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# Sloshing of a bubbly magma reservoir as a mechanism of triggered eruptions

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## Abstract

Large earthquakes sometimes activate volcanoes both in the near field as well as in the far field. One possible explanation is that shaking may increase the mobility of the volcanic gases stored in magma reservoirs and conduits. Here experimentally and theoretically we investigate how sloshing, the oscillatory motion of fluids contained in a shaking tank, may affect the presence and stability of bubbles and foams, with important implications for magma conduits and reservoirs. We adopt this concept from engineering: severe earthquakes are known to induce sloshing and damage petroleum tanks. Sloshing occurs in a partially filled tank or a fully filled tank with density-stratified fluids. These conditions are met at open summit conduits or at sealed magma reservoirs where a bubbly magma layer overlays a newly injected denser magma layer. We conducted sloshing experiments by shaking a rectangular tank partially filled with liquids, bubbly fluids (foams) and fully filled with density-stratified fluids; i.e., a foam layer overlying a liquid layer. In experiments with foams, we find that foam collapse occurs for oscillations near the resonance frequency of the fluid layer. Low viscosity and large bubble size favor foam collapse during sloshing. In the layered case, the collapsed foam mixes with the underlying liquid layer. Based on scaling considerations, we constrain the conditions for the oc-

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currence of foam collapse in natural magma reservoirs. We find that seismic waves with lower frequencies  $< 1$  Hz, usually excited by large earthquakes, can resonate with magma reservoirs whose width is  $> 0.5$  m. Strong ground motion  $> 0.1 \text{ m s}^{-1}$  can excite sloshing with sufficient amplitude to collapse a magma foam in an open conduit or a foam overlying basaltic magma in a closed magma reservoir. The gas released from the collapsed foam may infiltrate the rock or diffuse through pores, enhancing heat transfer, or may generate a gas slug to cause a magmatic eruption. The overturn in the magma reservoir provides new nucleation sites which may help to prepare a following/delayed eruption. Mt. Fuji erupted 49 days after the large Hoei earthquake (1707) both dacitic and basaltic magmas. The eruption might have been triggered by magma mixing through sloshing.

*Keywords:* large earthquake, foam collapse, magma mixing, outgassing

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## 1. Introduction

An increasing number of observations have shown that volcanic eruptions can be triggered by earthquakes (e.g., Yokoyama, 1971; Nakamura, 1975; Linde and Sacks, 1998; Hill et al., 2002; Manga and Brodsky, 2006; Walter and Amelung, 2007; Eggert and Walter, 2009; Watt et al., 2009). Earthquakes may also trigger milder types of volcanic activity, for example they may enhance the heat flux at active volcanoes (Harris and Ripepe, 2007; Donne et al., 2010), increase the seismicity rate in geothermal or volcanic areas (e.g., Hill et al., 1993; Linde et al., 1994; Brodsky and Prejean, 2005; West et al., 2005), reduce the seismic velocity of crustal rocks (Battaglia et al., 2012; Brenguier et al., 2014), or cause unusual degassing (Cigolini et al., 2007; Walter et al., 2009). After the 2011 Tohoku-Oki  $M_w = 9.0$  earthquake, triggered earthquakes, sudden changes of seismicity rate and subsidence were observed in volcanic areas throughout Japan (Yukutake et al., 2011; Fujita et al., 2013; Takada and Fukushima, 2013).

Earthquakes activate volcanoes through static and dynamic stress variations (e.g., Marzocchi et al., 2002; Manga and Brodsky, 2006; Walter, 2007). Static

17 stress changes due to earthquakes originate from the permanent displacement  
18 of faults. Static stress changes decay rapidly as  $r^{-3}$  with the distance from the  
19 hypocenter,  $r$ , (Hill and Prejean, 2007). Stress changes may involve volumet-  
20 ric expansions (Walter and Amelung, 2007; Watt et al., 2009), decompressing  
21 magma reservoirs and conduits, which in turn encourages bubble nucleation and  
22 growth, potentially leading to eruptions. Static stress changes last long-term  
23 and may explain time-delayed triggering of volcanic activity at a regional dis-  
24 tance (Marzocchi, 2002; Watt et al., 2009; Chesley et al., 2012; Bonali, 2013;  
25 Bonali et al., 2013), and may even control the locations of magma rise by pres-  
26 sure localization (Nostro et al., 1998; Walter and Amelung, 2006).

27 Dynamic stress changes are originated by seismic waves and can affect vol-  
28 canoes at greater distances, as they decay as  $r^{-2}$  or  $r^{-3/2}$  for body or surface  
29 waves, respectively (Hill and Prejean, 2007). Large earthquakes are usually orig-  
30 inated by the rupture of long faults, thus the seismic waves include long-periodic  
31 components. Long-period ground motion attenuates slowly with distance, po-  
32 tentially affecting widespread areas (Koketsu and Miyake, 2008). Low frequency  
33 waves are more effective at triggering than short-period waves of comparable  
34 amplitude (Brodsky and Prejean, 2005).

35 Based on increasing evidence of volcanic unrest triggered by distant earth-  
36 quakes (e.g., Linde and Sacks, 1998; Cannata et al., 2010), several mechanisms  
37 have been proposed (e.g., Hill et al., 2002). Seismicity may favor gas bubble  
38 nucleation and growth in magmas, as experimentally shown for ground water  
39 (Crews and Cooper, 2014). Dynamic stressing may change permeability and  
40 pore pressure, which can enhance ground water mobility (e.g., Woith et al.,  
41 2003; Elkhoury et al., 2006; Manga et al., 2012; Candela et al., 2014; Hur-  
42 witz et al., 2014). Shear deformation by seismic waves may induce liquefac-  
43 tion of crystalline mush (Sumita and Manga, 2008). Ascending bubbles over a  
44 long distance in a sealed magma reservoir may increase reservoir pressure (e.g.,  
45 Steinberg et al., 1989; Sahagian and Proussevitch, 1992; Pyle and Pyle, 1995).  
46 Earthquakes seem advancing the occurrence of eruptions of volcanoes which are  
47 ready to erupt (Bebbington and Marzocchi, 2011).



48 Here, we propose that oscillation of magma contained in conduits or reser-  
49 voirs may be another potential mechanism to trigger a volcanic eruption. This  
50 mechanism is adopted from engineering sciences, where petroleum tanks may  
51 be damaged by mass oscillations of the liquid inside the tank, a mechanism  
52 known as sloshing (e.g., Ohta and Zama, 2005; Hatayama, 2008; Faltinsen and  
53 Timokha, 2009). Sloshing has been studied mainly to prevent damage on liquid  
54 tanks mounted on moving vehicles (e.g., Housner, 1957, 1963; Faltinsen and  
55 Timokha, 2009; Rebouillat and Liksonov, 2010), but similarly applies also to  
56 earthquakes (e.g., Ohta and Zama, 2005). In volcanic systems, sloshing in the  
57 Overlook crater lava lake at Kilauea excited by rockfalls has been observed by  
58 visual and seismic records (Dawson and Chouet, 2014). Transient outgassing  
59 bursts and weak explosive eruptions have also been observed after the rockfall  
60 events (Carey et al., 2013; Orr et al., 2013).

61 In general, sloshing occurs in a partially filled tank, because the fluid needs  
62 free space to move (e.g., Popov et al., 1992; Winkler, 2000; Romero et al., 2006;  
63 Thiagarajan et al., 2011). Thus, this mechanism is directly applicable to open  
64 conduit volcanic systems or a lava lake. If a magma reservoir has a layered  
65 structure, however, we hypothesize that one layer can behave as a relatively  
66 mobile space when the density and compressibility contrasts between the two  
67 layers are sufficiently large. A foam layer overlying a dense melt layer in a  
68 closed magma reservoir meets this condition. If sloshing occurs inside a magma  
69 reservoir, the surface (interface) of the magma(s) will be strained. The bubbles  
70 in the flowing magma may become interconnected so that the gas inside the  
71 bubbles can separate from the surrounding melt and escape as volcanic gases  
72 or large bubbles (Namiki, 2012; Okumura et al., 2013). Furthermore, magma  
73 deformation by sloshing may cause magma mixing through overturn, recognized  
74 as an important process to trigger eruptions (e.g., Sparks et al., 1977; Pallister  
75 et al., 1992; Viccaro et al., 2006). Here, oscillation of a layered system made  
76 of a low viscosity foam and a liquid layer has been investigated, in which an  
77 overlying foam layer does not significantly affect the resonance frequency of the  
78 lower liquid layer during oscillations, but reduces the amplitude of the interface

79 (Bronfort and Caps, 2012; Sauret et al., 2015). However, it is still unknown how  
 80 sloshing deforms bubbles in a viscous foam layer, which in turn affects the gas  
 81 separation from the surrounding liquid.

82 In this paper, we present laboratory simulations in order to better under-  
 83 stand the sloshing of a magma reservoir. We shake a fluid-filled tank horizon-  
 84 tally by using a shaking table. We vary the oscillation parameters (amplitude  
 85 of horizontal displacement  $A$  and frequency  $f$ ) and the fluid properties inside  
 86 the tank (one and two layer fluids with varying thickness ratio, viscosity, bub-  
 87 ble volume fraction, and solid particle fraction). Our experiments show that,  
 88 under certain conditions, the bubbles inside the oscillating tank collapse and  
 89 the fluids overturn. After describing our observations, we present an analytical  
 90 model characterizing the foam collapse conditions, and apply our scaling to find  
 91 parameter ranges of foam collapse in geologic situations. At the end, we discuss  
 92 the 1707 eruption of Mt. Fuji as a potential application of the sloshing model.

## 93 2. Sloshing terminology and parameters

94 We simulate the oscillation of a magma reservoir (magma chamber or vol-  
 95 canic conduit) by shaking a tank filled with viscous fluids on a shaking table  
 96 (Figure 1). When the tank undergoes externally forced oscillations, the fluid  
 97 inside the tank moves. In the following, we call this fluid motion “sway” which  
 98 has same meaning of “slosh”. We thus call the amplitude of the surface undu-  
 99 lation as “sway amplitude ( $\xi$ )” instead of “slosh amplitude” to avoid confusion  
 100 with amplitude of horizontal displacement ( $A$ ). Notations are summarized in  
 101 Table 1.

102 Housner (1957, 1963) summarized the analytical approaches of sloshing by  
 103 assessing the balance of forces. If a mass  $M$  is located inside an oscillating  
 104 tank undergoing a displacement of  $A \sin(\omega t)$ , the force acting on the mass is  
 105  $-MA\omega^2 \sin(\omega t)$ , where  $\omega = 2\pi f$  is the angular frequency, and  $t$  is the time. In  
 106 a two dimensional tank with a fluid thickness  $h$ , if a wave forms on the fluid  
 107 surface with a wave length of  $\lambda$ , the mass of the fluid in the wave becomes

108  $M \sim \rho\lambda h$ . We thus approximate the maximum force acting on a fluid parcel as  
 109  $\rho\lambda h A \omega^2$  (Figure 1).

110 The dispersion law of an inviscid fluid inside an oscillating rectangular tank  
 111 with small sway amplitude is obtained by assuming the potential flow (e.g.,  
 112 Faltinsen and Timokha, 2009),

$$\omega = \sqrt{kg \tanh(hk)} = \sqrt{g \frac{\pi n}{l} \tanh\left(h \frac{\pi n}{l}\right)}, \quad (1)$$

113 where  $k = 2\pi/\lambda$  is the wave number and  $n = 1, 2, \dots$ . We note that Eq.(1)  
 114 is based on a linear approximation for small amplitude and an inviscid fluid.  
 115 However, it is empirically known that Eq.(1) frequently explains experiments  
 116 with large sway amplitudes and viscous fluids (e.g., Faltinsen and Timokha,  
 117 2009; Sauret et al., 2015). We also verify its validity in our experiments. We  
 118 thus use this dispersion law.

119 When the frequency of the tank oscillation overlaps with the natural modes  
 120 of the fluid inside the tank, the fluid motion resonates. Swaying excites standing  
 121 waves and amplifies the fluid surface. Eq.(1) indicates that the natural modes  
 122 for the sway depend mainly on the tank shape and the liquid thickness (e.g.,  
 123 Faltinsen and Timokha, 2009).

124 Here, we consider a fundamental mode of sloshing in which  $\lambda/2 \sim l$ , where  
 125  $l$  is the width of the tank, and calculate resonance frequency as

$$f_r = \frac{1}{2\pi} \sqrt{\frac{\pi g}{l} \tanh\left(\frac{\pi h}{l}\right)}. \quad (2)$$

126 In Eq.(2), when the fluid layer is sufficiently thin ( $h \ll l$ ),  $\tanh(\pi h/l) \sim \pi h/l$   
 127 so that the resonance frequency depends on fluid thickness as  $f_r \sim \sqrt{gh}/(2l)$ .  
 128 On the other hand, for a thick fluid layer ( $h \gg l$ ),  $\tanh(\pi h/l) \sim 1$ , so that  
 129 the resonance frequency is determined by the width of the tank only,  $f_r \sim$   
 130  $1/(2\pi)\sqrt{\pi g/l}$ .

131 Similarly, the wave propagation velocity,  $c = \omega/k$ , depends on the fluid layer  
 132 thickness. For a sufficiently thin layer,  $h \ll \lambda$ ,

$$c = \sqrt{gh}. \quad (3)$$

133 Contrary, when the liquid layer is sufficiently thick,  $h \gg \lambda$ ,

$$c = \sqrt{\frac{g}{k}}. \quad (4)$$

134 In most of our experiments, the fluid fills more than half of the tank width  
 135 ( $h > l/2$ ), so that the resonance frequency becomes  $f_r > 1.73$  Hz, resulting in  
 136 resonance frequencies around  $f_r \sim 1.8$  Hz, and that for mode 2,  $f \sim 2.5$  Hz.

### 137 3. Methods

#### 138 3.1. The shaking apparatus

139 We use a shaking table (GeoSIG GSK-166) at GFZ Potsdam to impose hor-  
 140 izontal oscillations on our fluid tank with a displacement  $A \sin(\omega t)$  (Figure 1).  
 141 The displacement amplitude  $A$  and the angular frequency  $\omega$  are changed inde-  
 142 pendently. For a fixed value of displacement amplitude  $A$ , we increase  $\omega$  step  
 143 by step, then increase  $A$  and conduct the experiments with the same sequence  
 144 of frequencies. Our experiments are conducted close to the upper-limit load-  
 145 ing of the shaking table  $A\omega^2 < 1g$ , where  $g = 9.8 \text{ m s}^{-2}$ . As a result, we  
 146 cannot explore cases where both amplitude and frequency of shaking are large,  
 147 simultaneously.

148 During the shaking, we measure acceleration rates and find that  $A\omega^2$  rep-  
 149 resents the maximum measured acceleration rate (the detailed waveform of ac-  
 150 celeration depends on the location of the sensor). We thus use the theoretically  
 151 calculated acceleration rate to interpret our experiments and do not further  
 152 discuss the detailed waveform.

153 The sway of the fluids in the tank is monitored by means of two cameras.  
 154 One is a high speed camera (CASIO EXILIM EX-ZR700) with a resolution of  
 155  $512 \times 384$  at 240 frames per second (fps). This camera is fixed to the shaking  
 156 table. The other is high vision digital video camera (SONY HDR-XR150) with  
 157 a resolution of  $1920 \times 1080$  at 30 fps, fixed to the ground.

158 *3.2. The magma and magma reservoir analogue*

159 We use glucose syrup solutions as a magma analogue. By varying the wa-  
 160 ter content of the syrup solution, we change its viscosity from 0.1 Pa s to  
 161 90 Pa s, which overlaps with the viscosity of basaltic melt and sub-solidus  
 162 basaltic magma with low crystal fraction, in the range  $1 - 10^4$  Pa s (e.g.,  
 163 Ishibashi, 2009; Vona et al., 2011; Lev et al., 2012). The surface tension of  
 164 syrup solutions is estimated as similar to that of water,  $0.07 \text{ N m}^{-1}$ , and similar  
 165 to those of silicate melt  $0.01\text{-}0.1 \text{ N m}^{-1}$  (e.g., Bagdassarov et al., 2000; Man-  
 166 gan and Sisson, 2005). The density of the bubble-free syrup is approximately  
 167  $\rho = 1400 \text{ kg m}^{-3}$ .

