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¹ Influence of pre-existing volcanic edifice geometry on ² caldera formation

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3 **Abstract.** Volcanic edifice construction at the Earth's surface significantly
4 modifies the stress field within the underlying crust with two main implica-
5 tions for caldera formation. First, tensile rupture at the Earth's surface is
6 favored at the periphery, which enables ring fault formation. Second, edifice
7 formation amplifies the amount of pressure decrease occurring within a magma
8 reservoir before the eruption stops. Taking into account both of these effects,
9 caldera formation can be initiated during a central eruption of a pre-existing
10 volcano even when assuming elastic behaviour for the surrounding crust. Pro-
11 viding the roof aspect ratio is small enough, conditions for caldera forma-
12 tion by reservoir withdrawal can be reached whatever the reservoir shape is.
13 However ring fault initiation is easier for laterally elongated reservoirs.

1. Introduction

14 Many caldera-forming deposits record energetic eruptive phases prior to the "syncol-
15 lapse" deposits characterized by ignimbrites, which is consistent with an onset of caldera
16 occurring during an ongoing eruption that is to say when the magma reservoir pressure
17 is decreasing by withdrawal [*Marti et al.*, 2008]. Based on this field observation as well as
18 experimental and mathematical modelling, *Marti et al.* [2009] define two types of caldera
19 depending on the pressure evolution within the magmatic reservoir leading to ring faults
20 formation and caldera-forming eruption. One caldera type is formed by magma pressure
21 increase within a sill-like magma reservoir in the presence of a regional extensive field
22 [*Gudmundsson*, 1998] and starts with the eruption. The other caldera type is formed by
23 magma pressure decrease during an ongoing eruption. Based on the compilation of in-
24 formation gathered in the Collapse Caldera Data Base (CCDB), *Geyer and Marti* [2008]
25 show that the second type that occurs during reservoir withdrawal is, by far, the most
26 common.

27 In the case of caldera formation induced by reservoir withdrawal, the key question to
28 address, concerns the amount of depressurization that a given reservoir can reach and
29 whether or not this depressurization is sufficient to ensure ring fault formation. Consid-
30 ering the crustal surrounding medium as elastic, reservoir depressurization is limited by
31 dyke closure at the reservoir wall [*McLeod and Tait*, 1999; *Marti et al.*, 2008]. However,
32 except for a few recent studies [*Geyer et al.*, 2006; *Folch and Marti*, 2009], most of the-
33 oretical work based on fluid dynamics [*Druitt and Sparks*, 1984], as well as analogical
34 [*Roche et al.*, 2000] and numerical studies [*Folch and Marti*, 2004] ignore this problem

35 and do not discuss whether or not conditions for ring fault initiation are compatible with
36 realistic pressure conditions within the reservoir. Besides, most authors favoring caldera
37 formation by reservoir withdrawal consider that the crust has to behave non-elastically
38 [*Marti et al.*, 2008].

39 The fact that caldera characteristics are linked to the pre-existing volcanic edifice ge-
40 ometry has long been recognised [*Wood*, 1984]. More recently, based on the compilation
41 of information gathered in the Collapse Caldera Data Base (CCDB), *Geyer and Marti*
42 [2008] showed that, in most cases (53, 3%) pre-caldera volcanic activity involves the devel-
43 opment of long lived stratovolcanoes or stratocones and that another significant amount
44 (11%) of calderas are formed on pre-existing shield volcanoes. It is known that eruptive
45 products accumulation at the Earth's surface and edifice formation significantly modifies
46 the underlying stress field within the crust with consequences for the magma plumbing
47 system development [*Pinel and Jaupart*, 2003]. However only a few studies dealing with
48 caldera formation take into account the edifice's potential influence [*Walter and Troll*,
49 2001; *Lavallée et al.*, 2004; *Pinel and Jaupart*, 2005].

50 In this study, numerical simulations in axisymmetric geometry are performed in order
51 to determine under which conditions a caldera formation might occur when considering
52 a realistic range of pressure within the magma reservoir and a volcanic edifice at the
53 Earth's surface. The model is developed following the framework proposed by *Pinel and*
54 *Jaupart* [2005] who performed an analytical study in 2D (plane strain approximation) for
55 cylindrical magma reservoirs. In this new paper, the influence of the roof aspect ratio
56 (reservoir depth/reservoir lateral extension), the reservoir size as well as the edifice slope

57 are discussed, and a primary additional contribution is to investigate the influence of the
58 reservoir shape (ellipticity).

