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Stability of volcanic conduits: Critical mechanical parameters

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Summary. — Several geological evidences support the occurrence of volcanic conduit enlargement during explosive events (*e.g.* presence of lithic fragments in most pyroclastic deposits), with significant effects on the eruptive dynamics, particularly on the mass discharge rate. Conduit wall collapse is supposed to be a relevant enlargement process, being more intense near and above the fragmentation level. Nonetheless, the influence of country rock conditions has never been addressed, and its implications on the eruptive dynamics are still unclear. This work focuses on the effects of the country rock mechanical parameters and the presence of unconfined aquifers on conduit stability, using a 1D steady-state model and the application of two collapse criteria. For given magma properties and conduit dimensions, it emerges that conduit stability is mainly controlled by the friction angle of the country rocks and, to a lesser extent, by the cohesion. The horizontal stress gradients are only significant when the Mohr-Coulomb criterion is employed, whereas the variability in the vertical stress gradient has a minor effect on conduit stability. Moreover, the presence of unconfined aquifers is an important destabilizing factor, which is consistent with the ejection of significant amounts of lithic fragments in many phreatomagmatic eruptions.

1. – Introduction

The mass discharge rate is one of the most relevant eruptive parameters of explosive events [1]. It controls the column height and the dispersal power of the pyroclasts [1], playing a main role in the evaluation of volcanic hazards [2]. In Plinian eruptions, the mass discharge rate varies over at least three orders of magnitude and it is positively correlated with the total erupted mass, thus it represents a high-interest eruptive parameter in volcanology [1, 3, 4]. Several authors have studied the factors which control the mass discharge rate [5, 6], showing the relative importance of gas content, magma chamber overpressure, temperature and ascending magma rheology, among others. Moreover, a positive correlation is expected between conduit radius and mass discharge rate, but the

Table I. – *Magma parameters and models used in numerical simulations, chosen in order to describe typical conditions of rhyolitic explosive volcanism.*

Property	Model/Value
Temperature	850 °C
Viscosity model	Hess and Dingwell [12]
Influence of crystals on viscosity	Costa [13]
Exsolved gas model	Ideal gas
Crystallinity model	de'Michieli Vitturi *et al.* [14]
Solubility model	Henry's law
Solubility constant (σ)	4.1×10^{-6} (a)
Solubility constant (ϵ)	0.5(a)
Inlet pressure	115–135 MPa
Water content	4.5–6.5 wt.%
Conduit radius	25–75 m

(a) Based on Zhang [11].

physical mechanisms controlling conduit enlargement/reduction during the course of an eruption are not clear enough.

Macedonio *et al.* [7] identified four erosion mechanisms in volcanic conduits: fluid shear stress, impact of pyroclasts, conduit wall collapse and volcanic tremors. The collapse of conduit walls is mainly controlled by the pressure field along the conduit, thus it is a relevant erosion mechanism near and above the fragmentation level [7]. Aravena *et al.* [8] presented a new methodology for studying the mechanical stability of volcanic conduits, with a focus on the relation between the ascending magma properties and the expected conduit dimensions. On the contrary, the effects of the country rock mechanical parameters have not been studied systematically, neither the influence of unconfined aquifers.

This work addresses the mechanical stability of volcanic conduits and the influence of the country rock conditions. I use a numerical approach based on two tools: a) a 1D steady-state model for studying the pressure profile along the conduit [9] and b) the application of the Mohr-Coulomb and Mogi-Coulomb collapse criteria [10]. This work consists of four parts: first, the methodology is described, with a clear focus on the adopted collapse criteria; second, I present the results of a sensitivity analysis, developed in order to evaluate the effects of four input parameters on conduit stability; third, I describe the results related to the influence of unconfined aquifers on conduit stability; and finally, the results are discussed, trying to shed some lights on the influence of the country rock conditions on the expected dimensions of volcanic conduits, and their consequences on the eruptive dynamics.