168 We introduce bubbles in the syrup by a chemical reaction of baking soda and  
 169 citric acid, following Namiki (2012). The bubble volume fraction,  $\phi_b$ , defined  
 170 as the ratio of the total volume of bubbles to the total volume of the bubbly  
 171 fluid, is controlled by the amount of chemicals and varied in the range of  $0 \leq$   
 172  $\phi_b \leq 0.95$ . The bubble radius varies with aging within  $0.2 \leq R \leq 5 \text{ mm}$ . We  
 173 do not include volatile exsolution in our experiments during sloshing because of  
 174 technical difficulties, but discuss briefly its role in the implication section.

175 As an analogue of crystals in magma, we introduce plastic particles with  
 176 irregular shapes. The density of particles is  $1500 \text{ kg m}^{-3}$ , and their size is 0.4 -  
 177 0.6 mm. The volume fraction of particles,  $\phi_p$ , defined as the ratio between vol-  
 178 umes of particles and bubble-free liquid, which is consistent with the definition  
 179 used for crystallinity of pumice and scoria, varied in the range of  $0 \leq \phi_p \leq 0.31$ .

180 We model rigid-wall magma reservoirs by a sealed acrylic tank with a rectan-  
 181 gular shape whose dimensions of height, width, and breadth are 0.24, 0.24, and  
 182 0.09 m, respectively (Figure 1). The tank is sealed with a lid and experiments  
 183 with different filling level can simulate the different geometries; i.e., the par-  
 184 tially filled tank simulates open conduits and the fully filled tank corresponds  
 185 to closed-conduit or reservoirs. The tank is filled with one or two layers of fluids.

186 We vary the thickness of the fluid layers ( $h$ ), the liquid viscosity ( $\eta$ ), and the  
 187 bubble ( $\phi_b$ ) and particle volume fractions ( $\phi_p$ ). The experimental conditions  
 188 are classified into 3 groups:

- 189 1. One liquid layer (later labeled with the symbol  $\times$ ),  
 190 2. One foam layer without particles ( $\circ$ ) and with particles ( $\diamond$ ),  
 191 3. A two-layer system where a foam without particles overlies a liquid layer  
 192 ( $\triangle$ ) and a foam with particles overlies a liquid layer ( $\star$ ).

193 We also vary the oscillation properties of horizontal displacement ( $A$ ) and fre-  
 194 quency ( $f$ ). In total, we shake the tank under 1167 different conditions. Shaking  
 195 duration is 10 seconds under each condition in most of experiments. The ex-  
 196 perimental conditions are summarized in Table 2, 3 and in Figure 2.

#### 197 4. Description of experiments

##### 198 4.1. Experiments with one liquid layer

199 In this section we describe the basic behavior of sloshing by showing the one  
 200 liquid layer experiments (Figures 3, 4, and supplementary video 1, 2), which are  
 201 consistent with previous works (e.g., Faltinsen and Timokha, 2009). We varied  
 202 the liquid viscosity (0.1 - 14 Pa s), the liquid layer thickness (0.015 - 0.24 m),  
 203 the frequency (0.2 - 6 Hz), and the amplitude of the horizontal displacement  
 204 (3-140 mm), see Table 3a.

##### 205 4.1.1. Responses to displacement amplitudes and frequencies

206 Figures 3 shows the response of the liquid layer to different displacement  
 207 amplitudes and frequencies. During the shaking, the surface of the liquid layer  
 208 sways; i.e., a surface wave appears. As the shaking proceeds, the swaying am-  
 209 plitude increases and reaches a steady-state within 2-3 oscillations. In Figures 3  
 210 and 4, we show the undulation of the liquid surface when the surface undula-  
 211 tion becomes the maximum at the left side, after the swaying has reached the  
 212 steady-state.

213 The swaying amplitude under steady-state increases with the tank oscillation  
 214 frequency,  $f$ , and displacement amplitude,  $A$  (Figure 3). However, we observe  
 215 that after increasing the oscillation frequency to a value as high as 6 Hz with  
 216  $A = 5$  mm, the amplitude and the wave length of the sway become smaller

217 again. This occurs because the imposed frequency is much larger than the  
 218 resonance frequency of the tank fluid at the fundamental mode,  $f_r = 1.8$  Hz.  
 219 The frequency of 6 Hz is close to the higher mode of  $n = 11$ , according to Eq.(1).

#### 220 4.1.2. Thickness effect

221 The vertical column in Figure 4 shows that the behavior of the liquid layer  
 222 in an oscillating tank strongly depends on the thickness of the liquid layer ( $h$ ).  
 223 When  $h$  is small, the swaying amplitude is also small (Figure 4, bottom). We  
 224 observe the same phenomena in the range of frequency of 0.5-2 Hz.

225 When a sealed tank is almost full of fluid, the sway amplitude is negligible  
 226 as shown by two small bubbles located at the top of the tank surrounded by the  
 227 blue circle. Those change their shapes but do not migrate (Figure 4, top). The  
 228 figure also illustrates heterogeneously dispersed particles in the tank that do  
 229 not get rearranged. This is because fluids need a free space to originate sloshing  
 230 (e.g., Popov et al., 1992; Winkler, 2000; Romero et al., 2006; Thiagarajan et al.,  
 231 2011).

#### 232 4.1.3. Viscosity effect

233 The horizontal row in Figure 4 shows the viscosity dependence. The swaying  
 234 amplitude of the fluid surface becomes small for larger fluid viscosities (Figure 4,  
 235 right). In contrast when the viscosity is low enough, the surface wave breaks  
 236 (Figure 4, left).

#### 237 4.2. Experiments with one foam layer

238 In the one foam layer experiments, we vary the foam parameters, i.e., layer  
 239 thickness, bubble volume fraction and liquid viscosity, in addition to the oscilla-  
 240 tion parameters, i.e., displacement amplitude  $A$  and frequency  $f$  (see Table 3b).  
 241 We observe foam collapse in experiments with a high bubble volume fraction  
 242 ( $\phi_b = 0.79$ ) oscillating with a large displacement amplitude ( $A \geq 20$  mm) and  
 243 frequency range of  $2 < f < 3$  Hz (Figure 5) which is close to the resonance  
 244 frequency  $f \sim f_r$ .

245 Figure 5 and supplementary video 3 summarize the sequence of experiments  
 246 in which foam collapse is observed. Figure 5a shows that the response of the  
 247 foam layer ( $\phi_b = 0.79$ ) depends on  $A$  and  $f$ . With  $A = 10$  mm, the surface  
 248 fluctuations are very small for  $f = 2$  Hz and still small for  $f = 3$  Hz (Figure 5a,  
 249 left column). However,  $A = 20$  mm and  $f = 3$  Hz lead to a foam collapse  
 250 (Figure 5a, middle column). After oscillating with a larger amplitude of  $A =$   
 251 30 mm, the foam volume reduces to less than half of the initial value (Figure 5a,  
 252 right column). Figure 5b is a time evolution of foam height, and shows that,  
 253 when the imposed frequency exceeds the resonance frequency of  $f_r = 1.8$ , the  
 254 foam height begins decreasing.

255 Other experiments show the conditions preventing foam collapse (Table 3b).  
 256 When a sealed tank is full ( $h = 0.24$  m), the oscillation does not affect the  
 257 foam. This is consistent with the experiments with a full tank of liquid (Fig-  
 258 ure 4). When the liquid viscosity is large, the foam volume decreases less than  
 259 in experiments with a less viscous liquid (Figure 5). A foam layer with small  
 260 bubbles and with a lower bubble volume fraction does not collapse. We thus  
 261 infer that a smaller bubble size, lower bubble fraction, and larger viscosity also  
 262 prevent foam collapse. The effect of the particles is unclear.

### 263 4.3. Experiments with two layers

#### 264 4.3.1. Foam collapse

265 The experiments described above show that fluids in a fully filled tank do  
 266 not move and that in such cases the foam does not collapse. Yet, if there exists a  
 267 layered structure defined by density contrast in the tank, the interface between  
 268 the liquid and the foam layer can slosh. This is what we observed in a series of  
 269 experiments with foams overlying liquid layers (Table 3c).

270 An example is shown in Figure 6a1-a4 and supplementary video 4, in which  
 271 the displacement amplitudes and frequencies are increased in a stepwise fashion  
 272 similar to the experiments with one foam layer (Figure 5). The sway amplitudes  
 273 increase for larger displacement amplitudes and frequencies around  $f \sim f_r$ . This  
 274 is consistent with the one liquid layer experiments (Figure 3). For instance, the



275 deformation of the interface is small at the displacement amplitude of  $A =$   
276 3 mm and 10 mm (Figure 6a1,2), but becomes large at  $A = 20$  mm for the  
277 same frequency of  $f = 2$  Hz, resulting in the collapse of most of the foam  
278 (Figure 6a3). For  $f = 3$  Hz, the remnants of the foam, including small bubbles  
279 and particles, mix with the liquid in the lower layer. The remnants of the foam  
280 can be recognized as dark regions in the pictures (Figure 6a4). Some parts of  
281 the remnants stick against the tank wall.

282 The sequence of the foam collapse is observed in Figure 6b1. The bright  
283 region in the foam indicates that the foam has collapsed in that region. The  
284 foam collapse begins at  $A = 10$  mm. The remnant of the foam mixes with the  
285 liquid in the lower layer at frequencies of  $f > 2$  Hz.

286 The flow velocity in the lower liquid layer of these experiments are presented  
287 in Figure 7a1-a4. The velocity is calculated by particle image velocimetry, which  
288 is an image-matching method widely used to extract shape, deformation, and  
289 motion measurements (Sutton et al., 2009). The method has been applied to  
290 many laboratory experiments (Sutton et al., 2009) and terrestrial photogram-  
291 metric problems (Walter, 2011). We defined squared subsets of  $(2n+1) \times (2n+1)$   
292 pixels, selected values were large enough to contain a distinctive intensity pat-  
293 tern but small enough to achieve a sub-pixel level of accuracy, and calculated  
294 the 2-dimensional offsets of the correlation peaks in two subsequent images. Re-  
295 sults are displayed in an image vector format together with contour maps, and  
296 show the fluid velocity. Note that gray regions do not always show the repre-  
297 sentative flow velocity inside the foam. For instance, when the foam is opaque  
298 and the bubbles adhering to the tank wall do not move, the calculated velocity  
299 is quite low even if inside the foam is flowing. Similarly, the calculated velocity  
300 for a homogeneous fluid does not represent the flow velocity. In general, the  
301 calculated velocity is faster for larger displacement amplitudes and frequencies,  
302 suggesting that a rapid and large deformation of the liquid layer contributes to  
303 the foam collapse.

#### 304 4.3.2. After the foam collapse

305 Figure 6a5-a8 and b2 show the results of oscillations after the foam collapse.  
306 Similar to Figure 6a1-a4, the deformation amplitude of the interface becomes  
307 larger for larger displacement amplitude. When  $A = 20$  mm and  $f = 2$  Hz,  
308 which is close to the resonance frequency of the liquid layer, the mixing (dark)  
309 region is restricted to the right and left sides of the tank, because the surface  
310 wave is a steady wave at this frequency so that the vertical flow of the liquid is  
311 localized. In contrast, for  $f = 3$  Hz, the surface wave becomes a progressive wave  
312 and mixing occurs in the entire layer. Figure 6b2 shows that mixing reaches the  
313 deeper part of the reservoir.

314 The calculated flow velocity for these experiments are shown in Figure 7a5-  
315 a8. Similar to Figure 7a1-a4, the flow velocity becomes faster for larger displace-  
316 ment amplitudes and frequencies. The velocity around the interface is almost  
317 the same as when the foam is present under the same displacement amplitude  
318 and frequencies. We thus conclude that the existence of a foam does not affect  
319 the liquid flow significantly.

320 By varying some of the experimental conditions in other series of experiments  
321 (Table 3c), we gathered that when the liquid viscosity of the foam becomes larger  
322 and the bubble size is smaller, the foam collapse becomes difficult. This result  
323 is consistent with that of a single foam layer.

## 324 5. Summary of experimental results

325 Our experimental results show that a foam can collapse during sloshing and  
326 remnant of the collapsed foam mixes with the underlying liquid layer. If these  
327 phenomena occur in a real magma reservoir, one might speculate that the foam  
328 collapse can release volcanic gasses and trigger volcanic activities. The collapsed  
329 foam mixing with the underlying liquid can supply nucleation sites to prepare  
330 subsequent eruptions.

331 In order to apply our experimental results to real magma reservoirs, we  
332 have to describe our experimental results with non-dimensional numbers which

333 are applicable to the real magma reservoirs. We infer that foam collapse has  
 334 two requirements 1) deformation of the whole foam layer, and 2) rupture of the  
 335 individual bubble films. This is because foam collapse occurs in our experiments  
 336 when sway amplitude is large and large bubbles are surrounded by low-viscosity  
 337 liquids.

338 We thus first derive a scaling law explaining the sway amplitudes and test  
 339 it with our experimental results in Section 5.1. Next, we introduce two non-  
 340 dimensional numbers in Sections 5.2.1 and 5.2.2. Using two non-dimensional  
 341 numbers, we make a regime diagram showing the conditions for foam collapse  
 342 and test it with our experimental results in Section 5.2.3.

### 343 *5.1. A scaling law for the sway amplitude*

#### 344 *5.1.1. Sway amplitude of liquid layers*

345 Our experiments showed that the sway amplitude depends on the imposed  
 346 frequency, displacement amplitude, fluid thickness, and viscosity. This is con-  
 347 sistent with previous works (e.g., Faltinsen and Timokha, 2009). In order to  
 348 derive the scaling law, first we consider the frequency dependence and then  
 349 incorporate other parameters.

350 Figure 8 summarizes the frequency dependence of the sway amplitude mea-  
 351 sured for liquid layer experiments with respect to the normalized frequency  
 352  $f/f_r$ . The maximum sway amplitude is observed when the imposed frequency  
 353 is around the resonance frequency. This is consistent with the widely known fact  
 354 that resonance excites the fluid motion. Figure 8 also indicates that the disper-  
 355 sion law shown in Eq.(1) for an inviscid fluid and small sway amplitudes is valid  
 356 in our experiments with large viscosity liquid and sway amplitudes similarly to  
 357 experiments with a low viscosity foam (Sauret et al., 2015).

358 The sway amplitude is measured from the recorded video of the experiments.  
 359 When the sway does not reach the roof of the tank, we measured the sway  
 360 amplitudes by averaging the upward and downward deformation of the surface.  
 361 In other cases, we measured the amplitude from the downward deformation of  
 362 the surface.

363 Here, our interest is in large sway amplitudes to originating foam collapse.  
 364 We thus focus on experiments with  $f/f_r < 1.2$  in the following.

365 Next, we consider the effect of other parameters. A horizontal oscillation,  
 366  $x = A \sin(\omega t)$ , originates both vertical and horizontal flow velocities and rises  
 367 the fluid surface vertically ( $\zeta$ ), while viscous dissipation tends to decrease the  
 368 sway amplitude. From the energy balance with a viscous damping parameter  
 369 derived by Keulegan (1959), we obtained an empirical equation to explain the  
 370 measured sway amplitude excited by imposed sinusoidal oscillation of the tank  
 371 (Appendix A),

$$\zeta \sim \frac{A\omega^2\sqrt{h}}{g\left(\sqrt{\frac{\eta}{\rho^*\omega}}\right)^{1/2}} \frac{(\lambda/2)}{2\pi}, \quad (5)$$

372 where  $\rho^* = \rho$  is the density of oscillating layer, and we use  $\lambda \sim 2l$ . Note,  $\sqrt{\frac{\eta}{\rho\omega}}$  is  
 373 a length scale of viscous dissipation (e.g., Keulegan, 1959; Landau and Lifshitz,  
 374 1987), so that Eq.(5) consists of ratios of accelerations and square root of length  
 375 scales.

376 We test Eq.(5) in Figure 9. The cross and plus symbols indicate experiments  
 377 conducted with a liquid layer. Figure 9 shows that crosses and pluses are plotted  
 378 on the black line. Here, the relative position of the camera with respect to the  
 379 fluid surface originates an uncertainty, so our measurements include an error of  
 380 a factor of about two. Therefore, we interpret Figure 9 as that the amplitudes of  
 381 the surface waves as calculated by Eq.(5) reproduce well the measured amplitude  
 382 in the experiments with one liquid layer.

