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► **To cite this version:**

Michael Heap, Tobias Baumann, H. Albert Gilg, Stephan Kolzenburg, Amy Ryan, et al.. Hydrothermal alteration can result in pore pressurization and volcano instability. *Geology*, 2021, 49 (11), pp.1348-1352. 10.1130/G49063.1 . hal-03547431

**HAL Id: hal-03547431**

**<https://hal.science/hal-03547431>**

Submitted on 25 Nov 2022

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1 Hydrothermal alteration can result in pore pressurization and  
2 volcano instability

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18

19 **ABSTRACT**

20       The collapse of a volcanic flank can have dire consequences. Hydrothermal alteration is  
21 common to volcanoes worldwide and is thought to promote volcano instability by decreasing rock  
22 strength. However, some laboratory studies have shown that not all alteration reduces rock

23 strength. Our new laboratory data for altered rhyodacites from Chaos Crags (Lassen Volcanic  
24 Center, USA) show that pore- and crack-filling mineral precipitation can reduce porosity and  
25 permeability and increase strength, Young's modulus, and cohesion. A significant reduction in  
26 permeability, by as much as four orders of magnitude, will inhibit fluid circulation and create zones  
27 of high pore fluid pressure. Here we explore the consequences of pore fluid pressurization on  
28 volcano stability using large-scale numerical modeling. Upscaled physical and mechanical  
29 properties for hydrothermally altered rocks are used as input parameters in our modeling. We show  
30 that a high pore pressure zone within a volcano increases volcano deformation and that increasing  
31 the size of this zone increases the observed deformation. Hydrothermal alteration associated with  
32 mineral precipitation, and increases to rock strength, can therefore promote pore pressurization  
33 and volcano deformation, increasing the likelihood of volcano spreading, flank collapses, and  
34 phreatic/phreatomagmatic explosions. We conclude that porosity-decreasing alteration, explored  
35 here, and porosity-increasing alteration can both promote volcano instability and collapse, but by  
36 different mechanisms. Hydrothermal alteration should therefore be monitored at volcanoes  
37 worldwide and incorporated into hazard assessments.

38

## 39 **INTRODUCTION**

40 Volcanoes are inherently unstable structures and mass wasting events, sometimes  
41 destructive and deadly, are commonplace. As a result, volcano stability assessments are performed  
42 at volcanoes worldwide and the mechanisms thought to influence volcano stability have been  
43 studied and debated at length. Hydrothermal alteration resulting from the circulation of hot,  
44 magmatic fluids is often considered to reduce rock strength and promote volcano instability (López  
45 and Williams, 1993; van Wyk de Vries et al., 2000; Reid et al., 2001; John et al., 2008; Rosas-

46 Carbajal et al., 2016). However, experimental studies suggest that alteration type dictates whether  
47 volcanic rock will weaken or strengthen (Wyering et al., 2014; Frolova et al., 2014). Alteration  
48 associated with porosity reduction and/or the formation of clays reduces strength (Petro and  
49 Hürlimann, 2009; Farquharson et al., 2019); conversely, alteration that decreases porosity  
50 increases strength (Mordensky et al., 2018; Heap et al., 2020a). Given the relationship between  
51 porosity and strength (Heap and Violay, 2021), alteration could be expected to either enhance or  
52 reduce volcano stability, depending on the alteration type. However, permeability is also greatly  
53 reduced by porosity-filling alteration (Mordensky et al., 2018; Heap et al., 2019) which can inhibit  
54 fluid circulation and promote pore fluid pressurization within the volcano, a phenomenon  
55 considered to facilitate volcano instability and collapse (Day, 1996; Reid, 2004; Ball et al., 2018).  
56 For example, the modeling of Ball et al. (2018) showed that water saturation and elevated pore  
57 pressure can decrease volcano stability and increase collapse volume. As noted by Ball et al.  
58 (2018), the scarcity of petrophysical properties for altered volcanic rocks limits the investigation  
59 of volcano stability using large-scale models.

60         Here we combine upscaled laboratory data for variably altered volcanic rocks with large-  
61 scale numerical modeling to explore the influence of hydrothermal alteration on volcanic stability.  
62 We show that alteration resulting in an increase in rock strength can promote pore pressurization  
63 and volcano deformation, increasing the likelihood of volcano spreading, flank collapses, and  
64 phreatic/phreatomagmatic explosions. We conclude that porosity-decreasing alteration, explored  
65 here, and porosity-increasing alteration can both promote volcano instability, but by different  
66 mechanisms.

