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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-03547431v1>

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} 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} 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 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 MPa and 54° and 16 MPa and 49° 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, λ_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

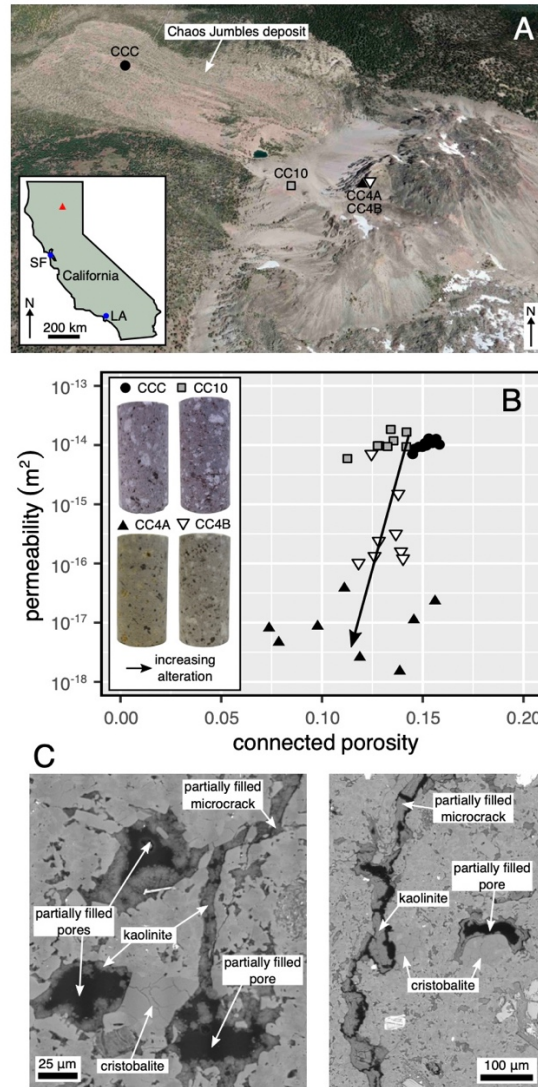
199 **ACKNOWLEDGMENTS**

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

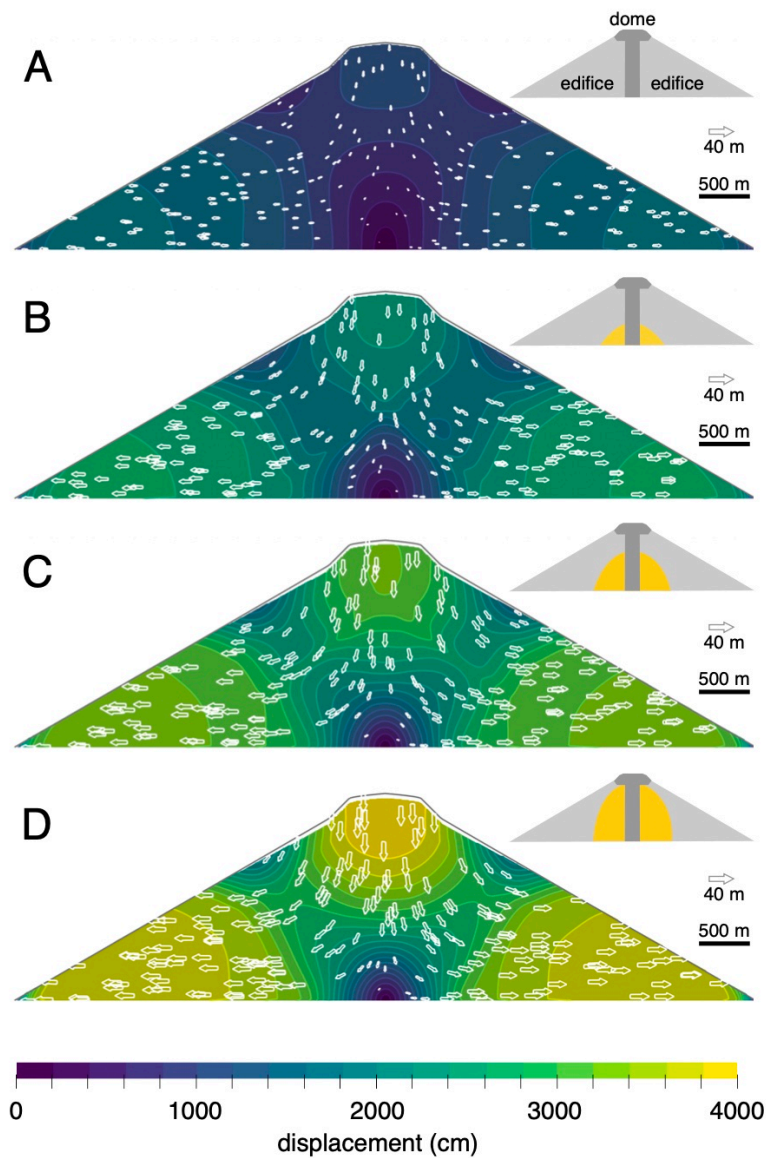
209 location of Chaos Crags (red triangle) in California (USA). SF – San Francisco; LA – Los Angeles.