383 Here, we only plot experiments with  $f/f_r < 1.2$ , whose frequencies are not  
 384 significantly larger than the resonance frequency, because Eq.(5) does not take  
 385 into account the decreasing sway amplitude for  $f/f_r > 1.2$  as shown in Figure 8.  
 386 Figure 9 also does not include experiments with small top space ( $< 30$  mm),  
 387 whose sway amplitudes are affected by the lack of space at the top.

### 388 5.1.2. Sway amplitude of foam layers

389 In order to estimate the sway amplitude of a foam layer by using Eq.(5),  
 390 we should take into account the bubble fraction dependence on the physical

391 properties of foams. As a representative density, for one foam layer experiments,  
 392 the averaged foam density  $\rho^* = \rho(1 - \phi_b)$  may be appropriate. For two layer  
 393 experiments, the density difference between the liquid layer and the foam layer  
 394 may affect the sway amplitude, we thus assume  $\rho^* = \rho\phi_b$ . The viscosity of  
 395 bubbly fluid depends on shear rate. Without an estimate of the sway amplitude,  
 396 we cannot obtain shear rate as well as foam viscosity. Here, the foam viscosity  
 397 varies within one order of magnitude, and can be scaled with liquid viscosity,  
 398 (e.g., Mader et al., 2013). We thus use liquid viscosity as a reference. In Eq.(5),  
 399 the sway amplitude is not sensitive to density and viscosity,  $\zeta \propto (\rho^*/\eta)^{(1/4)}$ . An  
 400 error of one order of magnitude in the estimate of viscosity or density results in  
 401 an error in the estimate of sway amplitude less than a factor of two.

402 Calculated sway amplitudes are plotted in Figure 9, solid circles, diamonds,  
 403 triangles, and stars indicate experiments with a foam layer. For two layer exper-  
 404 iments the y-axis shows the measured fluctuation of the interface. The measured  
 405 fluctuations are smaller than the predictions.

406 This discrepancy may be related to the opacity of the foam. In our three  
 407 dimensional experiments, we only can observe the deformation of opaque foam  
 408 close to the tank wall, and may underestimate the deformation. An alternative  
 409 explanation is that, for the two layer experiments, foam deformation needs an  
 410 extra force which is not included in Eq.(5). Indeed, it has been reported that a  
 411 thick foam layer overlying a low viscosity layer ( $\eta \sim 10^{-3}$  Pa s) in a quasi-two  
 412 dimensional tank reduces the sway amplitude (Sauret et al., 2015). Here, the  
 413 bubbles close to the tank walls have had a significant impact on the damping  
 414 of sloshing. In contrast, our experiments are conducted in a three dimensional  
 415 tank.

416 In order to identify the source of this discrepancy, we calculate the flow  
 417 velocity in Figure 7, and find that the flow velocity around the interface does  
 418 not show a clear dependence on the existence of the foam. This result suggests  
 419 that the measured sway amplitude around the wall is smaller than that inside  
 420 the tank. We also note that the deformed foam can collapse before reaching the  
 421 estimated sway amplitude and use the energy. We thus conclude that Eq.(5)

422 explains some trends of sway amplitude. In Figure 9, the effect of particles is  
423 not obvious.

## 424 5.2. Non-dimensional foam collapse conditions

### 425 5.2.1. Strain of a foam layer

426 First, we consider the strain of a foam layer as a non-dimensional parameter.  
427 This idea is based on previous shear deformation experiments (e.g., Namiki,  
428 2012; Okumura et al., 2013). Under shear deformation, foam collapse occurs  
429 when the strain in the foam exceeds a critical value.

430 The strain originating in a foam by sway can be calculated as:

$$\frac{\zeta}{h_f}, \quad (6)$$

431 where  $h_f$  is the thickness of the foam; i.e.,  $h_f = h$  for the one layer foam  
432 experiments, and  $h_f = h_{\text{upper}}$  for two layer experiments. Here we use  $\zeta$  defined  
433 in Eq.(5), so that Eq.(6) for foams will be a maximum estimate.

### 434 5.2.2. Non-dimensional bubble strength

435 Next, we consider non-dimensional number describing the deformation of a  
436 distinct bubble. In order to deform bubbles, the inertia force acting on each  
437 bubble originated by the oscillations should exceed the viscous resistance.

438 If an isolated bubble is surrounded by a uniform fluid, the inertia force ( $F_i$ )  
439 acting on the bubble during a sinusoidal oscillation can be written as (e.g.,  
440 Housner, 1957):

$$F_i = \Delta\rho A\omega^2 \left( \frac{4}{3}\pi R^3 \right), \quad (7)$$

441 where  $R$  is the bubble radius,  $A\omega^2$  is the acceleration, and  $\Delta\rho$  is the density  
442 difference between the fluid and gas inside the bubble. We here assume that a  
443 homogeneous foam surrounds each bubble, so that  $\Delta\rho = \rho(1 - \phi_b)$ .

444 The viscous force ( $F_v$ ) to deform the membrane surrounding a bubble can  
445 be written as:

$$F_v = \eta_f \omega \delta R, \quad (8)$$

446 where  $\eta_f$  is the viscosity of the liquid surrounding the bubbles,  $\delta$  is the thickness  
 447 of the membrane surrounding the bubble with a length scale of a bubble size.  
 448 Assuming that bubbles of the same size are distributed uniformly in the foam,  
 449  $\delta$  is estimated as

$$\delta = R \left( \frac{1}{\phi_b^{1/3}} - 1 \right). \quad (9)$$

450 The ratio of these two forces becomes:

$$\frac{F_i}{F_v} = \frac{\frac{4}{3}\pi\Delta\rho A\omega R}{\eta_f(\phi_b^{-1/3} - 1)}. \quad (10)$$

451 Eq.(10) indicates that a foam with larger bubbles and a larger bubble volume  
 452 fraction in a less viscous liquid collapses more easily.

### 453 5.2.3. Regime diagram

454 We here test two non-dimensional numbers described in Eq.(6) and Eq.(10)  
 455 with our experimental results. We plot the occurrence of foam collapse in Fig-  
 456 ure 10 using these two non-dimensional numbers. When the foam thickness  
 457 decreases more than approximately 5 mm after the shaking, we classify the  
 458 experiments as 'collapse'.

459 Figure 10 shows that when  $\zeta/h_f > 1$  and  $F_i/F_v > 1$ , foam collapse occurs.  
 460 Even for  $\zeta/h_f < 1$  foam collapse occurs, when  $F_i/F_v \gg 1$ . The black line  
 461 of  $F_i/F_v = (\zeta/h_f)^{-9/4}$ , divides the regimes of foam collapse well, whose slope  
 462 may originate from the angular frequency dependence of  $\zeta$  in Eq.(5). We thus  
 463 conclude that foam collapse is controlled by these two non-dimensional numbers.  
 464 Note that this scaling can explain the collapse of foams in both a single-foam  
 465 layer and a foam layer overlying a liquid layer.

466 Despite that  $\zeta/h_f$  is a maximum estimate (Figure 9),  $\zeta/h_f$  explains the  
 467 threshold well. Again, we infer that the foam is opaque and the deformation of  
 468 its inside is larger than that observed from the wall as we discussed based on  
 469 Figure 7.

470 Figure 10 also shows that the threshold of the foam collapse does not depend  
 471 on the presence of the particles. We infer that the particles used in these experi-  
 472 ments are sufficiently small not to make a density anomaly to enhance the foam

473 collapse by oscillation. Because of the technical limitations of the shaking table,  
474 we could not conduct experiments in the regime of  $\zeta/h_f > 1$  and  $F_i/F_v < 1$ .

## 475 6. Implications for triggering of eruptions

476 In Section 5, we described the conditions for foam collapse by sloshing in a  
477 regime diagram using two non-dimensional numbers (Figure10). In this section,  
478 we apply our experimental results to natural magma reservoirs. We first consider  
479 the geometries of reservoir to resonate with seismic waves (Section 6.1). Next,  
480 we calculate possible strain of magma foams and strength of bubbles in magmas  
481 to constrain the conditions for magma foam collapse (Sections 6.2). We then  
482 summarize the phenomena possibly occurring in magma reservoirs (Section 6.3).  
483 Finally, we apply our scaling to Mt. Fuji 1707 eruption as a specific example  
484 (Section 6.4).

### 485 6.1. Resonance frequencies of magma reservoirs

486 While the details of the dynamics of sloshing are difficult to calculate theoret-  
487 ically due to many unknowns in natural volcanoes such as a conduit or reservoir  
488 geometry and density gradient within the magma reservoir, it is possible to  
489 assess, based on simple scaling considerations.

490 The natural frequencies of sloshing for a fluid layer depend on the ratio of  
491 the thickness and width of the layer ( $h/l$ ). The analytical estimates and exper-  
492 iments show that, for a rectangular and conduit-like upright circular cylindrical  
493 tank, the resonance frequency increases with the thickness of the fluid layer  
494 and approaches an asymptotical value (Faltinsen and Timokha, 2009). This is  
495 because the resonance frequency is determined by the ratio ( $c/l$ ) of the wave  
496 propagation velocity ( $c$ ) and the width of the tank ( $l$ ). For a thin fluid layer  
497 ( $h \ll \lambda$ ) the wave velocity increases with its thickness ( $c = \sqrt{gh}$ ), as discussed  
498 with Eq.(3), but for a sufficiently thick layer ( $h \gg \lambda$ ) the wave velocity becomes  
499 independent from the fluid thickness ( $c = \sqrt{g\lambda}$ ) as discussed with Eq.(4). For a  
500 constant width tank, the resonance frequency approaches an asymptotical value



501 with increasing fluid thickness. This is the condition in our experiments using  
 502 fixed dimensions.

503 In Figure 11, the fundamental mode of resonance frequencies of a rectangular  
 504 magma reservoir is calculated by using Eq.(2) as a function of various liquid  
 505 thickness and reservoir widths. The tinted region indicates the frequency ranges  
 506 of seismic waves (e.g., Koketsu and Miyake, 2008; Psimoulis et al., 2014). The  
 507 frequency of 1 Hz is commonly observed while lower frequencies are observed  
 508 only for larger earthquakes or soft ground regions. An extraordinarily large  
 509 earthquake ( $\geq M 9$ ) may excite seismic waves with lower frequency components  
 510 ( $< 0.05$  Hz).

511 Figure 11 shows that vertically elongated magma reservoirs are likely to re-  
 512 sonate with seismic waves. A narrow volcanic conduit,  $l < 10$  m, can resonate  
 513 with seismic waves irrespective of its vertical extension. The conduit diame-  
 514 ter at active basaltic volcanoes is generally estimated as several meters (e.g.,  
 515 Kazahaya et al., 1994; Burton et al., 2007), and their height is greater than  
 516 width. Magmas at shallow depth in such a conduit can resonate with seismic  
 517 waves with frequencies of 0.3 – 1 Hz. The fact that seismic waves with fre-  
 518 quency components  $< 1$  Hz can resonate with magma reservoirs is consistent  
 519 with the observation that long-period waves are more effective at triggering than  
 520 comparable amplitude short-period waves (Brodsky and Prejean, 2005).

521 Some magma reservoirs are shaped as horizontal sills. Typical horizontal  
 522 sizes may be from a few hundreds of meters to tens of kilometers (e.g., Marsh,  
 523 2015). For a horizontally elongated magma reservoir, a width of  $l \sim 200$  m is a  
 524 maximum scale to resonate with seismic waves. An approximately rectangular  
 525 or large cylindrical magma reservoir whose horizontal size exceeds  $l \geq 1$  km is  
 526 usually difficult to resonate. Therefore, resonance is to be more expected in  
 527 conduit-like reservoirs rather than in extended chambers.

528 When the magma reservoir has a shape of vertical disk or a spherical cham-  
 529 ber, the resonance frequency depends on the filling level (Mciver, 1989; Faltinsen  
 530 and Timokha, 2009). This is because the length scale of free surface for wave  
 531 propagation ( $l$ ) becomes shorter for a fully filled reservoir. Even a large chamber

532 with a size of  $l \sim 1$  km at an intermediate depth may be able to resonate with  
 533 seismic waves, if its filling level is high.

534 In a solidifying magma reservoir, phenocrysts exist in a silicate melt. If  
 535 the magma is a crystal mush in which volume fraction of phenocrysts are close  
 536 to the random closed packing fraction, the crystal mush behaves like a solid  
 537 (e.g., Mader et al., 2013) and then sloshing is unlikely to occur. If a core with  
 538 lower viscosity in the reservoir exists in a crystal mush, it will likely oscillate  
 539 by sloshing (Bachmann and Bergantz, 2008). We consider that the inertial  
 540 effect of phenocrysts is negligible, because the density contrast between the  
 541 melt and phenocrysts is smaller than that between the bubbles and melt, which  
 542 is observed in our experiments.

#### 543 *6.2. Conditions leading to magma foam collapse*

544 Here, we estimate the possible sway amplitudes in a magma reservoir, and  
 545 roughly estimate the conditions for foam collapse. In order to calculate  $\zeta$  defined  
 546 in Eq.(5), we have to estimate  $\omega$  and  $A$ .

547 For angular frequency  $\omega$ , we use the resonance frequency  $\omega = 2\pi f_r$  defined  
 548 in Eq.(2). If the magma reservoir has a vertically elongated conduit-like shape,  
 549 the sway occurs only in the shallow region. In this case, the width of the conduit  
 550 determines the wavelength of the sway, in turn the wave length regulates the  
 551 depth of the flow, so that  $l \sim \lambda/2 \sim h$ .

552 The horizontal tank displacement ( $A$ ) consists with the ground displacement  
 553 during real earthquakes. Ground motions are frequently measured by velocity  
 554 rather than displacement, and ground velocity is estimated by  $v_g = A\omega$ . We thus  
 555 calculate the sway amplitude ( $\zeta$ ) for arbitrary ground displacement amplitudes  
 556 ( $A$ ), and plot it as a function of ground velocity ( $v_g$ ).

557 In Figure 12, the largest sway amplitude is obtained for the blue thick line,  
 558 suggesting that the sway amplitude becomes larger for less viscous magmas in a  
 559 larger reservoir. During a strong earthquake, the observed velocity of the ground  
 560 can exceed  $1 \text{ m s}^{-1}$  (Koketsu and Miyake, 2008). The viscosity of pre-eruptive  
 561 basaltic melt is  $1 - 10^3 \text{ Pa s}$  (Takeuchi, 2015). For a strong ground motion with

562 a velocity of  $1 \text{ m s}^{-1}$ , basaltic magma in a conduit several meters wide generates  
 563 a sway amplitude of 1 m. If a thin ( $< 1 \text{ m}$ ) foam layer exists above a melt layer,  
 564 the foam plausibly collapses. When the foam has large bubbles, a foam layer  
 565  $\zeta/h_f < 1$  can collapse (Figure 10).

566 The foam strength is evaluated by Eq.(10) and depends on  $A\omega$ , which has  
 567 a dimension of velocity. Again, we approximate the ground velocity  $v_g \sim A\omega$ .  
 568 Figure 13 shows calculated thresholds of foam strength  $F_i/F_v = 1$ . When the  
 569 liquid viscosity of the foam is sufficiently low ( $\eta_f < 10 \text{ Pa s}$ ) and the bubble  
 570 size is sufficiently large ( $R > 1 \text{ mm}$ ), a seismic wave with large ground velocity  
 571  $v_g > 0.1 \text{ m s}^{-1}$  may destroy the foam. A bubble size of  $R > 1 \text{ mm}$  has  
 572 been observed in erupted scoriae (e.g., Mangan and Cashman, 1996; Lautze  
 573 and Houghton, 2007). Foams with more viscous magma can collapse when the  
 574 bubbles are larger and ground velocity of the seismic wave is faster. Note that  
 575 low-frequency seismic waves (periods of 10 to 30 s) possibly causing triggered  
 576 activities are more likely Love- and Rayleigh- surface waves than body waves.  
 577 The vertical component associated with Rayleigh waves may also contribute to  
 578 induce fluid motion. Indeed, vertical shaking also causes surface undulation  
 579 known as Faraday instability (e.g., Faraday, 1831; Bronfort and Caps, 2012).