2. – Methods

For studying the pressure conditions along volcanic conduits ($P(z)$), I used the 1D steady-state model presented by de'Michieli Vitturi *et al.* [9] and Aravena *et al.* [8], which considers the main processes experimented by ascending magmas (*e.g.* crystallization, rheological changes, explosive fragmentation, outgassing and degassing). The set of input parameters and models adopted in numerical simulations (table I) were chosen in order to simulate typical conditions of rhyolitic explosive volcanism.

For evaluating conduit stability, the Mohr-Coulomb and Mogi-Coulomb collapse criteria were applied [10]. The Mogi-Coulomb criterion considers the effect of the intermediate stress, in contrast to Mohr-Coulomb collapse criterion, thus the latter is expected to be a more conservative formulation. Both collapse criteria consider three cases derived from the order relation between vertical, radial and tangential stresses (σ_z, σ_r and σ_θ, respectively) [10]:

$$\text{Case 1: } \sigma_z \geq \sigma_\theta \geq \sigma_r, \tag{1a}$$

$$\text{Case 2: } \sigma_\theta \geq \sigma_z \geq \sigma_r, \tag{1b}$$

$$\text{Case 3: } \sigma_\theta \geq \sigma_r \geq \sigma_z. \tag{1c}$$

The three remaining cases are related to rock fracture criteria (*i.e.* $\sigma_z \geq \sigma_r \geq \sigma_\theta$, $\sigma_r \geq \sigma_\theta \geq \sigma_z$ and $\sigma_r \geq \sigma_z \geq \sigma_\theta$). Indeed, under these stress conditions, a maximum pressure for avoiding conduit failure can be computed, while gravitational collapse of the conduit is not expected [10].

The minimum pressures for avoiding conduit collapse ($P_{collapse}(z)$) were calculated using eqs. (2) and (3) (Mohr-Coulomb and Mogi-Coulomb collapse criteria, respectively) [10]:

$$P_{collapse}(z) = \begin{cases} (B-C)/q, & \text{if } \sigma_z \geq \sigma_\theta \geq \sigma_r, \\ (A-C)/(1+q), & \text{if } \sigma_\theta \geq \sigma_z \geq \sigma_r, \\ A-C-qB, & \text{if } \sigma_\theta \geq \sigma_r \geq \sigma_z. \end{cases} \tag{2}$$

where z is the vertical coordinate, $A = 3\sigma_H - \sigma_h$, $B = \sigma_V + 2\upsilon(\sigma_H - \sigma_h)$, $C = 2c \cdot cos(\phi)/(1 - sin(\phi)) - P_0 \cdot (q-1)$, $q = tan^2(\pi/4 + \phi/2)$, σ_H is the maximum horizontal stress, σ_h is the minimum horizontal stress, σ_V is the vertical stress, υ is the Poisson ratio, c is the cohesion, ϕ is the angle of internal friction and P_0 is the pore pressure:

$$P_{collapse}(z) = \begin{cases} \frac{3A+2b'K-\sqrt{H+12(K^2+b'AK)}}{6-2b'^2}, & \text{if } \sigma_z \geq \sigma_\theta \geq \sigma_r, \\ \frac{3A-\sqrt{12[a'+b'(A-2P_0)]^2-3(A-2B)^2}}{6}, & \text{if } \sigma_\theta \geq \sigma_z \geq \sigma_r, \\ \frac{3A-2b'G-\sqrt{H+12(G^2-b'AG)}}{6-2b'^2}, & \text{if } \sigma_\theta \geq \sigma_r \geq \sigma_z, \end{cases} \tag{3}$$

where $a' = 2c \cdot cos(\phi)$, $b' = sin(\phi)$, $G = K + b'A$, $H = A^2(4b'^2 - 3) + (B^2 - AB)(4b'^2 - 12)$ and $K = a' + b'(B - 2P_0)$.

The stability conditions of volcanic conduits were studied by comparing $P_{collapse}(z)$ and $P(z)$. Indeed, the degree of instability was quantified using the instability index, defined as $\max(P_{collapse}(z) - P(z))$ [8], which exhibits positive values for unstable conduits and negative values for stable conduits. It is important to note that the instability index presents some inconveniences as an instability measure for highly stable conduits (*e.g.* instability indexes lower than -5 MPa), thus the inclusion of other instability measures is recommended in these cases.