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

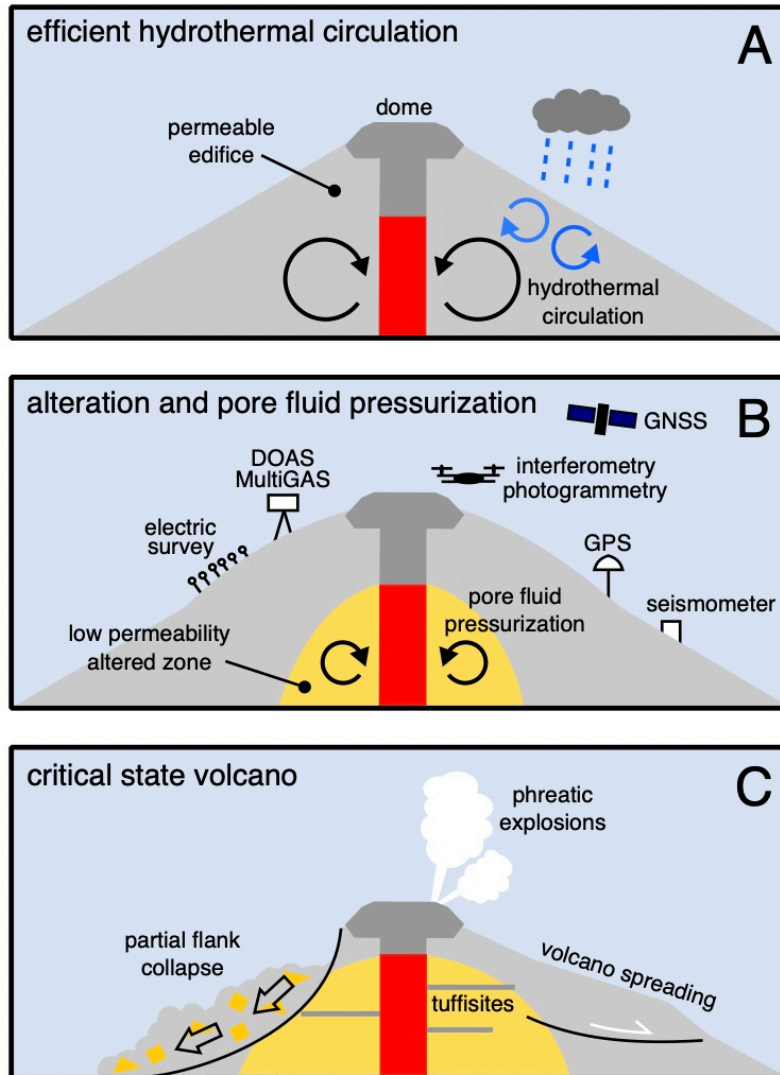
217 arrows show the displacement vectors. Models were run for 500 years. Thumbnails show the

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 ¹GSA 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, or on request from
332 editing@geosociety.org.