### 580 6.3. Possible scenarios in magma reservoir

581 We present a conceptual model illustrating the conditions necessary for a  
 582 magma reservoir to be affected by sloshing as well as the outcome the process  
 583 may have (Figure 14).

584 Open conduits at volcanoes (e.g. lava lakes, summit conduits), which con-  
 585 tain low-viscosity magma with a free surface, or alternatively magma reservoirs  
 586 where a foam layer has accumulated below the roof, are possible candidates for  
 587 sloshing-induced degassing. The filling fraction of the magma reservoir affects  
 588 the sloshing dynamics significantly. If a vacant space is present above the foam  
 589 layer, the surface of the foam undulates. Even when the magma reservoir is  
 590 filled up, a layered structure where a foam layer overlies a dense melt layer  
 591 may allow sloshing. On the other hand, when the magma reservoir is filled up

592 by a uniform foam or a liquid layer, the fluid inside the tank does not move  
593 (Figure 4).

594 When sloshing occurs and the energy supplied by the seismic waves is suf-  
595 ficiently large, the bubbles in the foam deform to be interconnected, and then  
596 foam collapses. The conditions required for the foam collapse are summarized in  
597 Figure 10. Low viscosity both for the foam and dense layer favor foam collapse  
598 (Figure 12 and 13). A seismic wave with significant energy at the resonance  
599 frequency is efficient in originating large sway amplitudes.

600 After foam collapse, some part of volcanic gases separate from the surround-  
601 ing melt and obtain mobility. At a top of an open conduit, a foam collapse  
602 increases the injection of volcanic gasses into the atmosphere. Similarly, if a  
603 closed reservoir connects to the surface of the earth by narrow cracks, in which  
604 the viscous foam cannot ascend, the released gasses from the foam can get  
605 through the crack to be fumaroles because of their low viscosity. The escape  
606 of gases to the outside of the reservoir decompresses the inside of the reservoir,  
607 stimulating further volatile exsolution. If there exist sufficient amount of bub-  
608 bles in the melt, the exsolved volatiles diffuse into preexisting bubbles rather  
609 than nucleate new bubbles, so that the bubble sizes increase. Given that larger  
610 bubbles easily deform, bubble growth can cause further foam collapses.

611 This could result in unusual outgassing (Cigolini et al., 2007; Walter et al.,  
612 2009), which in turn enhances the heat flux (Harris and Ripepe, 2007; Donne  
613 et al., 2010). Indeed, the Overlook crater lava lake in Kilauea shows transient  
614 outgassing bursts and weak explosive eruptions after rockfalls (Orr et al., 2013;  
615 Carey et al., 2013) which likely excite sloshing (Dawson and Chouet, 2014).

616 Foam collapse may also supply large bubbles into a conduit to originate  
617 gaseous eruptions such as Strombolian eruption (e.g., Jaupart and Vergnolle,  
618 1988). The ascending bubble inside a closed reservoir increases pressure and  
619 may also trigger an increase of seismicity (Linde et al., 1994; West et al., 2005).

620 When the shaking continues for long time after the collapse of a foam layer,  
621 the remnant of the foam including phenocrysts and small bubbles mixes with  
622 the lower layer. Once the lower layer is saturated with volatiles, the bubbles

623 and phenocrysts transported into the lower layer provide new nucleation sites  
624 for additional exsolution of volatiles. The following vesiculation pressurizes the  
625 inside reservoir to cause additional volcanic activity, including eruptions. This  
626 mechanism takes time and can explain delayed triggered eruptions. Mixing  
627 between the injected hot basalt and overlying silicic magma has been frequently  
628 pointed out as a trigger of a big eruption (e.g., Pallister et al., 1992; Murphy  
629 et al., 2000). Usually, newly injected basalt is heavier than overlying silicic  
630 magma. The mechanism of mixing is not obvious. Our experiments show that  
631 a strong seismic wave can mix density stratified magmas and favor vesiculation.

632 The duration of the oscillation also affects the occurrence of foam collapse.  
633 In our experiments we impose oscillations for 10 seconds which is shorter than  
634 the typical duration of strong ground motion (e.g., Anderson, 2007). The oscilla-  
635 tion duration of natural earthquakes is likely long enough to collapse magmatic  
636 foams. This is especially true for large earthquakes followed by aftershocks,  
637 which also may contribute to elongate the oscillation duration. Also, the me-  
638 chanical and thermal softening of a volcano may lead to secondary earthquake  
639 and enhance the resonance.

640 As we have discussed above, it is likely that magma foams collapse by slosh-  
641 ing, and trigger eruptions. However, the causal link between a triggering earth-  
642 quake and a putative triggered response is always ambiguous. Most proposed  
643 mechanisms for earthquake-volcano triggering, although physically rigorous, re-  
644 main very speculative when applied to specific cases, due to the difficulty to link  
645 univocally the complex processes leading to an eruption to geophysical measure-  
646 ments. The magma reservoir sloshing we propose does not make exception. We  
647 next estimate the possible parameter sets to consider whether the occurrence of  
648 sloshing can be recognized by observations.

649 A seismic wave at 0.5 Hz can resonate with a 3 m wide conduit (Figure 11). If  
650 we assume the amplitude of the seismic wave displacement is 0.1 m, the velocity  
651 of the ground motion is  $0.3 \text{ m s}^{-1}$ , which is a reasonable assumption. Ground  
652 displacement amplitudes of about 0.1 m may originate from the shaking due  
653 to an M 6 earthquake in the epicentral region, an M 6.5 at 10 km distance or

654 an M 7.5 at 100 km. If a basaltic magma with a viscosity of 1 Pa s fills the  
 655 conduit, the seismic waves may cause a sway amplitude of 1 m (Figure 12). If  
 656 there exists a basaltic foam layer whose thickness is 1 m, a bubble radius of  
 657 100  $\mu\text{m}$ , a bubble volume fraction is  $> 0.6$  and the surrounding melt viscosity  
 658 is 1 Pa s, the foam collapses (Figure 13). If the bubble radius is larger, thicker  
 659 foam layers can collapse (Figures 10). These conditions can be easily achieved  
 660 at active basaltic volcanoes, but cannot for inactive volcanoes.

661 In this case, the sloshing energy is calculated as  $E_p \sim \rho g \zeta^2 l^2 / \pi \sim 7 \times 10^4 \text{ J}$   
 662 by Eq.(13), where we assume the density of magma as  $2500 \text{ kg m}^{-3}$ . Given  
 663 that a M 0.0 earthquake releases an energy of about 60 KJ, we see that the  
 664 resonance could be measurable if the source locates at shallow depth with a  
 665 very good network. Of course, the waves would not be very impulsive and the  
 666 focal mechanism (assuming that it could be calculated) would not be double  
 667 couple but complex, due to the sloshing hitting back and forth.

668 When the Rayleigh waves of a triggering earthquake reach a volcano and  
 669 cause resonance in a magma reservoir, this could be seen both by broad band  
 670 seismometers and high-frequency strain meters. We predict that around the  
 671 sloshing frequency, the amplitude of oscillation would increase over a few cycles  
 672 in stations close to the upper volcano conduit, or around the volcanic edifice  
 673 if the reservoir is deep, while they would just register the earthquake shaking  
 674 at stations far away. Of course, the seismic waves originated by the magma  
 675 sloshing on the chamber or conduit walls are quickly dissipated around it, so  
 676 the stations need to be very close to register the resonance. How close could  
 677 be estimated by converting the sloshing energy in one cycle into seismic energy  
 678 and then into equivalent moment or magnitude.

679 In any case, to test the above flow chart with real volcanoes, we need to  
 680 know the pre-eruptive conditions in the magma reservoir; i.e., melt viscosity and  
 681 bubble sizes. Especially, the shape of the magma reservoir is a key parameter  
 682 for sloshing but is not well constrained, usually.

683 *6.4. An application to Mt. Fuji*

684 Now, we apply our model to the 1707 Mt. Fuji Hiei eruption, which occurred  
685 49 days after the Hiei earthquake. Both eruption and earthquake are well  
686 studied. Because of this short time interval after the Hiei earthquake, a causal  
687 relation has been suggested, (e.g., Yokoyama, 1971; Nakamura, 1975).

688 The Hiei eruption began with a Plinian eruption of dacite magma and de-  
689 veloped into a basaltic Plinian eruption, which was uncommonly explosive as  
690 a basaltic eruption (e.g., Miyaji et al., 2011). Because of this transition in  
691 magma composition, more than two magma sources and their mixing has been  
692 suggested (e.g., Fujii et al., 2002; Kaneko et al., 2010; Miyaji et al., 2011).  
693 During the transition, the SiO<sub>2</sub> content changed gradually and the measured  
694 bubble fraction in the pumices and scoriae became low (Miyaji et al., 2011).  
695 Available seismic tomographies show two velocity anomalies below current Mt  
696 Fuji. One is a low- $V_P$ , low- $V_S$  and low- $V_P/V_S$  anomaly at depths of 7-17 km  
697 in which deep low-frequency (DLF) earthquakes are observed, suggesting exis-  
698 tence of fluids, such as H<sub>2</sub>O and CO<sub>2</sub>. Another locates beneath it, a low- $V_P$ ,  
699 low- $V_S$  and high- $V_P/V_S$  anomaly at depths of 15-25 km that may represent a  
700 zone of basaltic partial melt (Nakamichi et al., 2007). This deeper anomaly is  
701 also electrically conductive (Aizawa et al., 2004).

702 Based on these observations of the current state of Mt. Fuji, it has been  
703 suggested that two vertically separated magma reservoirs existed before the  
704 Hiei earthquake. The static stress changes associated with the Hiei earthquake  
705 is estimated in which the normal stresses are reduced at shallow (< 8 km)  
706 depth and increased at 20 km depth (Chesley et al., 2012). As a result, basaltic  
707 magma located in the deeper magma reservoir began ascending. An injection  
708 of basaltic magma into the upper silicic magma reservoir caused magma mixing  
709 (Fujii et al., 2002; Miyaji et al., 2011). Magma mixing associated with the  
710 Hiei earthquake is also supported by the observation of plagioclase phenocrysts  
711 originated from dacite magma found in basaltic scoriae. Based on the reverse  
712 zoning of MgO profiles in the plagioclase phenocrysts, the time duration after  
713 the magma mixing until eruption is estimated to be less than 49 days (Aruga

714 et al., 2015).

715 However, a simple mixing cannot explain the observed low bubble fraction  
716 during the compositional transition from dacite to basaltic magmas (Miyaji  
717 et al., 2011). The silicic melt inclusions hosted by olivine phenocrysts in the  
718 scoriae suggest that basaltic magma coexisted with silicic magma (Kaneko et al.,  
719 2010). In addition, the depth of the magma chamber before the Hoei eruption  
720 is not necessarily the same as the current ones.

721 We thus conjecture that sloshing might have taken place, according to the  
722 following scenario (Figure 15a). 1) Dacite magma was cooling in a magma  
723 reservoir. Phenocrysts were growing so that the exsolved volatiles were forming  
724 bubbles. Long waiting times allowed bubbles to grow large in size with a high  
725 gas volume fraction. 2) Hot basaltic magma was gradually injected beneath  
726 the bubbly dacite magma foam, creating a density stratified structure. The  
727 melt viscosity of the dacite foam close to the interface was reduced by the  
728 heating from the underlying basaltic magma. 3) The Hoei earthquake shook the  
729 magma reservoir. The sway of the interface between the basalt and dacite layer  
730 deformed the bubbles in the dacite foam layer, inducing foam collapse. Part of  
731 the collapsed foam including the plagioclase phenocrysts and dissolved volatiles  
732 mixed with the lower basaltic layer. The basaltic layer was invaded by nucleation  
733 sites and the volatiles vesiculated. 4) The gas released from the collapsed foam  
734 ascended through the dacite layer, pressurizing the magma reservoir (Steinberg  
735 et al., 1989; Sahagian and Proussevitch, 1992; Pyle and Pyle, 1995). The newly  
736 nucleated bubbles in the basalt layer increased the volume of the magma in the  
737 reservoir. Lowered normal stress might have prompted the additional input of  
738 basaltic magma. These effects and/or a strong aftershock eventually triggered  
739 the eruption. 5) The magmas erupted out from the top of the reservoir. First,  
740 un-deformed dacite foam erupted out with high volume fraction of bubbles,  
741 next the collapsed dacite layer with a low bubble fraction, and then an andesite  
742 magma which may be a mixed basalt and dacite followed. Finally, an explosive  
743 eruption of basalt magma with high bubble fraction occurred. This scenario  
744 is consistent with observations (Fujii et al., 2002; Kaneko et al., 2010; Miyaji



745 et al., 2011).

746 In Figure 15b, we estimate the possible parameters involved in this process.  
 747 The estimated magnitude of the Hoei earthquake has a wide range from M 8.4  
 748 to close to M 9, but a recent estimate of tsunami heights suggests approxi-  
 749 mately a M 9.0 earthquake (e.g., Furumura et al., 2011; Ishibashi, 2004; Hyodo  
 750 et al., 2014). Assuming M 9.0, the size of the source region had an extent of  
 751  $\sim 400$  km length and  $\sim 150$  km width and a slip displacement of 20 m (Hyodo  
 752 and Hori, 2013). The Mt. Fuji locates at 350 km from the epicenter. Thus,  
 753 the displacement amplitude of the seismic wave at Mt. Fuji is estimated as the  
 754 order of 1 m. Assuming that the rupture of the fault travels 150 km at S wave  
 755 velocity of  $5 \text{ km s}^{-1}$ , the frequency of the waves could have been as low as  
 756 0.03 Hz which can resonate a large magma reservoir of 1 km size (Figure 11).  
 757 The erupted volume of the Hoei eruption is estimated as  $1.6 \text{ km}^3$  (Miyaji et al.,  
 758 2011). We assume that the newly injected basalt was water rich and at high  
 759 temperature ( $> 1200 \text{ }^\circ\text{C}$ ) so that the melt viscosity was 1 Pa s. The lines in  
 760 Figure 15b show the combination of bubble radius and foam thickness to be  
 761  $F_i/F_v = (\zeta/h_f)^{(-9/4)}$ , the threshold of foam collapse shown by the black line in  
 762 Figure 10. The difference of the line color indicates the dacite viscosity. The  
 763 typical pre-eruptive dacite viscosity is  $10^3 - 10^4$  Pa s. Here, the silicate melt  
 764 viscosity is sensitive to temperature rather than  $\text{SiO}_2$  content (Takeuchi, 2015).  
 765 As discussed above, the underlying hot basaltic magma heated up the overlying  
 766 dacite magma, lowering its viscosity to values of  $10^2 - 10^3$  Pa s. If the bubble  
 767 radius in the foam layer is as large as 1 mm, which is a reasonable assumption,  
 768 10 m thick dacite foam layer could have collapsed.

769 Thus, sloshing-induced foam collapse and magma mixing can explain the  
 770 characteristics of the Mt. Fuji Hoei eruption with a reasonable combination of  
 771 parameters.

772 **7. Conclusions**

773 We conducted shaking experiments of viscous liquid and foams to simulate  
774 the sloshing in a magma reservoir induced by earthquakes. Our experimental  
775 results show that when there is a vacant space or density heterogeneities in the  
776 experimental tank, external oscillation induces sway of the fluid. Resonance  
777 may occur depending on the fluid layer shape, with the sway amplitude be-  
778 coming large around the resonance frequencies. When the fluid inside the tank  
779 includes bubbles, the sway of the fluid may deform the bubbles until the bubble  
780 films rupture and the foam collapses. The collapsed foam may mix with the  
781 underlying liquid layer.

782 Based on our experimental results, we conclude that the parameters critical  
783 for the plausibility of this process are: the geometry of the magma reservoir  
784 or conduit, the density structure of the magma within the reservoir or conduit,  
785 the gas bubble size and fraction in the foams, and the melt viscosity. Seismic  
786 waves of frequency  $> 1$  Hz are unlikely to induce resonance, because they would  
787 require conduits of width  $< 0.5$  m, which are thermally short-lived. Seismic  
788 waves with  $\sim 1$  Hz can collapse less viscous ( $< 10^3$  Pa s) basaltic magma foams  
789 with large bubbles (1 mm) in a conduit with several meters width. In order  
790 to oscillate magmas in a larger reservoir, seismic waves with lower frequency  
791 typical of large earthquakes are required. Once a larger reservoir without less  
792 internal obstructing walls resonates, the moving mass of fluid may become large,  
793 resulting in a more severe sloshing.