67

68 **MATERIALS AND METHODS**

69 Four blocks were collected from Dome C at Chaos Crags (Lassen Volcanic Center, USA;  
70 Fig. 1A). The majority of Dome C collapsed ~350 years ago (Clynne and Muffler, 2017), leaving  
71 a semi-spherical collapse scar and an avalanche deposit called Chaos Jumbles (Fig. 1A). We  
72 sampled one block from the Chaos Jumbles deposit, considered to represent largely unaltered  
73 dome material (sample CCC), and three visibly-altered blocks (CC4A, CC4B, and CC10) collected  
74 from the altered carapace of the dome that now forms the collapse scar.

75 All blocks are porphyritic rhyodacitic dome lavas that contain phenocrysts within a  
76 crystallized groundmass (backscattered scanning electron microscope (SEM) images are provided  
77 in the Data Repository). The mineral content of the four blocks was quantified using X-ray powder  
78 diffraction (see Data Repository). The unaltered dome material (CCC) contains plagioclase (52.6  
79 wt.%), K-feldspar (16.8 wt.%), and quartz (17.8 wt.%) with minor quantities (<10 wt.%) of  
80 cristobalite, biotite, hornblende, clinopyroxene, magnetite, and hematite. The mineral contents of  
81 samples CC4A and CC4B are similar to CCC, but contain more cristobalite and additional smectite  
82 (0.9–1.3 wt.%) and kaolinite (4.2–4.8 wt.%) (i.e. intermediate argillic alteration). Sample CC10  
83 has similar quantities of plagioclase as CCC, but less K-feldspar and quartz and more cristobalite.

84 Rock physical and mechanical properties were measured to characterize each block and to  
85 provide input parameters for the large-scale modeling. Cylindrical samples, 20 mm in diameter  
86 and 40 mm in length, were prepared from each of the blocks. Connected porosity was calculated  
87 using the bulk sample volume and the skeletal sample volume measured by a helium pycnometer.  
88 Permeability was measured using a gas permeameter (Heap and Kennedy, 2016) under a confining  
89 pressure of 1 MPa. Uniaxial compressive strength experiments were performed on select oven-dry  
90 samples of each of the blocks using a constant axial strain rate of  $10^{-5} \text{ s}^{-1}$ . The static Young's  
91 modulus was determined from the elastic portion of the uniaxial stress-strain curves. Triaxial

92 compression experiments were performed on water-saturated samples of the least (sample CCC)  
93 and most altered (sample CC4A, the sample that contains the highest wt.% of alteration minerals)  
94 blocks using a pore fluid (water) pressure of 10 MPa, confining pressures between 12.5 and 30  
95 MPa, and a constant axial strain rate of  $10^{-5} \text{ s}^{-1}$ .

96

## 97 **INFLUENCE OF ALTERATION ON ROCK PROPERTIES**

98 Permeability is plotted as a function of connected porosity in Fig. 1B (plots of Young's  
99 modulus and uniaxial compressive strength as a function of connected porosity are provided in the  
100 Data Repository). The permeability of the unaltered dome material (CCC) is consistently  $\sim 10^{-14}$   
101  $\text{m}^2$ . Although the permeability of altered block CC10 is also  $\sim 10^{-14} \text{ m}^2$ , the permeability of altered  
102 blocks CC4A and CC4B vary from  $\sim 10^{-18}$  to  $\sim 10^{-17} \text{ m}^2$  and from  $\sim 10^{-16}$  to  $\sim 10^{-14} \text{ m}^2$ , respectively  
103 (Fig. 1B). The decrease in porosity and permeability as a result of increasing alteration is indicated  
104 by the black arrow (Fig. 1B). The Young's modulus and uniaxial compressive strength of blocks  
105 CCC, CC4B, and CC10 are  $\sim 7\text{--}10 \text{ GPa}$  and  $\sim 40\text{--}55 \text{ MPa}$ , respectively. Altered block CC4A,  
106 however, has a much higher Young's modulus of  $\sim 30\text{--}35 \text{ GPa}$  and a uniaxial compressive strength  
107 of  $\sim 120\text{--}140 \text{ MPa}$  (data are available in the Data Repository). The triaxial deformation  
108 experiments show that the strength of the unaltered (sample CCC) and altered (CC4A) blocks  
109 increase as a function of increasing effective pressure (stress-strain curves are provided in the Data  
110 Repository). The laboratory-scale cohesion and angle of internal friction, calculated using these  
111 triaxial data, are  $9 \text{ MPa}$  and  $54^\circ$  and  $16 \text{ MPa}$  and  $49^\circ$  for blocks CCC and CC4A, respectively. In  
112 summary, hydrothermal alteration decreased the porosity and permeability and increased the  
113 strength, Young's modulus, and cohesion.