Both collapse criteria exhibit four poorly-constrained input parameters [15, 16]: cohesion, friction angle, vertical stress gradient and horizontal stress gradients. In order to study the relative importance of them, for each scenario (*i.e.* set of input conditions

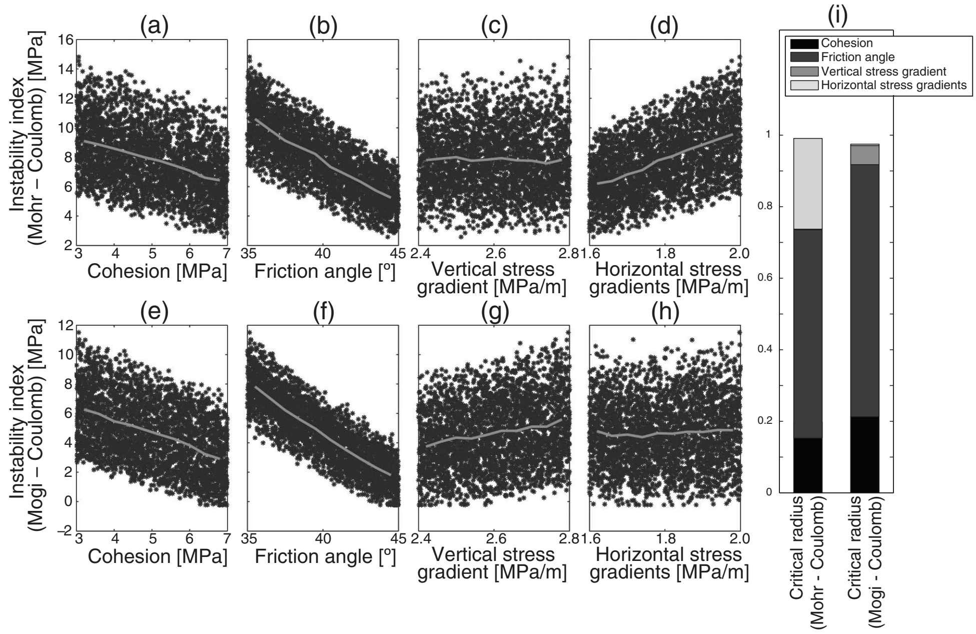

Fig. 1. – Results related to the sensitivity analysis of instability indexes (Mohr-Coulomb and Mogi-Coulomb collapse criteria), for a specific scenario (conduit radius of 25 m, water content of 6.5 wt.% and inlet pressure of 135 MPa). (a) Instability index (Mohr-Coulomb) *versus* cohesion. (b) Instability index (Mohr-Coulomb) *versus* friction angle. (c) Instability index (Mohr-Coulomb) *versus* vertical stress gradient. (d) Instability index (Mohr-Coulomb) *versus* horizontal vertical gradients. (e) Instability index (Mogi-Coulomb) *versus* cohesion. (f) Instability index (Mogi-Coulomb) *versus* friction angle. (g) Instability index (Mogi-Coulomb) *versus* vertical stress gradient. (h) Instability index (Mogi-Coulomb) *versus* horizontal vertical gradients. (i) Total effect Sobol sensitivity index.

for conduit dimensions and magma properties), I developed a sensitivity analysis of the input mechanical parameters, determining the first-order Sobol sensitivity index (S_{ij}, eq. (4)) [17].

$$S_{ij} = \frac{\mathrm{Var}(E(Y_j|X_i))}{\mathrm{Var}(Y_j)}, \tag{4}$$

where Y_j is the instability index, using both stability criteria ($j = 1$ for Mohr-Coulomb criterion, $j = 2$ for Mogi-Coulomb criterion). I assumed uniform probability distributions for the input parameters: (a) cohesion (X_1, 3 MPa–7 MPa), (b) friction angle (X_2, 35°–45°), (c) vertical stress gradient (X_3, 2400 kPa/m–2800 kPa/m), and (d) horizontal stress gradients (X_4, 1600 kPa/m–2000 kPa/m).