794 The volcanic gas released from the collapsed foam can increase the out-  
795 gassing and heat flux, or may generate a large slug to cause Strombolian erup-  
796 tion. Further oscillation mixes the collapsed foam with the underlying melt  
797 layer to prepare a following eruption. These experimental results are applied  
798 to natural systems and help to explain the mechanism of triggered eruptions in  
799 a near field as well as far field. Results are consistent with the fact that only  
800 very few eruptions are triggered and that only some volcanoes respond to large  
801 earthquakes. The Hiei eruption of Mt. Fuji might be an example of a triggered

802 eruption by sloshing, and serve as a well-studied case example that is applicable  
 803 elsewhere as well.

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## 811 Appendix. A: Sway amplitude

812 The elevation of the liquid surface  $\zeta$  should be determined by the energy  
 813 balance (Keulegan, 1959; Faltinsen and Timokha, 2009; Sauret et al., 2015).  
 814 During the sloshing, viscous dissipation reduces the sway amplitude. This effect  
 815 is defined theoretically and measured by the decrease of sway amplitude after  
 816 an impulse excitation

$$\langle \dot{E} \rangle \sim \alpha \omega E_p / \pi \quad (11)$$

817 where  $\langle \dot{E} \rangle$  is the energy dissipation over one cycle, and  $\alpha$  indicates the damping  
 818 by viscous dissipation (Keulegan, 1959; Faltinsen and Timokha, 2009).

$$\alpha \propto \sqrt{\frac{\eta}{\rho \omega}} \frac{1}{l}. \quad (12)$$

819 The potential flow energy within one wave length in a cycle of two-dimensional  
 820 flow is

$$E_p \sim \rho g \zeta^2 / k. \quad (13)$$

821 In our experiments, the fluid-filled tank is oscillated repeatedly. Some part

822 of the energy input dissipates to determine the sway amplitude.

$$E_t \propto \langle \dot{E} \rangle / \omega \propto \alpha E_p, \quad (14)$$

823 where the energy input by the tank oscillation in a cycle of two-dimensional flow  
824 is

$$E_t \sim \rho A^2 \omega^2 h l. \quad (15)$$

825 Assuming the thick fluid layer,  $\sqrt{k} \sim \omega / \sqrt{g}$ , and we obtain

$$\zeta \propto \frac{A \omega^2 \sqrt{h l}}{g \left( \sqrt{\frac{\eta}{\rho \omega}} \right)^{1/2}}. \quad (16)$$

826 In Eq.(5), we determined the prefactor  $1/(2\pi)$  by the fitting the experimental  
827 data.

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Table 1: Notations.

Parameter	Unit	Description
$A$	m	Amplitude of the horizontal displacement of the tank
$c$	$\text{m s}^{-1}$	Wave propagation velocity
$f$	Hz	Frequency
$f_r$	Hz	Resonance frequency defined in Eq.(2)
$F_i$	N	Inertia force acting on a bubble defined in Eq.(7)
$F_v$	N	Viscous force acting on a bubble membrane defined in Eq.(8)
$g$	$\text{m s}^{-2}$	Gravitational acceleration
$h$	m	Thickness of the liquid layer
$h_f$	m	Thickness of the foam layer
$k$	$\text{rad m}^{-1}$	Wave number
$l$	m	Width of the tank
$M$	kg	Mass of the shaking fluid
$n$	-	Positive integer
$R$	m	Bubble radius
$t$	s	Time
$v_g$	$\text{m s}^{-1}$	Ground velocity
$\delta$	m	Thickness of bubble membrane defined in Eq.(9)
$\eta$	Pa s	Viscosity
$\eta_f$	Pa s	Liquid viscosity of foam
$\lambda$	m	Wavelength
$\omega$	$\text{rad s}^{-1}$	Angular frequency
$\phi_b$	-	Volume fraction of bubble
$\phi_p$	-	Volume fraction of particles
$\rho$	$\text{kg m}^{-3}$	Density of liquid
$\rho^*$	$\text{kg m}^{-3}$	Effective density determining $\zeta$ used in Eq.(5)
$\zeta$	m	Amplitude of free surface wave (sway amplitude)
$\zeta/h_f$	-	Strain of the foam layer

Frequency	Amplitude	acceleration	a/g
0.1	1.00E-03	3.94E-04	4.02E-05
0.3	1.00E-03	3.55E-03	3.62E-04
1	1.00E-03	3.94E-02	4.02E-03
3	1.00E-03	3.55E-01	3.62E-02
10	1.00E-03	3.94E+00	4.02E-01
0.1	3.00E-03	1.18E-03	1.21E-04
0.3	3.00E-03	1.06E-02	1.09E-03
1	3.00E-03	1.18E-01	1.21E-02
3	3.00E-03	1.06E+00	1.09E-01
10	3.00E-03	1.18E+01	1.21E+00
0.1	1.00E-02	3.94E-03	4.02E-04
0.3	1.00E-02	3.55E-02	3.62E-03
1	1.00E-02	3.94E-01	4.02E-02
3	1.00E-02	3.55E+00	3.62E-01
10	1.00E-02	3.94E+01	4.02E+00
0.1	3.00E-02	1.18E-02	1.21E-03
0.3	3.00E-02	1.06E-01	1.09E-02
1	3.00E-02	1.18E+00	1.21E-01
3	3.00E-02	1.06E+01	1.09E+00
10	3.00E-02	1.18E+02	1.21E+01
0.1	1.00E-01	3.94E-02	4.02E-03
0.3	1.00E-01	3.55E-01	3.62E-02
1	1.00E-01	3.94E+00	4.02E-01
3	1.00E-01	3.55E+01	3.62E+00
10	1.00E-01	3.94E+02	4.02E+01

Table 2: Experimental conditions for all experiments. Table 2b indicates the symbol colors in Figures.

$$*: \phi_b = \text{Volume}_{\text{bubble}} / \text{Volume}_{\text{total}}$$

$$*: \phi_p = \text{Volume}_{\text{particle}} / (\text{Volume}_{\text{liquid}} + \text{Volume}_{\text{particle}})$$



Frequency	Amplitude	acceleration	a/g
0.1	1.00E-03	3.94E-04	4.02E-05
0.3	1.00E-03	3.55E-03	3.62E-04
1	1.00E-03	3.94E-02	4.02E-03
3	1.00E-03	3.55E-01	3.62E-02
10	1.00E-03	3.94E+00	4.02E-01
0.1	3.00E-03	1.18E-03	1.21E-04
0.3	3.00E-03	1.06E-02	1.09E-03
1	3.00E-03	1.18E-01	1.21E-02
3	3.00E-03	1.06E+00	1.09E-01
10	3.00E-03	1.18E+01	1.21E+00
0.1	1.00E-02	3.94E-03	4.02E-04
0.3	1.00E-02	3.55E-02	3.62E-03
1	1.00E-02	3.94E-01	4.02E-02
3	1.00E-02	3.55E+00	3.62E-01
10	1.00E-02	3.94E+01	4.02E+00
0.1	3.00E-02	1.18E-02	1.21E-03
0.3	3.00E-02	1.06E-01	1.09E-02
1	3.00E-02	1.18E+00	1.21E-01
3	3.00E-02	1.06E+01	1.09E+00
10	3.00E-02	1.18E+02	1.21E+01
0.1	1.00E-01	3.94E-02	4.02E-03
0.3	1.00E-01	3.55E-01	3.62E-02
1	1.00E-01	3.94E+00	4.02E-01
3	1.00E-01	3.55E+01	3.62E+00
10	1.00E-01	3.94E+02	4.02E+01

Table 3: Experimental conditions for specific experiments.

Figure 1: A schematic diagram of the experimental apparatus. A fluid tank with width  $l$  above a shaking table is horizontally oscillated with a time ( $t$ ) dependent displacement of  $A \sin(\omega t)$ . Oscillations generate the surface undulation  $\zeta$ . We call  $\zeta$  as sway amplitude.

Figure 2: Experimental conditions. (a) Imposed frequencies and fluid layer thickness for one-layer experiments and lower layer thickness for two layer experiments. Different symbols indicate the fluid layer types, cross is liquid one layer, circle is one layer of foam without particles, diamond is one layer of foam with particles, triangle is a foam layer without particles overlies a liquid layer, and star is a foam layer with particles overlies a liquid layer. The color of the symbols represents the liquid viscosity. For two layer experiments, the color of the symbols represent the viscosity of lower layer (Table 2b). Symbol size is proportional to the amplitude of the imposed displacement; smaller symbols indicate the smaller  $A$ . (b) Foam conditions. X-axis indicates the liquid viscosity of the foam and Y-axis indicates the volume fraction of bubbles in the foam. Color and shape of symbol are the same as those for (a). Size of symbol indicates the bubble size in the foam; larger symbols indicate larger bubbles. Filled symbols indicate that the foam volume decreases after shaking.

Figure 3: Digital photographs of a liquid layer in a sinusoidally oscillating tank  $A \sin(2\pi ft)$  with various displacement amplitudes,  $A$  and frequencies,  $f$ . Photographs are taken after 10 seconds of oscillation and when the left side surface becomes maximum height. Green region is the liquid with viscosity of 1 Pa s whose initial thickness is 0.15 m. The resonance frequency calculated by Eq.(2) is  $f_r = 1.8$  Hz. Images are taken by a video camera off the shaking table with a speed of 30 fps.

Figure 4: Same as Figure 3 but showing the dependence on the liquid viscosity and thickness of the liquid layer at  $A = 30$  mm and  $f = 2$  Hz. Experimental conditions are summarized in Table 3. The resonance frequency of this tank calculated by Eq.(2) for the thin layer experiment is 0.8 Hz, and  $f_r = 1.7 - 1.8$  Hz for other experiments. In the thin liquid layer experiment, right side of the image is behind of camera on the shaking table. The liquid with different viscosity is dyed with different colors for visualization.

Figure 5: (a) Same as Figure 3 but for a foam layer with particles in the sinusoidally oscillating tank with various displacement amplitudes,  $A$  and frequencies,  $f$ . Dark region is the foam whose liquid viscosity is 1 Pa s and initial thickness is 0.21 m. Experiments are performed in the order of increasing frequencies  $f = 0.7, 0.8, 0.9, 1, 1.2, 1.5, 2, 2.5, 3$  Hz for  $A = 10$  mm, at the same set of frequencies for  $A = 20$  mm, and then  $0.5 \leq f \leq 2.7$  Hz with increment of 0.1 Hz for  $A = 30$  mm. The resonance frequency of this foam layer calculated by Eq.(2) is  $f_r = 1.8$  Hz. (b) Time evolution of the surface height within the range of white lines in (a) for the experiments with  $A = 30$  mm and a time span of 4.3 minutes. Time increases to the right. X-axis labels indicate imposed frequencies. Oscillation is imposed during 10 seconds at each frequency. Vertical lines indicate the quiescent time. The vertical fluctuations include both spatial and temporal changes, because the original images for this picture are taken from a fixed camera on the ground.

Figure 6: (a) Same as Figure 5a but for a two-layer system. Experimental conditions are summarized in Table 3c. We first shake two layers: an upper foam layer with particles and a lower liquid layer (a1-a4, b1). After the collapse of the upper foam, we shake the tank again with the same set of amplitude and frequency oscillations (a5-a8, b2). The reddish violet region is the foam whose liquid viscosity is 10 Pa s and initial thickness is 0.07 m. The green region indicates the liquid layer whose viscosity is 1 Pa s and initial thickness is 0.17 m. Amplitude and frequency of oscillation are changed as labeled in (b). The resonance frequency of the lower liquid layer calculated by Eq.(2) is  $f_r = 1.8$  Hz. (b) Same as Figure 5b but for Figure 6a: time evolution of the horizontally averaged interface within the range of white lines in (a) for a time span of 6.6 minutes. (b1) shows the collapse of the foam by shaking and (b2) shows the oscillations of the liquid layer after the collapse of the upper foam layer.

Figure 7: Flow velocity of Figure 6a1-a8 calculated by the image correlation method. Images are taken from the camera on the shaking table at low angle with a frame rate of 240 per second, so that the downward interface between the liquid/foam or liquid/air is observed as shown in the original images at the left. White boxes on the images show the region in which velocity is calculated. Arrows indicate the flow direction and color shows the velocity. The calculated slow velocity in gray region sometimes does not show the real flow velocity (see text). The intensity difference in gray region indicates the original still images. The interface between the foam and liquid layer is traced manually for reference but it has width as shown in the original images at the left.

Figure 8: Measured maximum sway amplitudes of liquid layer experiments for each condition as a function of the imposed frequency normalized by resonance frequency. The resonance frequency is calculated by using Eq.(2). The color of symbols represent the liquid viscosity (Table 2b). The plus and crosses indicate whether the sway reaches the roof of the tank or not, respectively.

Figure 9: Measured amplitude of the surface wave as a function of the calculated amplitude by Eq.(5). Experiments performed with a liquid layer are denoted by plus and cross, in which plus indicates that the sway reaches the roof of the tank. Other solid symbols are the same as Table 2; circle is one layer of foam without particles, diamond is one layer of foam with particles, triangle is foam layer without particles overlies a liquid layer, and star is foam layer with particles overlies a liquid layer. The color of symbols represents the liquid viscosity. The black line indicates the slope 1. We plot experiments with frequencies of  $f/f_r < 1.2$ . For one-layer experiments, we do not plot experiments without a top free space.

Figure 10: Regime diagram of the foam collapse as a function of strain and force ratio defined by Eqs.(6) and (10). Solid and open symbols indicate occurrence and no occurrence of foam collapse, respectively. Other characteristics of symbols are the same as Table 2, in which shapes indicate the foam types and color indicates the liquid viscosity of the lower layer. Experiments in which the tank is fully filled with a single foam layer are excluded from this figure. The black line indicates  $F_i/F_v = (\zeta/h_f)^{-9/4}$ .

Figure 11: Contour curves showing resonance frequencies (in Hz) of magma reservoirs as a function of its height  $h$  and width  $l$  calculated by Eq.(2). Pink to blue region indicates the higher to lower frequency range of seismic waves possibly excited by smaller and larger earthquakes, respectively. Ordinal seismic waves  $> 1$  Hz do not resonate with conduits or dikes wider than  $> 0.5$  m, suggesting that only large earthquakes can cause sloshing. The red dashed line indicates  $h \sim l$ . Green region indicates the dimensions of magma reservoirs.