114 Experimental studies have shown that porosity-filling alteration can greatly reduce  
115 permeability (Mordensky et al., 2018; Heap et al., 2019; Kennedy et al., 2020) and increase  
116 strength (Wyering et al., 2014; Mordensky et al., 2018; Heap et al., 2020a), highlighting that the  
117 observed alteration-induced permeability reduction is not restricted to the rhyodacites measured  
118 here. Heap et al. (2019) showed that porosity-filling alunite group minerals reduced the  
119 permeability of basaltic-andesites from Merapi volcano (Indonesia) by up to four orders of  
120 magnitude. Mordensky et al. (2018) found that porosity-filling clay precipitation (smectite and  
121 kaolinite) increased the strength of andesites from Ruapehu (New Zealand). SEM images of block  
122 CC4A, the block with the lowest permeability, show that pores and cracks are filled with early  
123 cristobalite and late colloform hematite and kaolinite (Fig. 1C; Data Repository). Therefore, we  
124 conclude that the lower porosity and permeability and the higher strength, Young's modulus, and  
125 cohesion of CC4A, compared to the relatively unaltered sample (CCC), is the result of porosity-  
126 filling mineral precipitation.

127

## 128 **INFLUENCE OF PORE PRESSURIZATION ON VOLCANO STABILITY**

129 We use numerical modeling to demonstrate the potential influence of high pore pressure  
130 zones on volcano stability. We use the hydro-thermo-mechanical modeling code LaMEM  
131 (Lithosphere and Mantle Evolution Model; Kaus et al., 2016; described in detail in the Data  
132 Repository), which models the non-linear, visco-elastoplastic deformation of rocks and uses the  
133 Drucker-Prager failure criterion to constrain plastic strain rates. Numerically, LaMEM uses a  
134 staggered-grid finite difference method for discretization and a marker-and-cell method to assign  
135 and track rock properties within a Eulerian advection framework (Harlow and Welch, 1965).

136 Models were run on simplified 2D cross-sections of an idealized volcano, with a height of  
137 2000 m, a slope angle of 30°, and a numerical grid of 4 × 3 m, built using the geomIO tool  
138 (Bauville and Baumann, 2019). The triangle-shaped volcano structure with volcanic dome (see  
139 thumbnail in Fig. 2A) is deformable and the sides and top of the volcano are free surfaces. The  
140 area beneath this structure is non-deformable and a free-slip boundary separates the two domains  
141 (i.e. we assume that the edifice rocks are weaker than the basement rocks). Additional models with  
142 no-slip boundary (edifice rocks have a similar strength to those of the basement) are provided in  
143 the Data Repository. By modifying the segmentation of the deformable domain, we prepared cross-  
144 sections for (1) a homogeneous volcano with no high pore pressure zone (thumbnail in Fig. 2A)  
145 and (2) volcanoes featuring high pore pressure zones of different sizes (thumbnails in Fig. 2B-D).  
146 Zones within the volcano cross-sections were designated as either unaltered (light and dark gray  
147 zones) or altered (yellow zones). Upscaled mechanical properties of samples CCC and CC4A were  
148 assigned to the unaltered and altered zones, respectively (Table 1; upscaling methods are described  
149 in detail in the Data Repository). Based on the results of Ball et al. (2018), which show that an  
150 order of magnitude decrease in permeability can increase pore pressure by a factor 2–4, we doubled  
151 the pore pressure ratio,  $\lambda_i$ , in the altered zone to account for its low permeability (Fig. 1B). We  
152 assume that the volcano is entirely fluid saturated, and that  $p_f = p_h + \lambda_i (p_{lith} - p_h)$ , where  $p_f$ ,  
153  $p_h$ , and  $p_{lith}$  are the pore fluid, hydrostatic, and lithostatic pressure, respectively.