2. Model description

2.1. Geometry and general settings

59 An ellipsoidal magma reservoir filled with liquid magma embedded in an homogeneous
60 elastic medium (rigidity G and Poisson's ratio ν) is considered (see Fig 1 a). The magma
61 density is assumed equal to the density (ρ) of the surrounding crust and the state of
62 reference is lithostatic ($\sigma_{rr} = \sigma_{zz} = \sigma_{\theta\theta} = -\rho gz > 0$ with $-z$, the depth). Departure
63 from this lithostatic state of reference is induced by either a differential magma pressure
64 ($\Delta P > 0$ for an overpressurized reservoir and $\Delta P < 0$ for an underpressurized reservoir)
65 or the presence of an edifice at the Earth's surface, whose geometry is characterized by its
66 radius R_v and slope α . The magma reservoir geometry is characterized by its horizontal
67 semi-axis a , its vertical semi-axis b and its roof depth H . A key parameter is the reservoir
68 ellipticity (e) defined by the ratio $e = a/b$, ellipticity being equal to 1 for the spherical
69 case, smaller than 1 for vertically elongated reservoirs (prolate) and larger than 1 for
70 horizontally elongated reservoirs (oblate). The maximum value of the semi-axis will be
71 referred to as L_c ($L_c = a$ for oblate shapes and $L_c = b$ for prolate ones). Another key
72 parameter when studying calderas is the roof aspect ratio (R) defined as the ratio of the
73 reservoir roof thickness over its width ($R = H/(2a)$) [Roche *et al.*, 2000; Geyer *et al.*,
74 2006].

75 Stress and strain within the crust are numerically calculated solving the equations for
76 linear elasticity with the "Finite Element Method" (COMSOL software). The domain of
77 calculation is a 100*100 km square box with a mesh of about 100 000 triangular units that

78 is refined around the volcanic edifice and magma reservoir. No displacement perpendicular
79 to the boundary is allowed at the bottom and lateral boundaries, the upper boundary is
80 considered as a free surface. The edifice is modelled with a normal stress applied at
81 the upper surface ($\sigma_n = \rho_m g \alpha R_v (1 - r/R_v)$ for $r < R_v$) and a normal stress equal to
82 the magma overpressure is applied at the reservoir walls. Numerical solutions have been
83 validated using well-known analytical solutions as detailed in *Albino et al.* [2010]. Figure
84 1b shows that the edifice load at the surface tends to induce, respectively, compression in
85 the central part, and tension at the periphery, the tensile effect having a smaller amplitude.
86 An underpressurized reservoir has roughly the same effect (Fig. 1c) whereas the effect of
87 an overpressurized reservoir (Fig. 1d) is opposite (large tensile stress in the central part
88 and comparatively small compressive stress at the periphery).

2.2. Condition for caldera formation

89 Most numerical studies consider that the main criterion required for caldera formation
90 is that tensile failure can occur at the Earth's surface at some lateral distance from the
91 axis in order to produce ring faults [*Gudmundsson et al.*, 1997; *Folch and Marti*, 2004;
92 *Pinel and Jaupart*, 2005]. It is also often required for the rupture location to be above
93 the maximum lateral extension of the underlying magma reservoir [*Folch and Marti*,
94 2004; *Kinzig et al.*, 2009] to ensure the mechanical behaviour of the ring fault linking the
95 Earth's surface to the reservoir walls and to reproduce field observations. For a detailed
96 description of conditions required for ring faults formation see *Folch and Marti* [2004];
97 *Kinzig et al.* [2009]; *Geyer and Binderman* [2011].

98 Here, the criterion considered for caldera formation only requires that tensile failure of
99 the Earth's surface occurs at some distance from the axis. However the position of this

100 rupture with regards to the reservoir walls is discussed later.