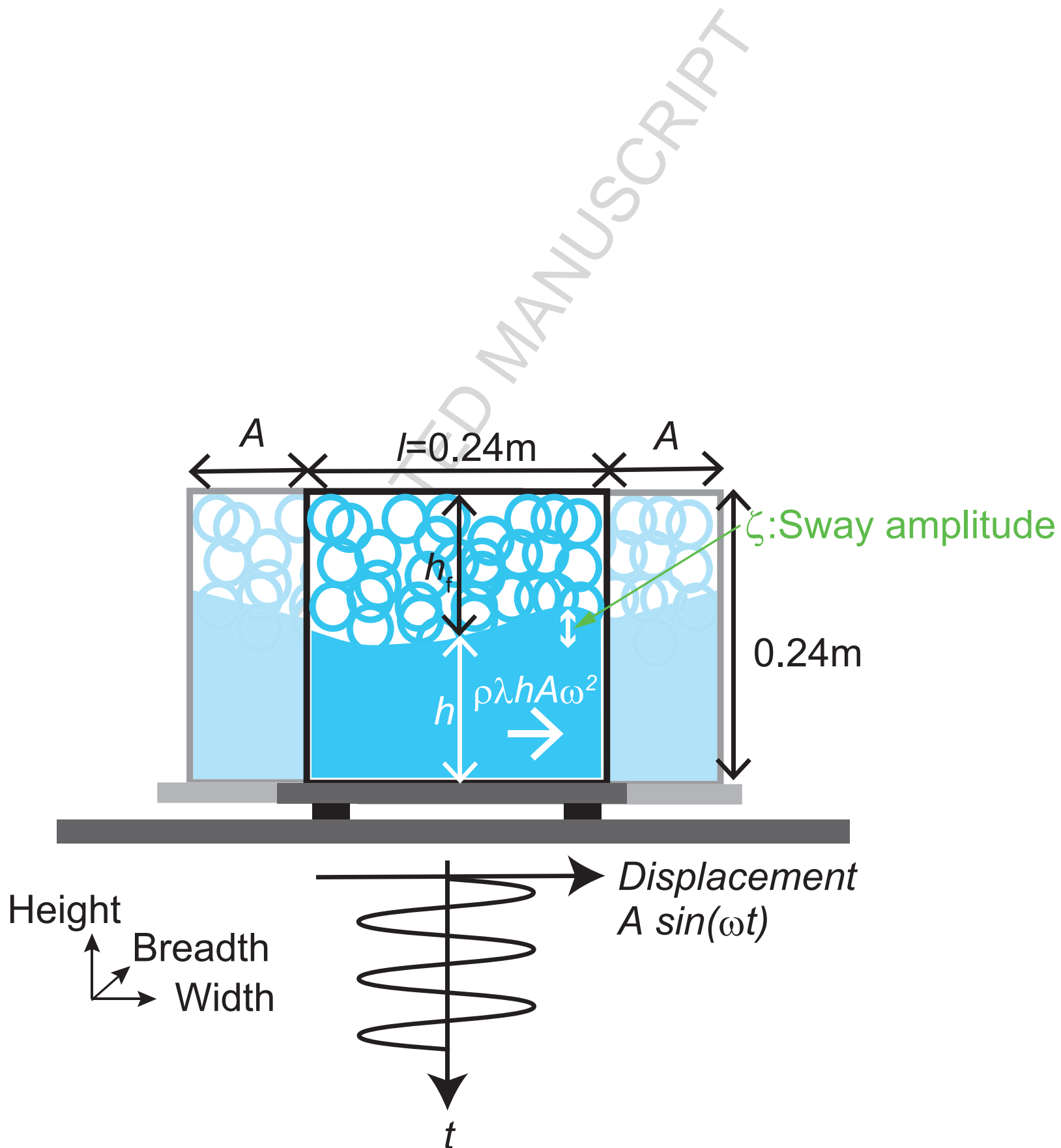
Figure 12: Calculated sway amplitudes by Eq.(5) in a magma reservoir with a condition of  $l \sim \lambda/2 \sim h$  as a function of the ground velocity  $v_g = A\omega$ . A foam layer thinner than  $\zeta$  can collapse. The line color and thickness indicate the viscosity and conduit width, respectively. The resonance frequency is calculated by Eq.(2) and  $l = 1$  m: 0.9 Hz,  $l = 10$  m: 0.3 Hz,  $l = 100$  m: 0.09 Hz for each conduit width.

Figure 13: Contour lines of  $F_i/F_v = 1$  calculated by Eq.(10). Above each line, foams can collapse by oscillation of the magma reservoirs. Line color indicates the melt viscosity of the foam. The line type shows the bubble fraction; solid and dotted line indicates  $\phi_b = 0.6$  and  $\phi_b = 0.8$ , respectively. The black lines are references for a bubble radius of  $R \sim 10^{-3}$  m, and a seismic wave velocity of  $1 \text{ m s}^{-1}$ , respectively.

Figure 14: A flow chart of a magma reservoir oscillation. When seismic waves strongly shake a magma reservoir which has a space above a magma foam or have a density stratification, sloshing can occur. If the energy supplied by the seismic waves is sufficiently large, the foam collapses. The foam collapse releases volcanic gas, which results in unusual degassing. The collapsed foam mixes with the underlying fresh magma layer to prepare following eruption.

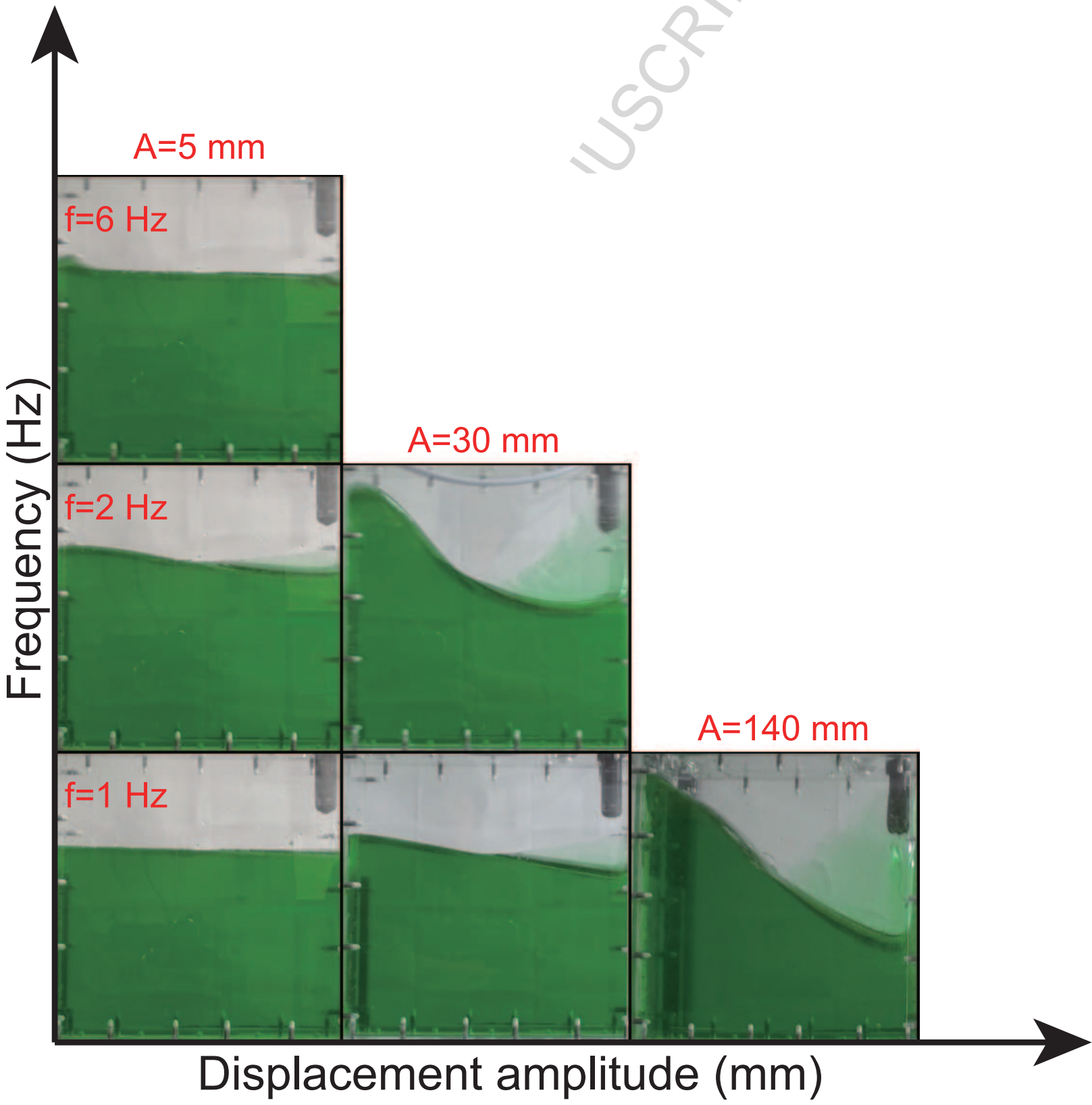
Figure 15: (a) Schematic diagram of possible settings before the 1707 Mt. Fuji eruption. We consider that high temperature basaltic magma with viscosity of 1 Pa s locates beneath a dacite magma foam with a bubble volume fraction of 0.8 in a reservoir whose width is  $l = 1$  km. Resonance frequency of the magma reservoir calculated by Eq.(2) is 0.03 Hz. (b) Foam collapse conditions, when a seismic wave with a displacement amplitude of  $A = 1$  m oscillates this reservoir as a function of foam thickness and bubble radius. The color shows the liquid viscosity of the upper layer foam.