154 Fig. 2 shows the total displacement field and displacement vectors after 500 years for each  
155 of the four modeled scenarios. Our modeling shows, for scenarios when alteration decreases  
156 porosity and permeability, that the presence of a high pore pressure zone within the volcano greatly  
157 increases volcano deformation and that increasing the size of the high pore pressure zone  
158 exacerbates the deformation (Fig. 2). The modeled deformation of the volcano consists of the



159 downward movement of the high central portion of the volcano and the lateral spreading of the  
160 flanks (Fig. 2), consistent with the analog modeling of Cecchi et al. (2004). Volcano spreading,  
161 promoted here by alteration and high pore pressure zones, is understood to initiate catastrophic  
162 flank collapses (van Wyk de Vries and Francis, 1997). Our modeling therefore suggests that high  
163 pore pressure zones, the result of porosity-decreasing alteration, can create a “critical state  
164 volcano” that is prone to volcano spreading and partial flank collapse, but also  
165 hydrofracturing/tuffisite formation and phreatic and phreatomagmatic explosions (Fig. 3).  
166 Ancillary models using the no-slip boundary condition show that deformation is more concentrated  
167 on the flanks, and that the maximum displacement is reduced (Data Repository).

168 Our modeling assumes that high pore pressures are maintained in the altered zone. We  
169 highlight that both volcano deformation and high pore fluid pressures can result in fracturing,  
170 which can decrease pore pressure. We envisage a scenario, similar to that described in Kennedy et  
171 al. (2020), in which fractures are eventually sealed by hydrothermal minerals within the alteration  
172 zone, allowing pore pressure to re-increase (i.e. long-term high pore pressure is punctuated by  
173 transient pore pressure reductions).

174

## 175 **CONCLUDING REMARKS**

176 Our large-scale numerical modeling, used in conjunction with well-constrained physical  
177 and mechanical property input parameters for hydrothermally altered rock, shows that high pore  
178 pressure zones promote volcano instability and collapse. High pressure zones in volcanoes can  
179 result from porosity reduction attending hydrothermal alteration. Thus, volcano stability can be  
180 undermined by alteration that results in either an increase or decrease in porosity, but by different  
181 mechanisms. Previous studies have shown that increasing porosity lowers the strength, Young’s

182 modulus, and cohesion of volcanic rock, leading to a reduction in rock mass stability (Apuani et  
183 al., 2005). Although decreasing the porosity increases strength, we show here that it also  
184 significantly decreases permeability (Fig. 1B) and allows high pore pressure zones to develop that  
185 create a “critical state volcano” that is prone to not only volcano spreading and partial flank  
186 collapse, but also hydrofracturing/tuffisite formation and phreatic and phreatomagmatic  
187 explosions (Fig. 3). Since most volcanoes likely contain zones characterized by both of these  
188 different alteration styles, both mechanisms likely work in tandem to promote volcano instability.  
189 Therefore, it is important to monitor the extent and evolution of hydrothermal alteration zones  
190 using methods such as geological mapping (van Wyk de Vries et al., 2000), deformation  
191 monitoring (Moretti et al., 2020), muon (Rosas-Carbajal et al., 2017) and electrical tomography  
192 (Rosas-Carbajal et al., 2016), gas monitoring (de Moor et al., 2019), magnetic methods (Finn et  
193 al., 2007), and spectroscopic methods (John et al., 2008; Kereszturi et al., 2020). However, we  
194 also show that it is of equal importance to know the locations within the volcano prone to porosity-  
195 increasing (e.g., dissolution) and porosity-decreasing (e.g., precipitation) alteration styles, which  
196 will depend on factors such as pressure, temperature, and the pH and composition of the  
197 hydrothermal fluids.