101 Tensile failure of the Earth's surface periphery should be favored by the edifice load (Fig.
102 1b) and the reservoir depressurization (Fig. 1c). The tensile failure criterion given by
103 *Pinel and Jaupart* [2005] is generalised here in the three-dimensions, in order to calculate
104 the magma pressure required within the reservoir for roof breakdown. It follows that
105 tensile rupture occurs when $[2\sigma_{rr}(r, z = 0) - \sigma_{zz}(r, z = 0) - \sigma_{\theta\theta}(r, z = 0)]/3 = -T_s$,
106 where σ_{rr} , σ_{zz} and $\sigma_{\theta\theta}$ are the three principal components of the stress tensor at the
107 Earth's surface expressed in the cylindrical coordinate system, and T_s is the rock tensile
108 strength. Due to the tensile effect, respectively, induced by an overpressurized reservoir in
109 the central part (see Figure 1 d), and an underpressurized reservoir at the periphery (see
110 Figure 1 c), tensile rupture induced by reservoir inflation only occurs at the axis ($r=0$)
111 and cannot account for ring fault formation. Earth's surface rupture at the periphery is
112 thus the consequence of reservoir pressure decrease (reservoir deflation) below a threshold
113 value (ΔP_{crit}), such that the above equation is verified.

2.3. Realistic pressure range within the reservoir

114 Magma pressure within a reservoir might increase by replenishment and/or by volatiles
115 exsolution due to magma crystallisation [*Tait et al.*, 1989]. However this increase is lim-
116 ited by the rupture of the reservoir walls leading to magma propagation away from the
117 reservoir. Failure of the reservoir wall occurs when the deviatoric stress component, at
118 the walls, reaches the tensile strength [*Tait et al.*, 1989; *Pinel and Jaupart*, 2003]. When
119 magma leaves the reservoir, it induces a pressure decrease within the storage zone. Con-
120 sidering an elastic behaviour of the crust, this pressure decrease is also limited. When the
121 magma pressure fails below the normal pressure applied at the dyke walls, the dykes get

122 closed. Conditions for the cessation of magma withdrawal define a lower bound for the
123 reservoir pressure noted ΔP_{min} . One must assess whether or not the pressure decrease
124 within the magma reservoir can be sufficient to induce ring fault formation, that is to say
125 that we have to specify conditions under which one may have $\Delta P_{min} < \Delta P_{crit}$.

3. Results

126 Figure 2 shows, for various reservoir ellipticities, the edifice size required for caldera
127 formation (to have $\Delta P_{min} < \Delta P_{crit}$). Within the framework of this particular model,
128 which considers an initial lithostatic stress field, ring fault formation is not expected,
129 when no edifice is present at the Earth's surface, whatever the reservoir shape is. The
130 edifice growth at the surface always acts to favor tensile rupture at the periphery and, in
131 most case, enables the reservoir to becomes underpressurized ($\Delta P_{min} < 0$) [Pinel *et al.*,
132 2010]. Both effects tend to favor ring faults formation. In the case of a roof aspect ratio
133 equal to 1, caldera formation can only occur for horizontally elongated reservoirs, whereas,
134 when the roof aspect ratio is equal to 0.25, caldera formation might occur whatever the
135 reservoir shape is, the edifice size required being larger for prolate reservoirs. Results
136 previously obtained in 2D by Pinel and Jaupart [2005] are similar to this paper's new
137 results in 3D when considering a spherical shape, except for a small reservoir (Fig. 2 a),
138 for which ring fault initiation appears more difficult in 2D. Figure 2 also shows that the
139 fault linking the Earth's surface rupture to the reservoir wall is nearly vertical only for
140 small roof aspect ratios. For a given reservoir ellipticity, the edifice size required for caldera
141 formation usually increases with the roof aspect ratio. For a strato-volcano characterized
142 by a slope of 30 degrees, the maximum roof aspect ratio allowing caldera formation is
143 close to 1 and I checked that this maximum value does not evolve when considering larger

144 ellipticities.