Finally, I include a systematic analysis of the influence of unconfined aquifers on conduit stability, varying its depth and thickness, and comparing them with aquifer-free calculations.

3. – Results

For Mohr-Coulomb collapse criterion, the minimum pressure for avoiding conduit collapse is reached under the second stress condition (*i.e.* $\sigma_\theta \geq \sigma_z \geq \sigma_r$) in the 95% of cases, while the remaining 5% is related with the first stress condition (*i.e.* $\sigma_z \geq \sigma_\theta \geq \sigma_r$). When the Mogi-Coulomb collapse criterion is employed, the differences are smaller (60% of simulations are related with the second stress condition, while the remaining 40% is associated with the first stress condition). The third stress condition (*i.e.* $\sigma_\theta \geq \sigma_r \geq \sigma_z$) was never reached for reasonable sets of input parameters.

Figure 1 presents a summary of the sensitivity analysis performed for a specific scenario, and fig. 2 exhibits the histograms of the first order Sobol sensitivity indexes (eq. (4)), considering all the scenarios and both stability criteria. The variability of the instability index is mainly controlled by the friction angle variability ($S_{21} = 0.48 \pm 0.07$ and $S_{22} = 0.49 \pm 0.13$). The cohesion variability exhibits a significant influence on the instability index ($S_{11} = 0.27 \pm 0.08$ and $S_{12} = 0.29 \pm 0.07$), while the horizontal stress gradient is only relevant for the Mohr-Coulomb collapse criterion ($S_{41} = 0.22 \pm 0.02$ and $S_{42} < 0.01$). Finally, the vertical stress gradient exhibits a limited effect on conduit stability ($S_{31} < 0.01$ and $S_{32} < 0.05$).

Figures 3 and 4 exhibit the relation between the instability indexes of aquifer-free conduits (x-axis) and the results related to the presence of unconfined aquifers (y-axis, depths of 1000 and 2000 m, thicknesses of 100, 300 and 500 m), for both stability criteria. It emerges that 300 m thick aquifers are enough for producing a significant destabilizing effect on volcanic conduits, especially when the aquifer is located some hundreds of meters above the fragmentation level and when the Mogi-Coulomb criterion is employed.

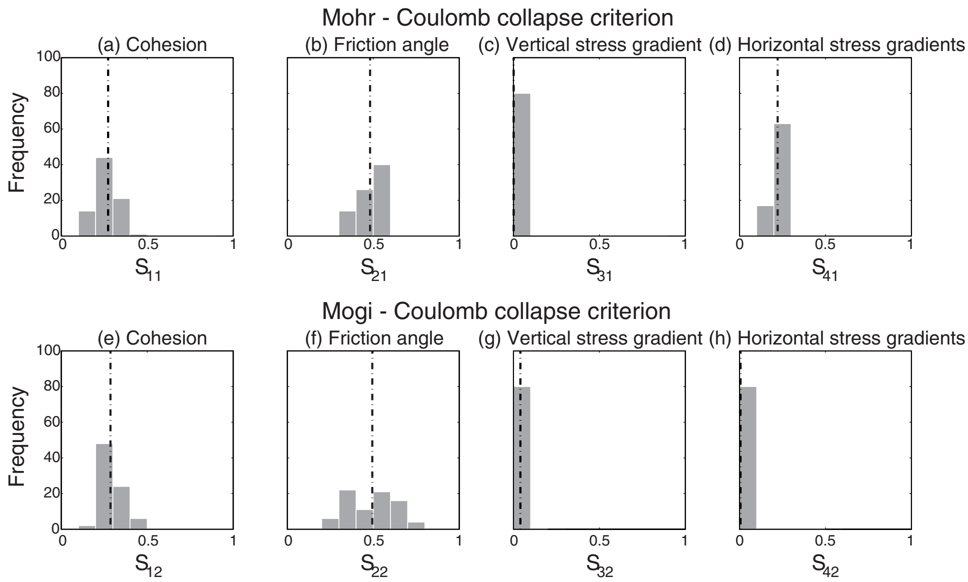

Fig. 2. – Histograms of the first order Sobol sensitivity indexes estimated in numerical simulations (all the scenarios), considering four input parameters (cohesion, friction angle, vertical stress gradient and horizontal stress gradients) and two output parameters (instability indexes, using both stability criteria). Dashed lines represent the mean value.