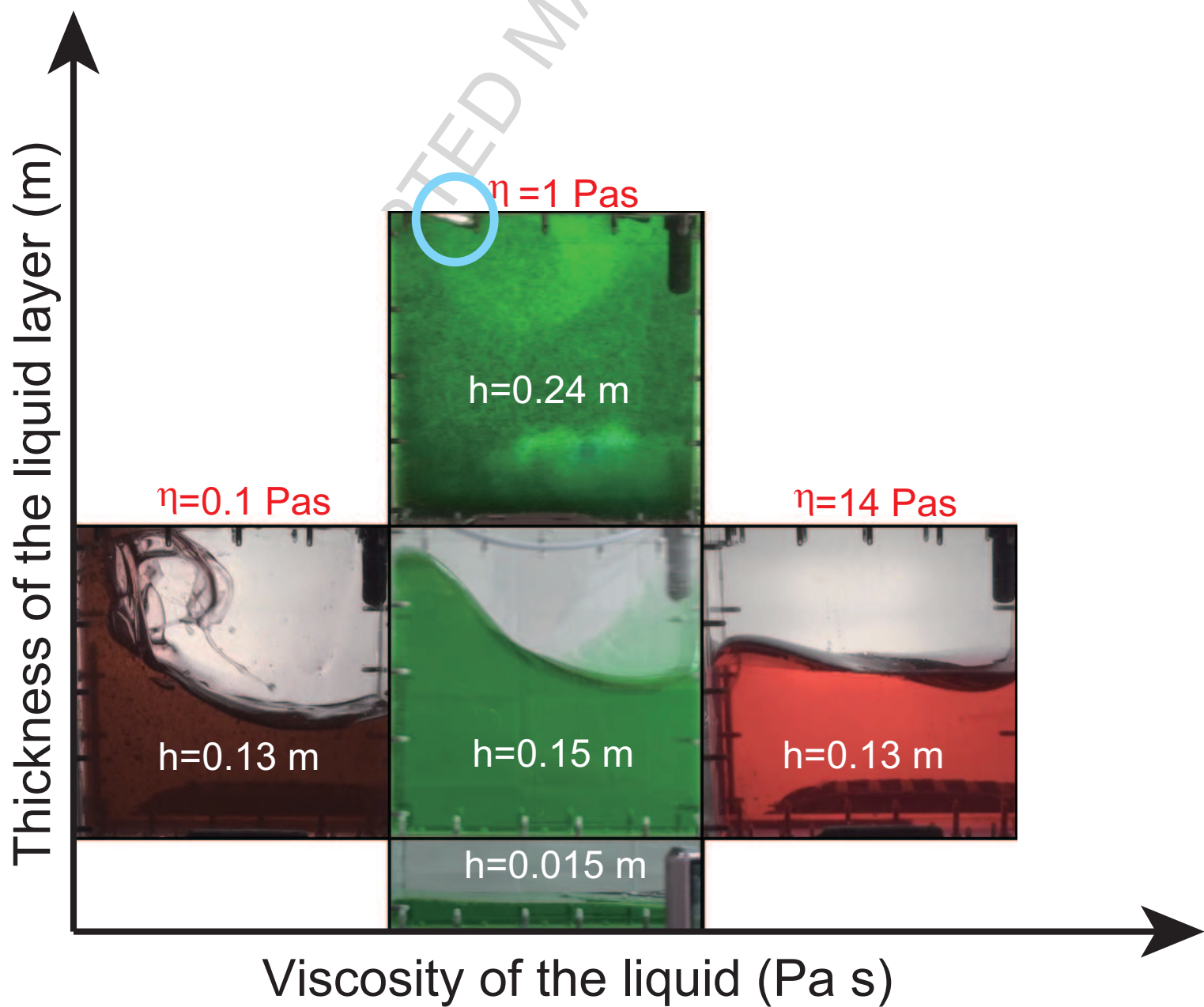
Figure 1

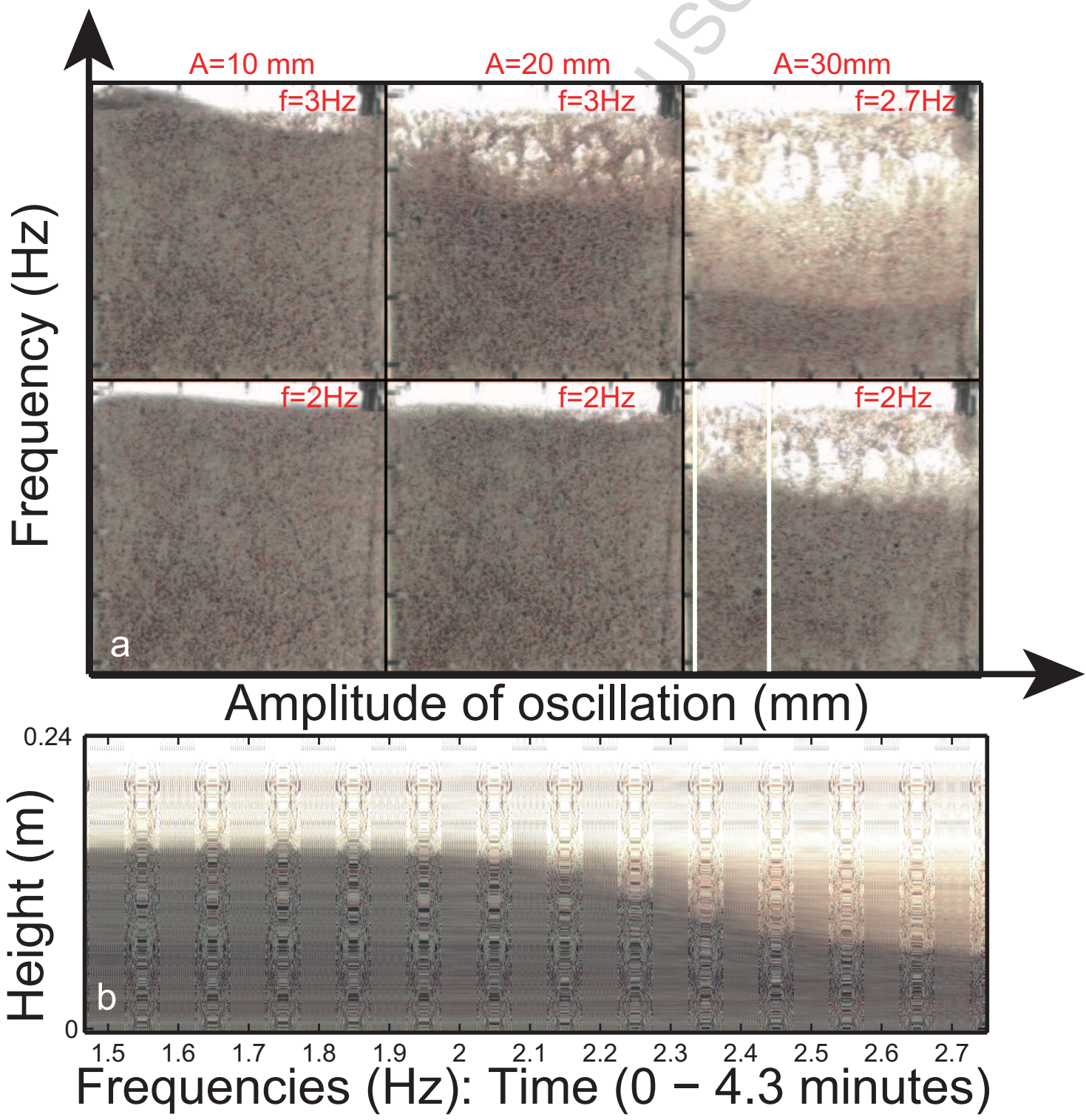






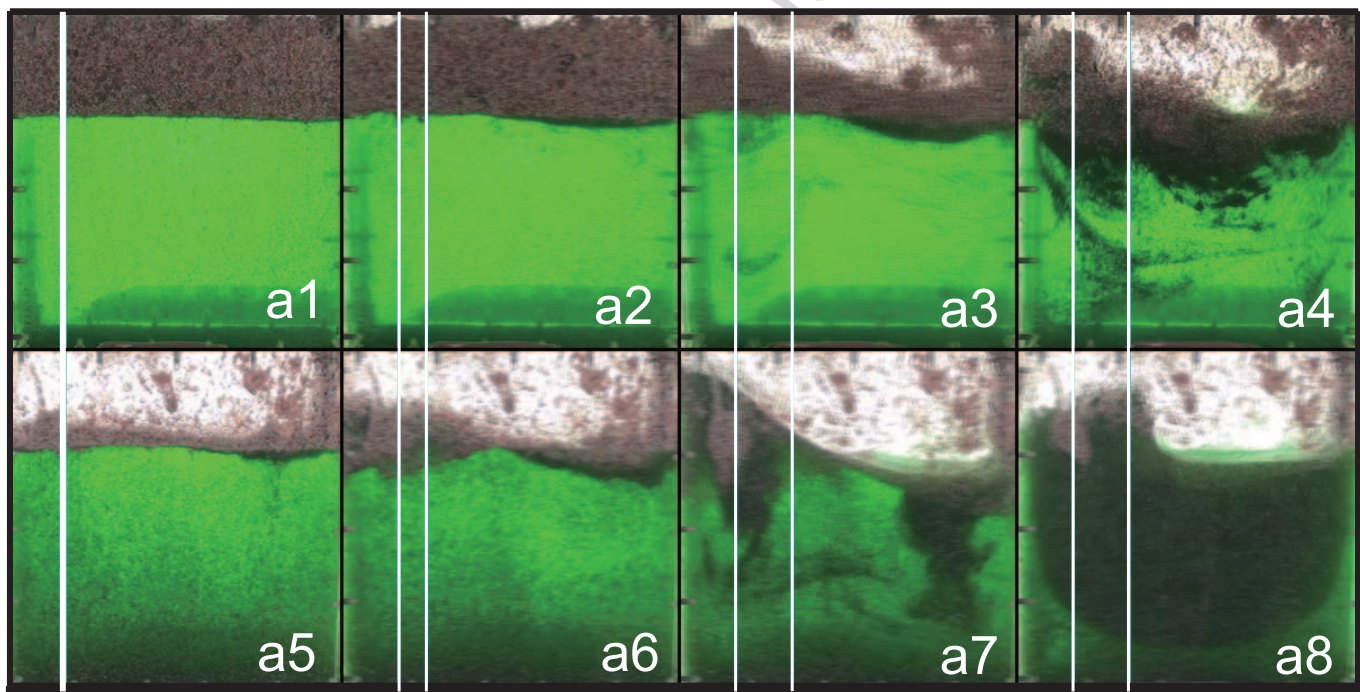




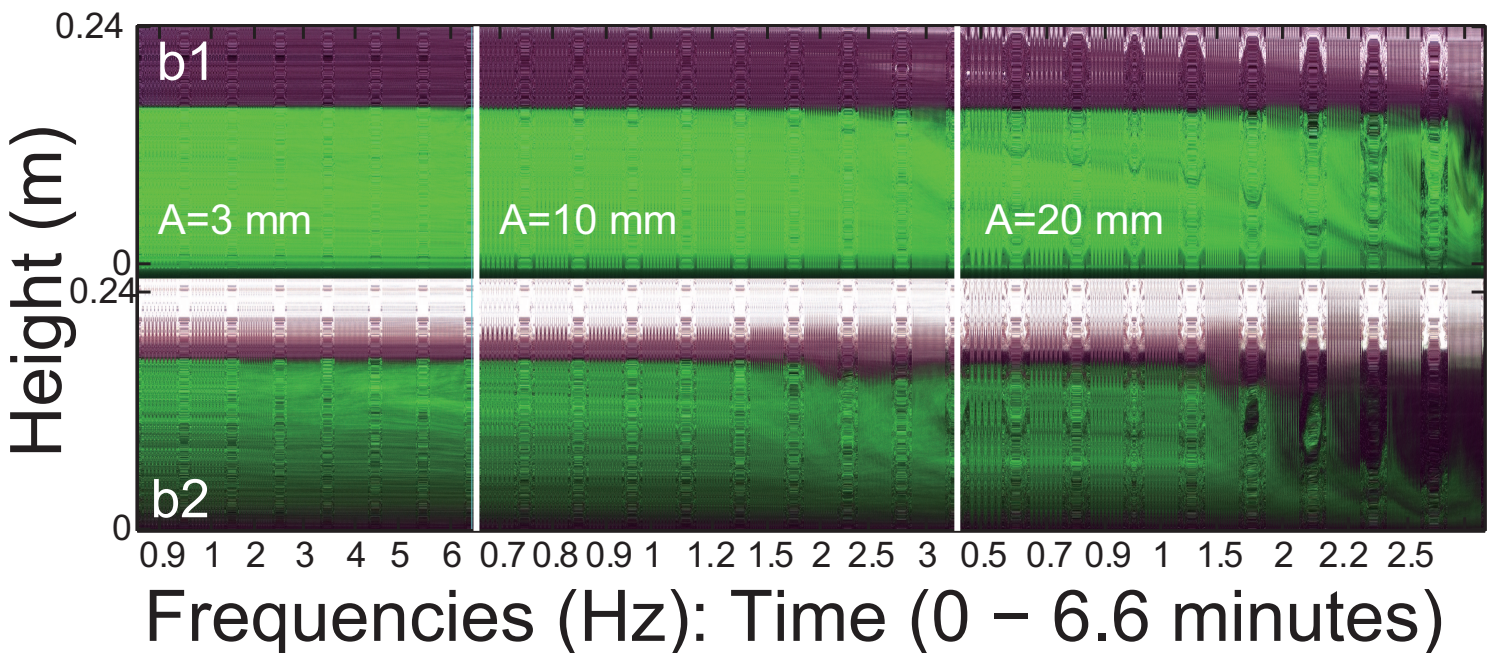


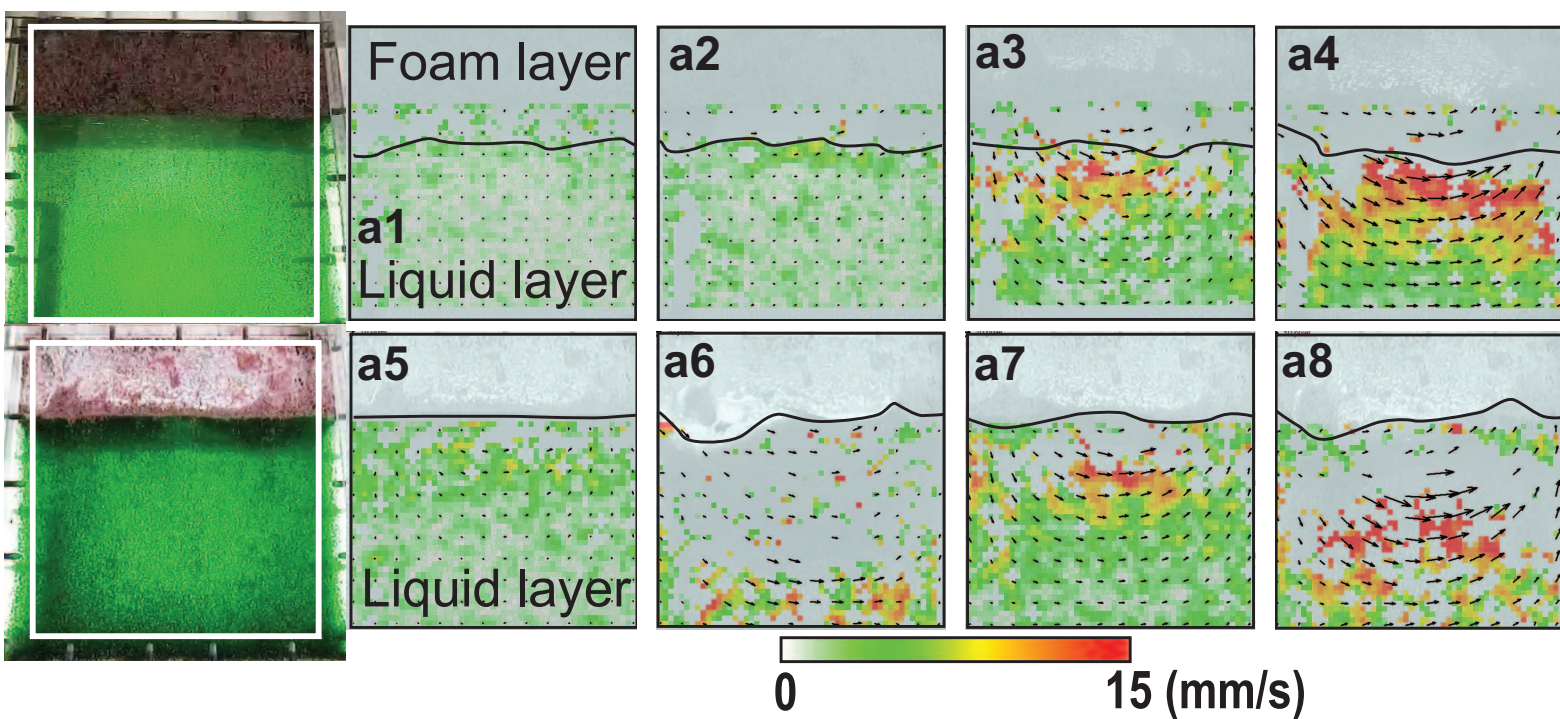


$A=3\text{ mm}, f=2\text{Hz}$ :  $A=10\text{ mm}, f=2\text{Hz}$ :  $A=20\text{ mm}, f=2\text{Hz}$ :  $A=20\text{ mm}, f=3\text{Hz}$



Time, Amplitude and Frequency





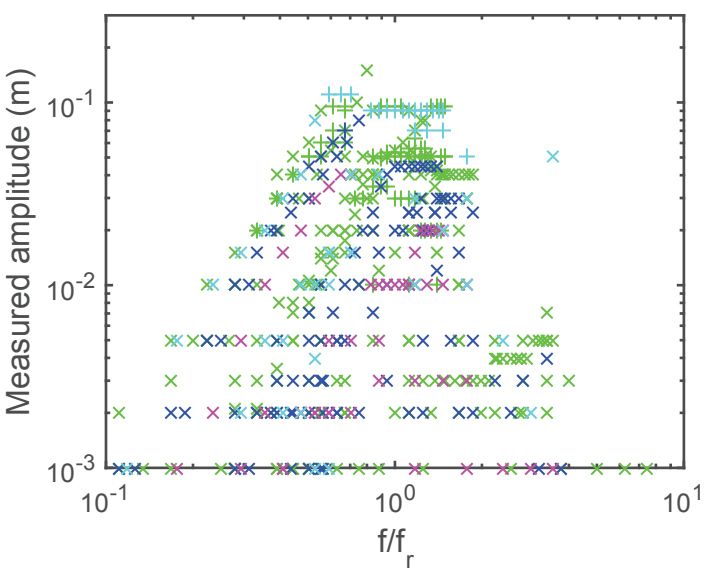


Figure 9

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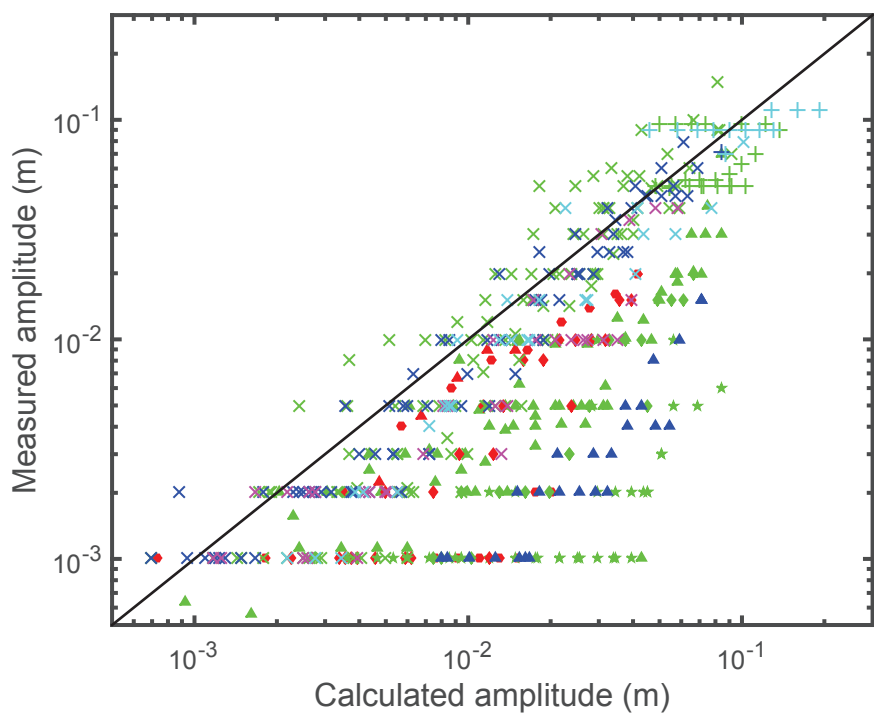
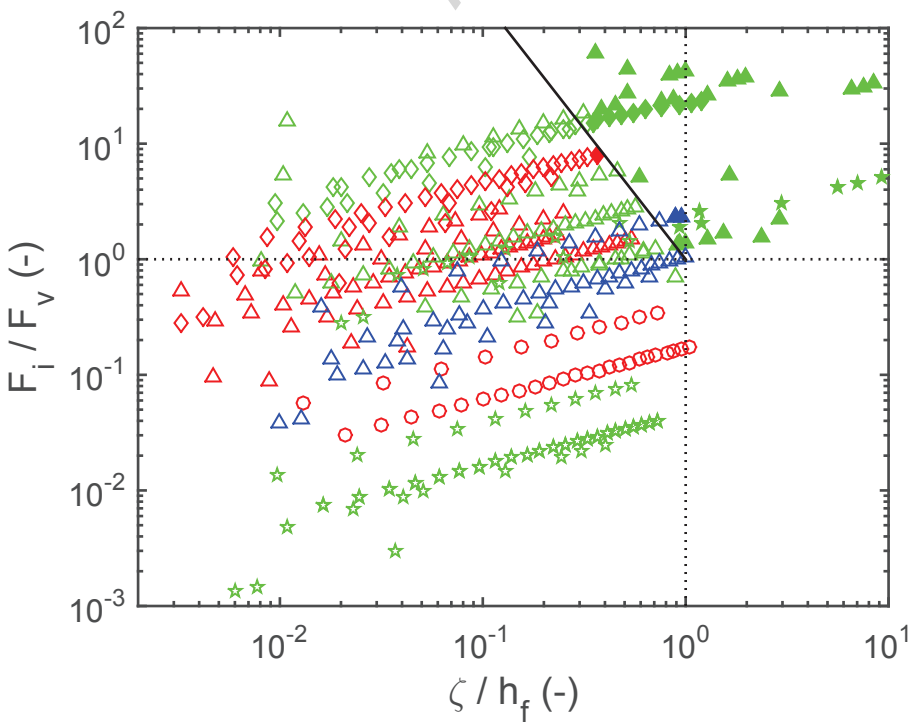
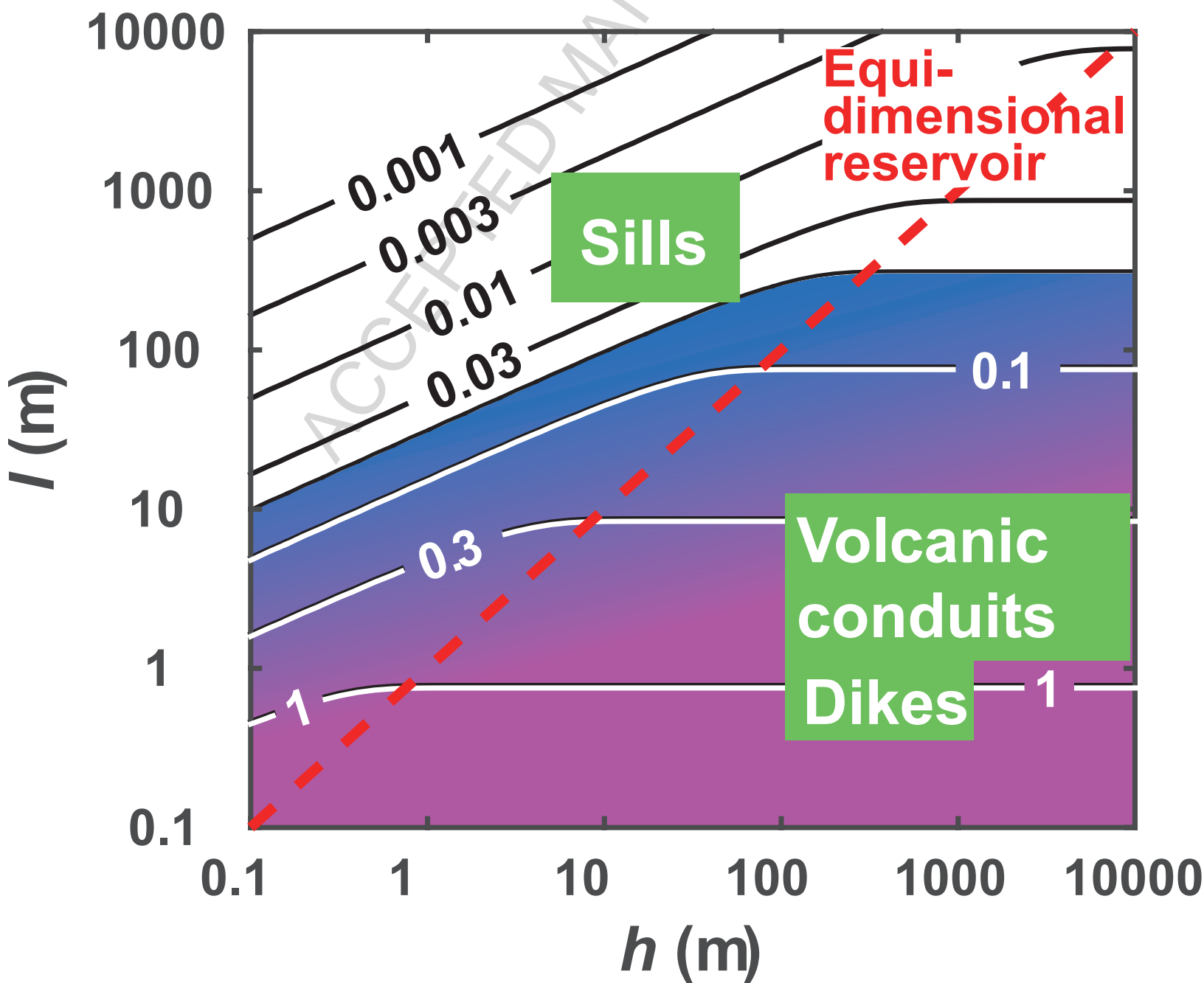




