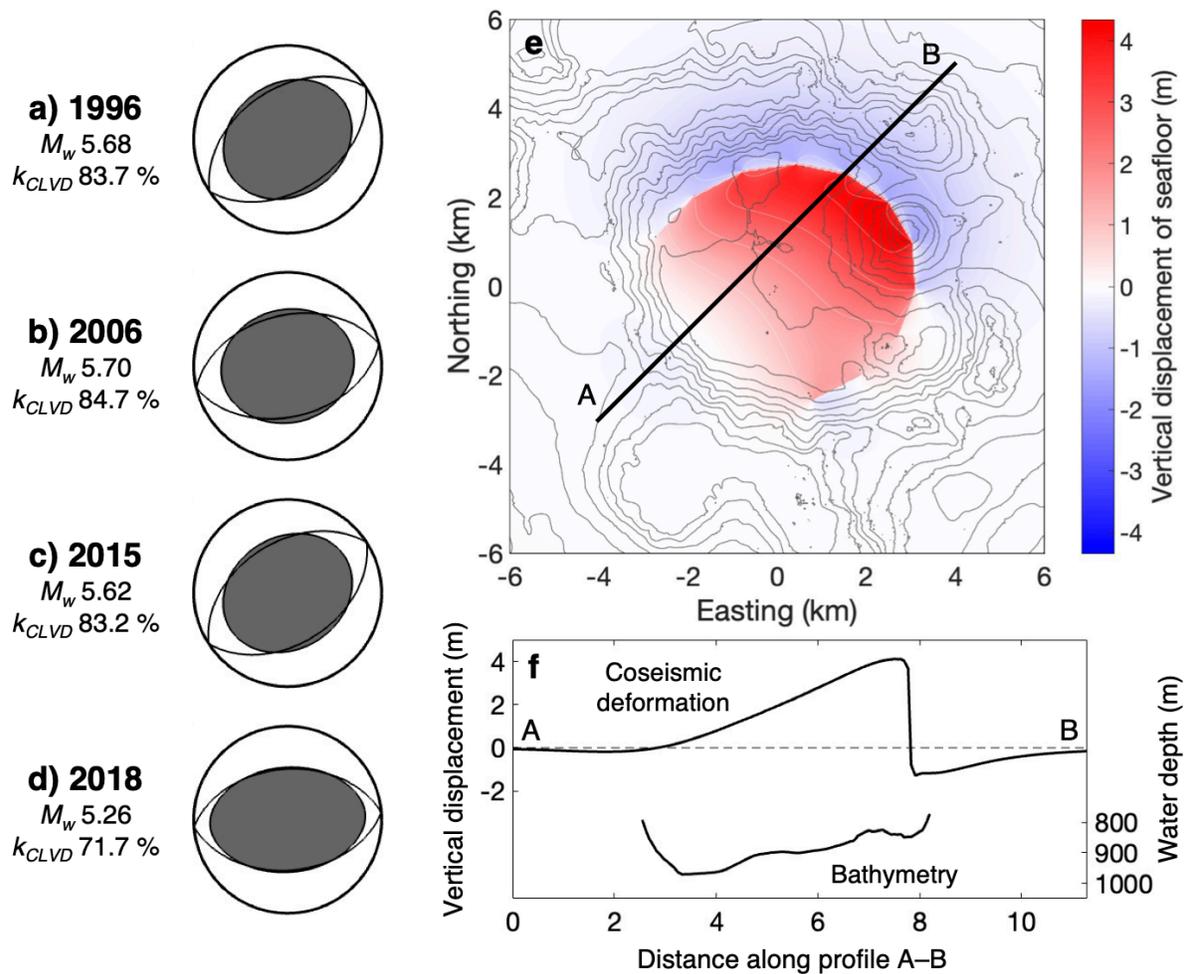
888



889

890 **Figure 11.** Schematic illustration of submarine trapdoor faulting mechanism at Sumisu caldera  
 891 (not to scale). Reverse slip occurs along the ring fault, the sill-like reservoir opens vertically on  
 892 the northeastern side of the caldera and consequent depressurization of the inner magma causes  
 893 the downward motion of the upper wall of the southwestern part of the magma reservoir.

894



895

896 **Figure 12.** Recurrence of trapdoor faulting at Sumisu caldera. (a–d) Resolvable moment tensors  
 897  $M_{res}$  for the earthquakes in (a) 1996, (b) 2006, (c) 2015, and (d) 2018 estimated by our moment  
 898 tensor analysis. The orientation of the best double-couple solution is shown by thin curves.  $M_w$   
 899 and  $k_{CLVD}$  indicate the moment magnitude of  $M_{res}$  and the dominance of the vertical-CLVD  
 900 component in  $M_{res}$ , respectively. (e) Vertical seafloor displacement computed with the best-fit  
 901 source model for the 2015 earthquake (Figure 4a). (f) Profiles of the vertical seafloor  
 902 displacement and the topography along A–B shown in e.