198

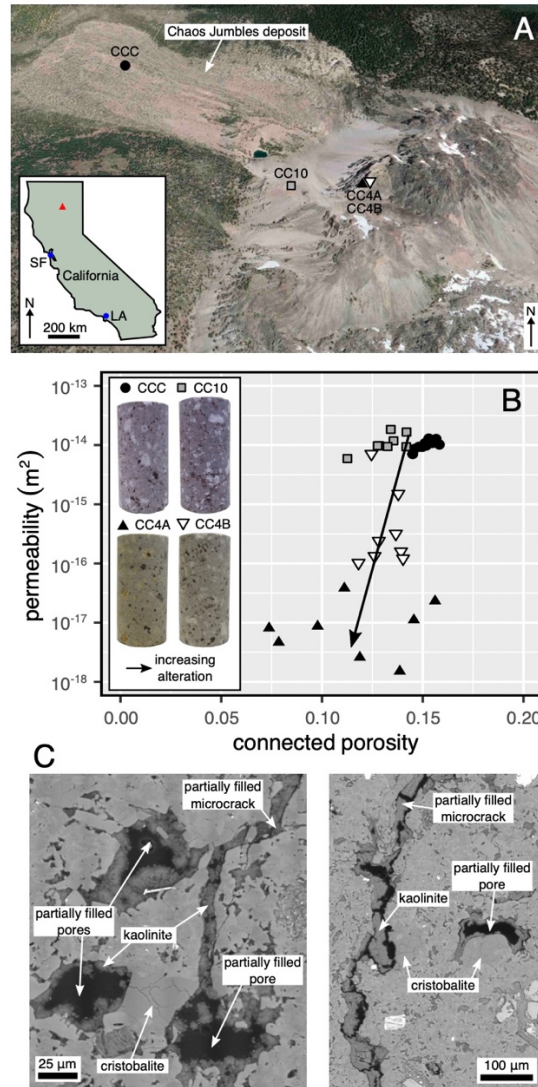
## 199 **ACKNOWLEDGMENTS**

200 We thank M. Harris, B. Renaudié, T. Reuschlé, the United States National Park Service  
201 (LAVO-00050; LAVO-2019-SCI-0010), and the Canadian NSERC Discovery Grants program  
202 (RGPIN-2018-03841). Any use of trade, firm, or product names is for descriptive purposes only  
203 and does not imply endorsement by the U.S. Government.

204

205 **FIGURE CAPTIONS**

206



207

208 **Fig. 1.** A: Google Earth® image of Chaos Crags showing the sampling sites. Inset shows the

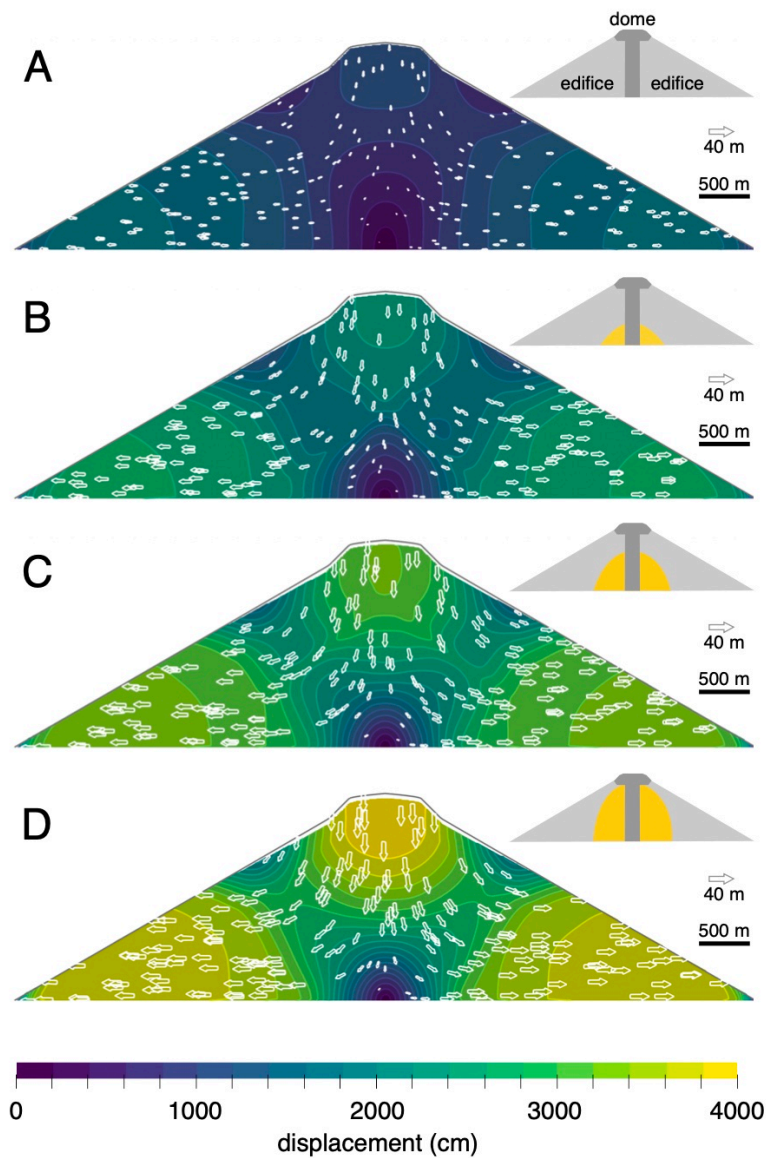
209 location of Chaos Crags (red triangle) in California (USA). SF – San Francisco; LA – Los Angeles.