145 In order to interpret field observations, it might be useful to compare the caldera and
146 edifice predicted sizes. Figure 3 shows that, in general, the caldera is smaller than the pre-
147 existing edifice (caldera/edifice radius smaller than 1). The amount of the edifice surface
148 affected by the caldera collapse increases with the magma reservoir size (larger values of
149 caldera/edifice radius for plain curves than for dotted ones). Another observation is that
150 the caldera accounts for a larger fraction of the edifice in stratovolcanoes ($\alpha > 0.3$, Fig
151 3a,b) than in shield volcanoes ($\alpha \approx 0.1$, Fig 3c), which is consistent with field observations
152 [Wood, 1984]. The caldera versus edifice ratio can bring additional constraints on the
153 magma reservoir shape and size. Information on caldera geometry is available in most
154 cases from the CCDB whereas the volcanic edifice size can be inferred from the topography
155 provided by the SRTM Digital Elevation Model. In a few cases, the CCDB also provides
156 an estimation of the roof aspect ratio. Such data have been reported for seven volcanoes
157 to Figure 3. For instance, Crater Lake caldera formed on Mount Mazama, 6845 yr ago, is
158 characterized by an edifice slope close to 0.3, a caldera versus edifice radius of 0.4 [Pinel
159 and Jaupart, 2005] and a roof aspect ratio between 0.5 and 1. From Figure 3 b), this
160 geometry is consistent with a 4 km radius spherical reservoir or a smaller reservoir (2.5 km
161 radius) as previously proposed by Pinel and Jaupart [2005] but having a laterally elongated
162 shape. Vesuvius is characterized by a slightly larger caldera/edifice radius (around 0.5)
163 as well as a slightly larger roof aspect ratio (between 0.6 and 1.2), which is consistent
164 with a 4km radius laterally elongated reservoir. An oblate shape is thus required for the
165 magma reservoir at Vesuvius, as previously proposed by Pinel and Jaupart [2005]. From
166 Figure 3 c) the formation of Medicine Lake or Newberry calderas, on pre-existing shield

167 volcanoes could be explained by the presence of a very shallow reservoir of radius 2.5 km
168 or a slightly larger and deeper one (radius around 4km), whereas the formation of Opala,
169 Ksudach and Krashennikov calderas in Kamchatka can only be explained by shallow and
170 large spherical reservoirs ($L_c \geq 4km$).

4. Discussion and Conclusion

171 In order to explain caldera formation by magma withdrawal, *Marti et al.* [2008] con-
172 sider that the reservoir wall behaviour departs from elasticity. Some phenomena such as
173 conduit wall erosion could eventually prevent dyke from closure. However erosion of the
174 central conduit by respectively, abrasion or fluid shear stress, is mainly restricted to a
175 limited portion, respectively, above or around, the fragmentation level [*Macedonio et al.*,
176 1994], which is supposed to be located within the upper 1 km of the conduit [*Massol and*
177 *Koyaguchi*, 2005]. It follows that, in most cases, it seems realistic to neglect conduit wall
178 erosion at the magma reservoir level, before ring faults formation. The main conclusion
179 of the present study is that caldera formation by reservoir withdrawal (that is to say,
180 pressure decrease) can occur even considering an elastic behaviour for the surrounding
181 crust. However, in order to further discuss the potential effects of previous events, lateral
182 variations of the physical properties of the crust should be taken into account.

183 This study based on an elastic model only allows discussion of the initiation of caldera
184 formation that is to say the onset of medium fracturation. It does not bring any insight into
185 the further development of the caldera and the way the initial fracture propagates, which
186 would require analog modelling [*Roche et al.*, 2000] or the use of numerical modelling based
187 on the Discrete Element Method (DEM) [*Hardy*, 2008; *Holohan et al.*, 2009]. Once the

188 caldera formation has started the crustal behaviour can obviously no longer be considered
189 as elastic.

190 This work only considers caldera formation associated with a summit eruption. Some
191 caldera formations, mainly in the case of basaltic volcanoes, are caused by lateral eruptions
192 or magma intrusions [*Michon et al.*, 2011]. Lateral magma propagation as well as often
193 associated large flank displacements, indicate an extensional regime within the edifice.
194 It follows that the model presented here, which relies on the assumption of an initial
195 lithostatic stress field, is not appropriated to discuss such cases.