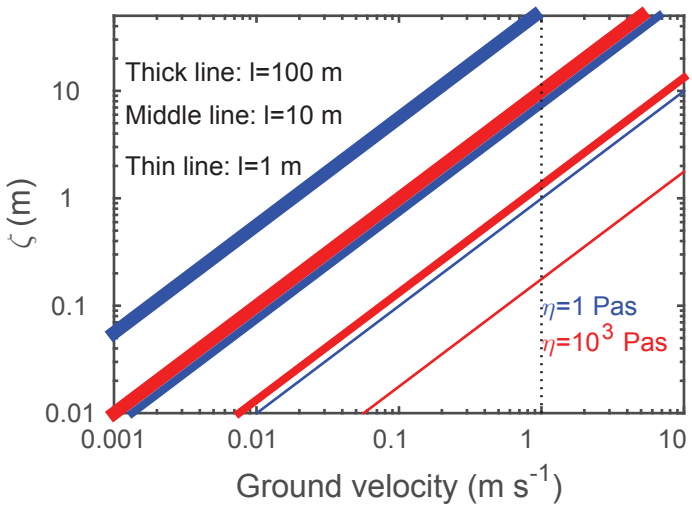
Figure 10



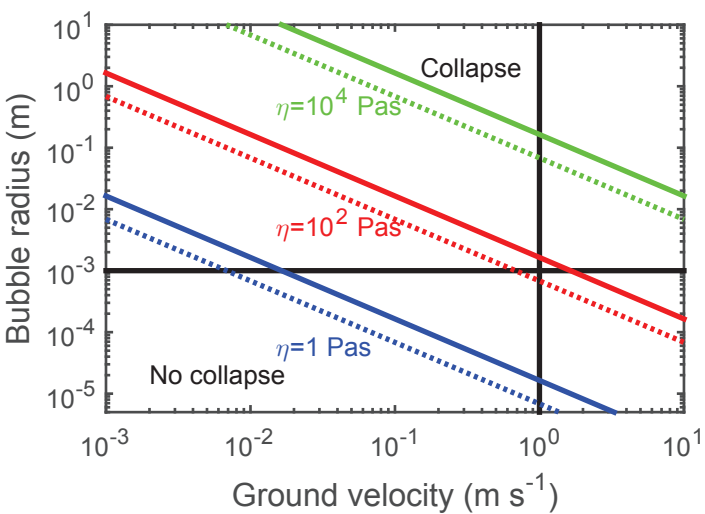


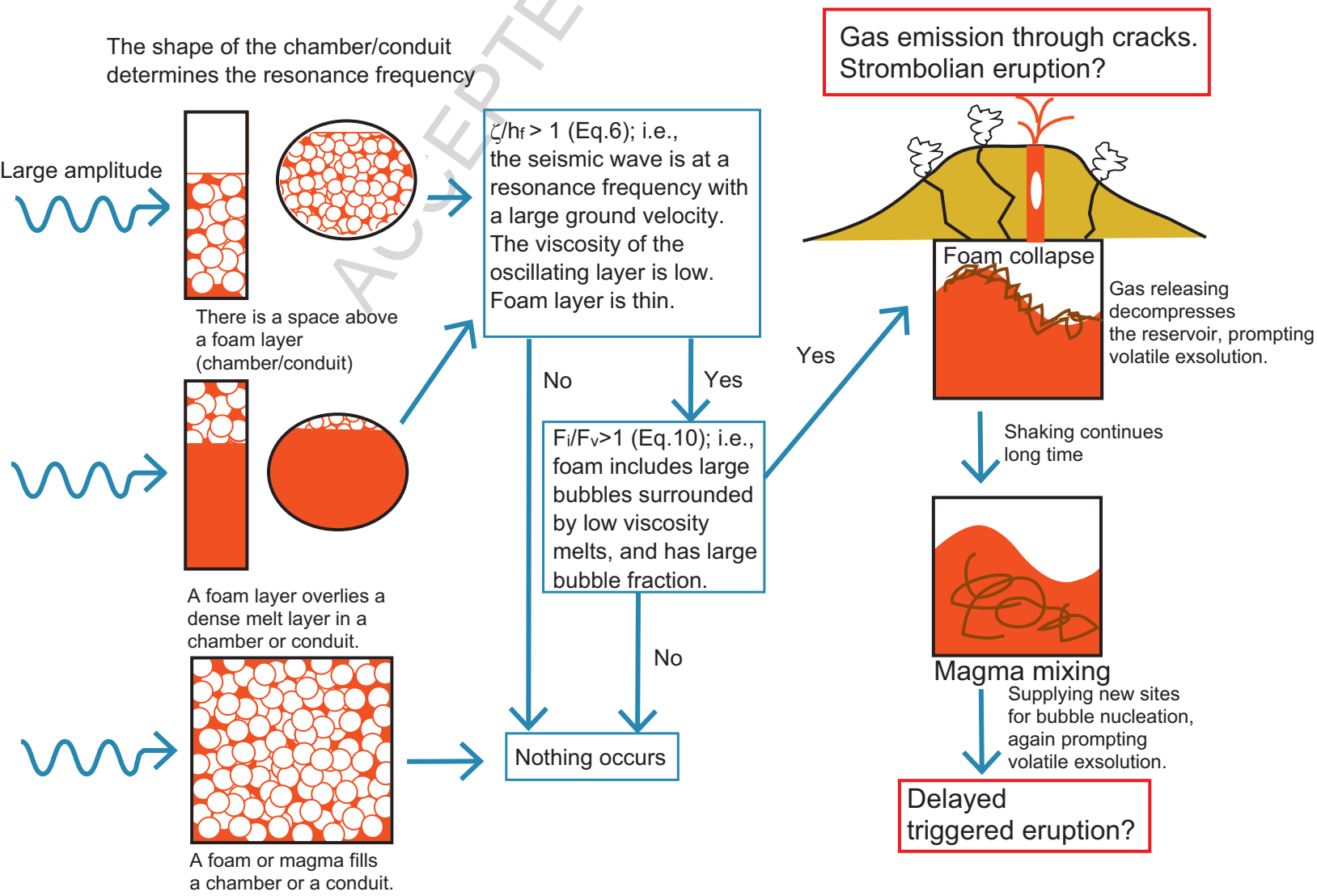


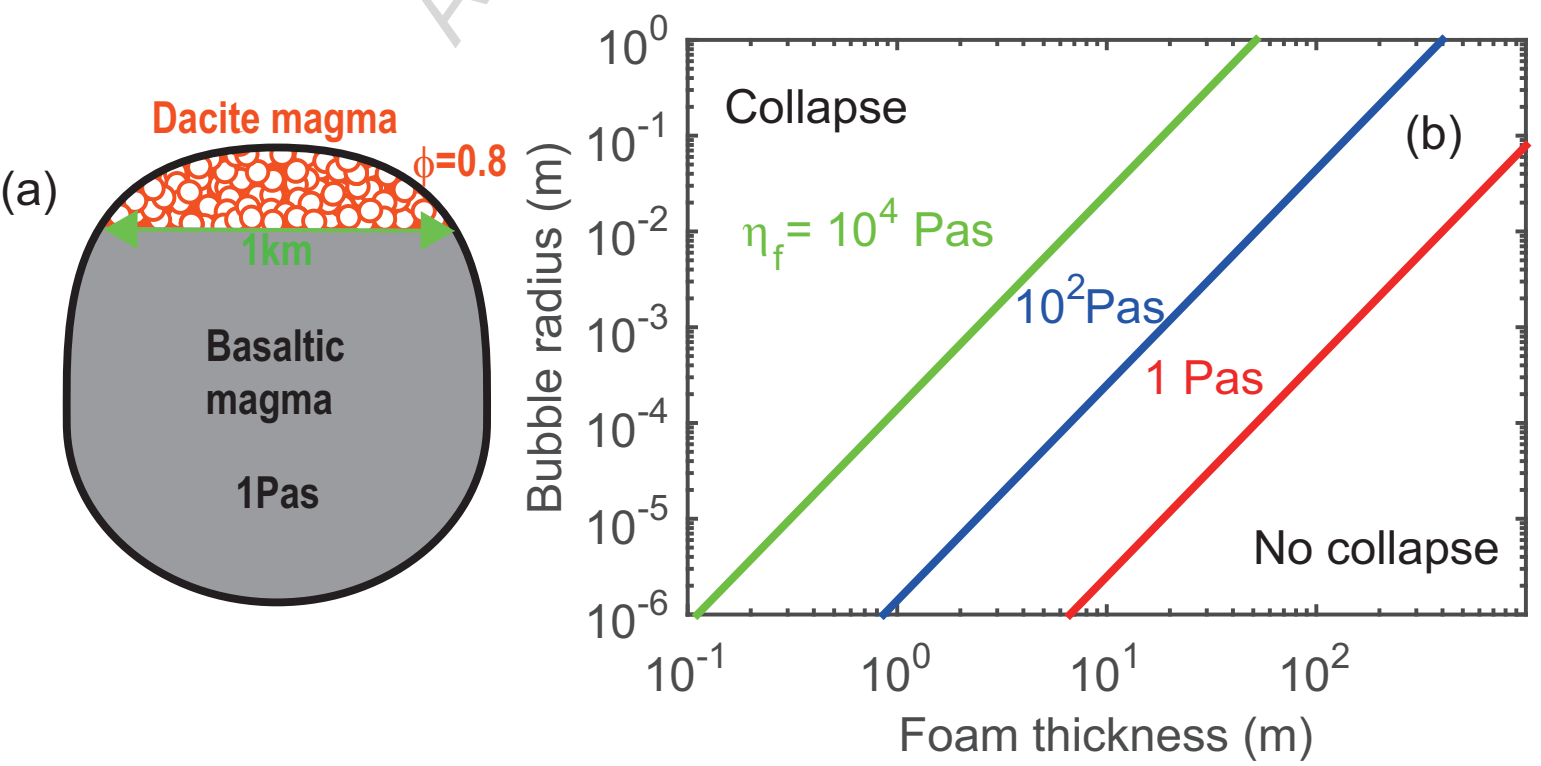
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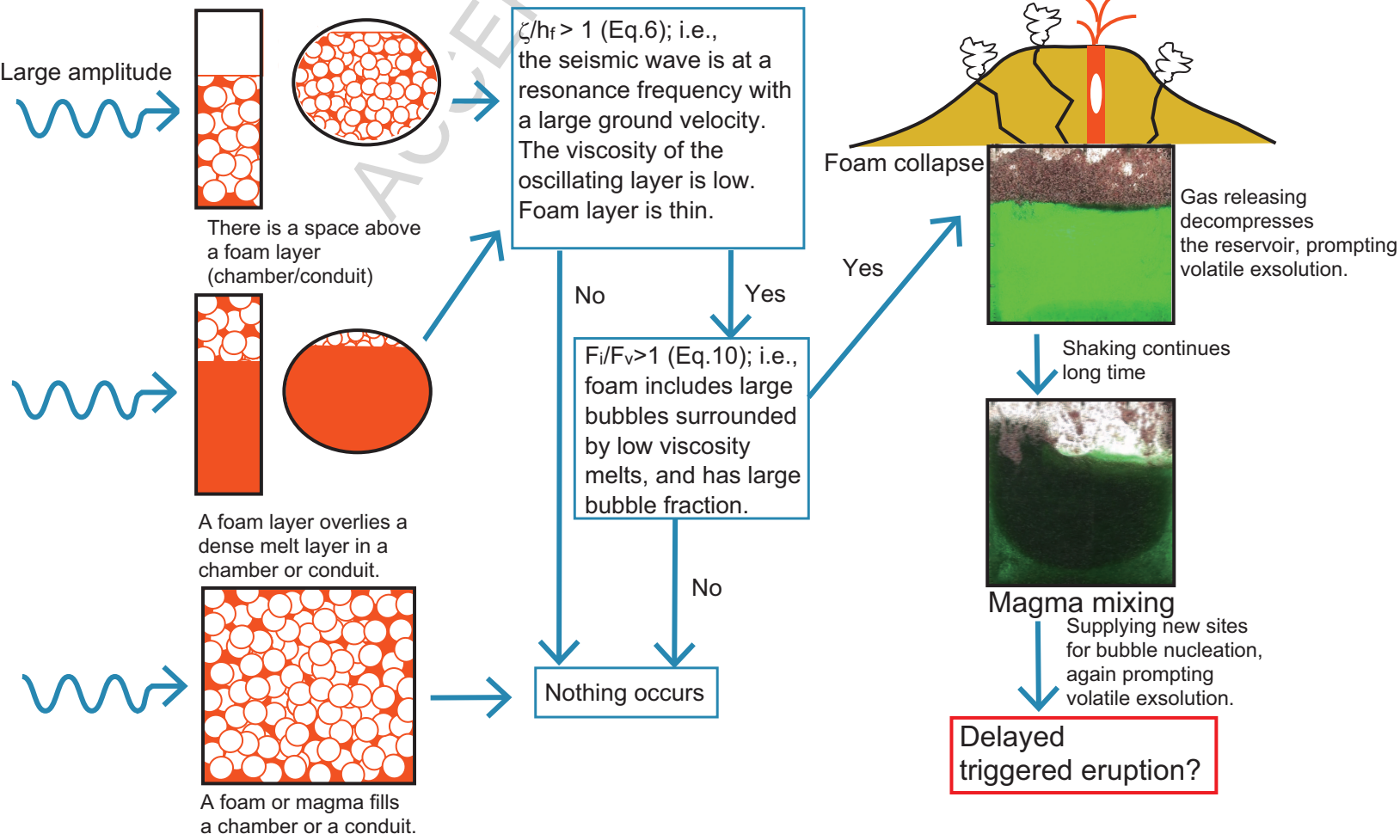






## Graphical Abstract

The shape of the chamber/conduit determines the resonance frequency



**Highlights**

- We conducted sloshing experiments by shaking viscous foams as a magma analogue.
- Foam collapse occurs by sloshing when the fluid layer resonates.
- Thinner foam layers in a less viscous melt with larger bubbles easily collapse.
- Sloshing can mix the collapsed magma foam with an underlying dense melt layer.
- Magma mixing during Hiei eruption of Mt. Fuji might be explained by sloshing.