210 B: Permeability as a function of connected porosity for the four blocks collected. Inset shows

211 photographs of the 20 mm-diameter samples. The black arrow indicates the increasing degree of

212 alteration. C: Backscattered scanning electron microscope images of sample CC4A showing

213 porosity-filling alteration.



214

215 **Fig. 2.** Results of the large-scale volcano stability modeling. Colors indicate the total displacement

216 field (blue and yellow colors indicate low and high displacement, respectively) and the white

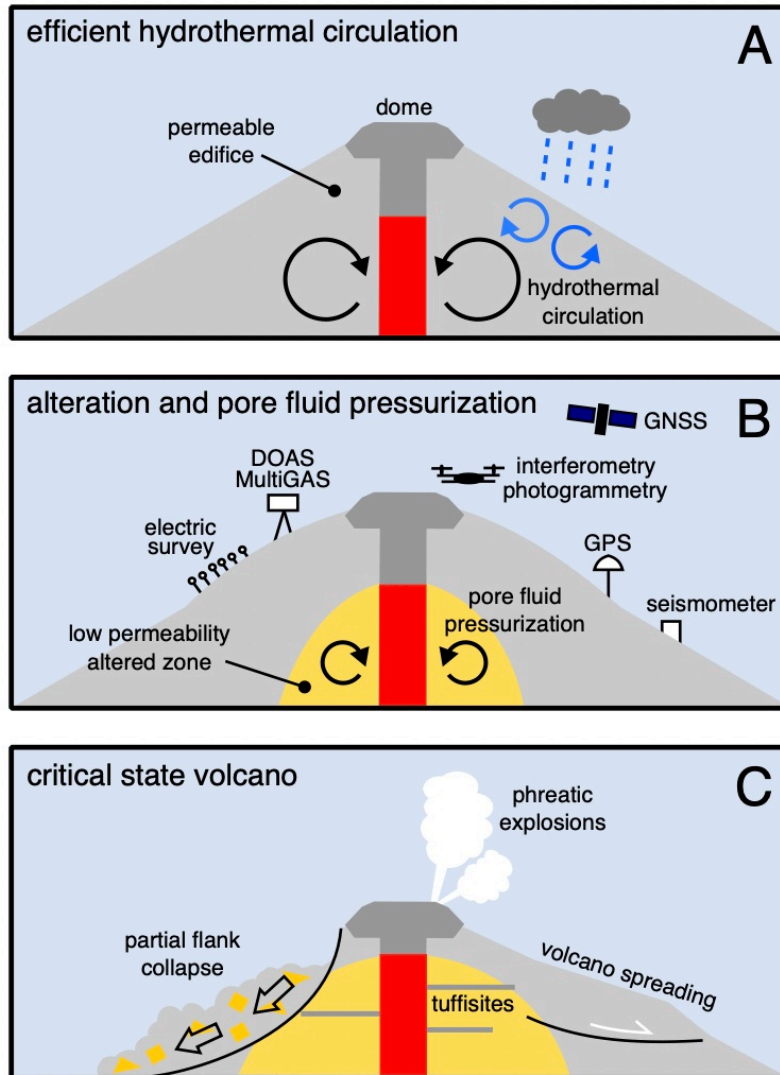
217 arrows show the displacement vectors. Models were run for 500 years. Thumbnails show the

218 model setup, where gray and yellow zones are unaltered and altered zones with a high pore

219 pressure, respectively (see Table 1 for model input parameters). A: Homogeneous volcano. B:

220 Volcano with a small alteration zone. C: Volcano with the medium alteration zone. D: Volcano

221 with a large alteration zone.



222

223 **Fig. 3.** A: Efficient hydrothermal circulation within a porous and permeable edifice. B:

224 Hydrothermal circulation creates an alteration zone with a lower permeability (yellow zone) that

225 results in pore fluid pressurization. “Geomojis” highlight some of the monitoring techniques. C:

226 Implications of a pressurized critical state volcano include: volcano spreading, partial flank

227 collapse, hydrofracturing/tuffisite formation, and phreatic/phreatomagmatic explosions.

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328 <sup>1</sup>GSA Data Repository item 202Xxxx, containing a sample location maps and photographs, sample  
329 photographs, thin section images, the mineral componentry of the samples, additional methods,  
330 the presentation of some of the laboratory data, more details on the upscaling and model, and  
331 additional models is available online at [www.geosociety.org/pubs/ft20XX.htm](http://www.geosociety.org/pubs/ft20XX.htm), or on request from  
332 [editing@geosociety.org](mailto:editing@geosociety.org).