196 This study shows that the building of a volcanic edifice by accumulation of eruptive
197 products at the Earth's surface favors caldera formation by inducing tensile stress at the
198 Earth's surface and enabling larger depressurization within the magma reservoir. This
199 conclusion was already supported by an earlier analytical study [*Pinel and Jaupart*, 2005]
200 however it is, here, generalised for the 3-dimensional case and various reservoir shapes.
201 Conditions for coherent caldera formation are easier to achieve in the case of small roof
202 aspect ratios, as shown by *Roche et al.* [2000]; *Pinel and Jaupart* [2005]; *Geyer et al.*
203 [2006]. For larger roof aspect ratios, larger edifice size are required to induce caldera
204 formation. Caldera collapse can even affect vertically elongated reservoirs provided that
205 the roof aspect ratio remains small. However horizontally elongated reservoir are much
206 more favorable. With this particular geometry, caldera formation might occur for larger
207 roof aspect ratios. The present model considering an initial lithostatic stress field cannot
208 explain caldera formation in the case where there is no pre-existing edifice at the Earth's
209 surface (which represents less than 15% of the documented calderas as reported by the
210 CCDB *Geyer and Marti* [2008]) or if the roof aspect ratio is larger than 1 for stratovol-

211 canoes or larger than 1.3 for shield volcanoes (which represents a few documented cases,
212 for example Ceburoco, as reported by the CCDB). It can also not explain ring fault ini-
213 tiation by reservoir inflation. However the initial stress field could be, in many cases,
214 different from the lithostatic one and most calderas are formed in extensional tectonic
215 regime (which is the case for Ceboruco). The effect of an extensional regime should favor
216 caldera formation and could be easily quantified with the framework used in this study.
217 The model presented here predicts that the caldera size versus the edifice one should be
218 smaller in case of shield volcanoes than for strato-volcanoes, which is consistent with ob-
219 servations [Wood, 1984]. It also places some constraints on the magma reservoir geometry
220 based on surface observations.

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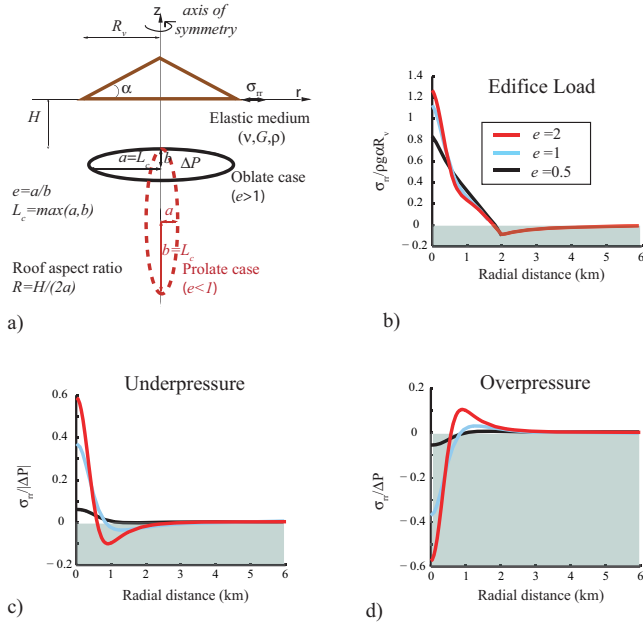


Figure 1. Model geometry and stress field induced at the Earth's surface. a) Model geometry and key parameters. b) Radial stress ($\sigma_{rr}(r)$) induced at the Earth's surface by an edifice load (radius $R_v = 2$ km) when the magma reservoir is at lithostatic equilibrium ($\Delta P = 0$). The stress is normalised by the load applied at the axis. c) Radial stress ($\sigma_{rr}(r)$) induced at the Earth's surface by an underpressurized magma reservoir ($\Delta P < 0$) with no edifice at the surface. The stress is normalised by the magma reservoir underpressure ($|\Delta P|$). d) Radial stress ($\sigma_{rr}(r)$) induced at the Earth's surface by an overpressurized magma reservoir ($\Delta P > 0$) with no edifice at the surface. The stress is normalised by the magma reservoir overpressure (ΔP). Radial stress calculations are obtained for a reservoir depth H of 0.5 km and maximum extension L_c of 0.5 km. Poisson's ratio is equal to 0.25. The black, blue and red curves are obtained, respectively, for a reservoir ellipticity (e) of 0.5, 1 and 2. The grey area corresponds to tensile stress (negative values).

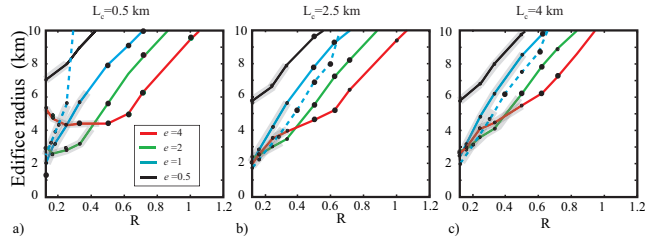


Figure 2. Edifice size required for caldera formation as a function of the roof aspect ratio. The edifice considered is a strato-volcano of slope $\alpha = 0.6$, maximum radius of 10 km and a density of 2800 kgm^{-3} . Poisson's ratio is equal to 0.25 and the rock tensile strength is equal to 200 bars. Results are presented for various reservoir sizes: a) Maximum reservoir extension L_c of 0.5 km, b) Maximum reservoir extension L_c of 2.5 km, c) Maximum reservoir extension L_c of 4 km. Various reservoir ellipticities are considered: the black, blue, green and red curves are, respectively, for a prolate reservoir of ellipticity 0.5, a spherical reservoir, an oblate reservoir of ellipticity 2 and an oblate reservoir of ellipticity 4. The dashed blue curves are analytical results obtained by *Pinel and Jaupart* [2005] for the 2D plane strain case considering a cylindrical magma reservoir. Parts of the curves where the fault linking the Earth's surface rupture location to the reservoir walls is nearly vertical (dip larger than 80 degrees), are surrounded by a grey halo. Black circles are for the numerical simulations performed.

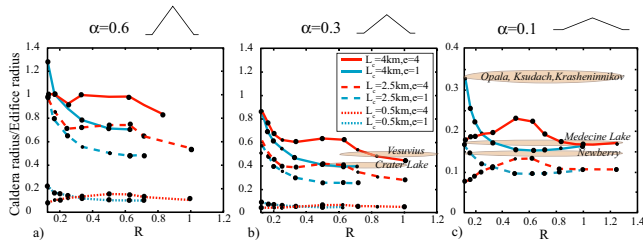


Figure 3. Caldera versus edifice radius as a function of the roof aspect ratio. Two different reservoir ellipticities are considered: the blue and red curves are, respectively, for a spherical reservoir and an oblate reservoir of ellipticity 4. Results are presented for various reservoir sizes: Dotted curves for a maximum reservoir extension L_c of 0.5 km, dashed curves for a maximum reservoir extension L_c of 2.5 km and plain curves for a maximum reservoir extension L_c of 4 km. Poisson's ratio is equal to 0.25 and the rock tensile strength is equal to 200 bars. Volcanic edifice density is 2800 kgm^{-3} . Circles are for the numerical simulations performed. a) The edifice considered is a strato-volcano of slope $\alpha = 0.6$ and maximum allowed size 10 km. b) The edifice considered is a strato-volcano of slope $\alpha = 0.3$ and maximum allowed size 20 km. Characteristics of two strato-volcanoes with a slope close to 0.3, are reported (brown areas): Mount Mazama (caldera/edifice radius close to 0.4 and roof aspect ratio between 0.5 and 1, from [Pinel and Jaupart, 2005] and the CCDB) and Vesuvius (caldera/edifice radius close to 0.5 and roof aspect ratio between 0.6 and 1.2, caldera geometry is taken from the CCDB and edifice geometry is estimated from the SRTM Digital Elevation Model). c) The edifice considered is a shield volcano of slope $\alpha = 0.1$ and maximum allowed size 60 km. Characteristics of five shield volcanoes (edifice slope around 0.1) are reported (brown areas): Medicine Lake (caldera/edifice radius close to 0.17), Newberry (caldera/edifice radius close to 0.15), Ksudach, Krasheninnikov and Opala (caldera/edifice radius close to 0.33). Caldera geometry is taken from the CCDB and edifice geometry is estimated from the SRTM Digital Elevation Model.