Moreover, since aquifer-dominated conduit collapse likely occurs only at shallower levels than the fragmentation level ($\alpha_g = 0.7$), a minor effect on the bubble growth process is expected [18], which would preserve the features of a mainly "dry" fragmentation process (*i.e.* relatively high vesicularity indexes).

4. – Discussion

Conduit enlargement is controlled by the physical conditions of the ascending magma and the country rocks, with important effects on the eruptive dynamics (*e.g.* changes in mass discharge rate, erupted mixture density and temperature). The wide range of eruptive styles exhibited by volcanic systems has been traditionally attributed to different conditions of the magma source, magma properties and some processes experimented during the ascent (*e.g.* outgassing, degassing) [19-22], while the influence of country rock mechanical parameters and hydrological substrate characteristics have been only occasionally considered [23, 24].

The results obtained in this work indicate that country rock conditions are non-negligible parameters for studying and predicting the behaviour of volcanic systems. For a given magma-feeding system (*i.e.* a given set of ascending magma properties), the instability index and thus the expected conduit dimensions is mainly controlled by the friction angle and to a less extent, by the cohesion. The effect of the vertical stress gradient seems to be less relevant, and thus the volcanic edifice overload would have

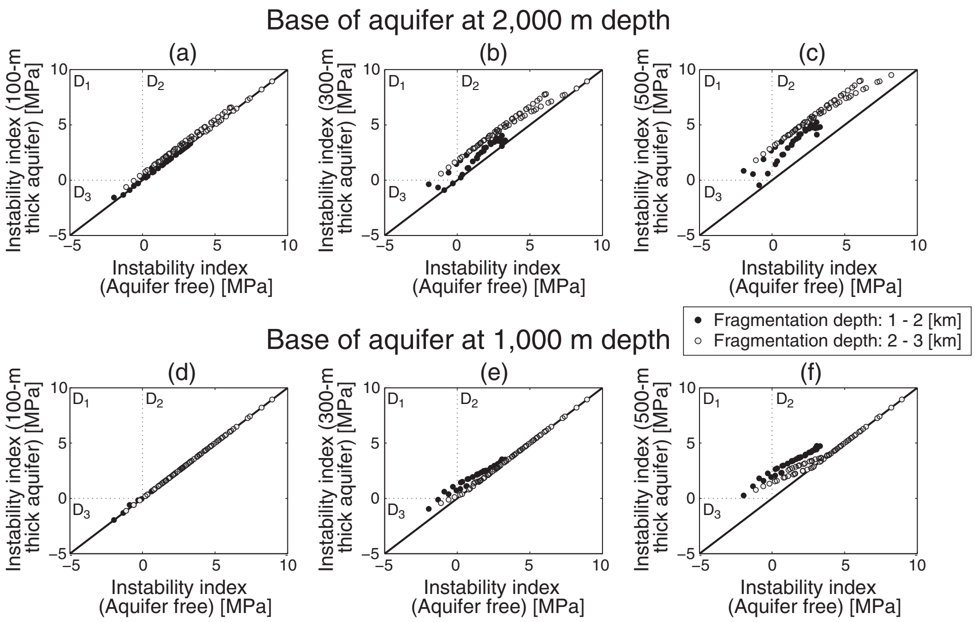

Fig. 3. – Relation between the instability indexes of aquifer-free conduits (x-axis) and results related to the presence of unconfined aquifers (depths and thicknesses are indicated in titles and y-axis), using Mohr-Coulomb collapse criterion. D_1: domain of mechanical stability for aquifer-free simulations and mechanical instability for simulations with shallow aquifers. D_2: domain of mechanical instability for both sets of simulations. D_3: domain of mechanical stability for both sets of simulations.

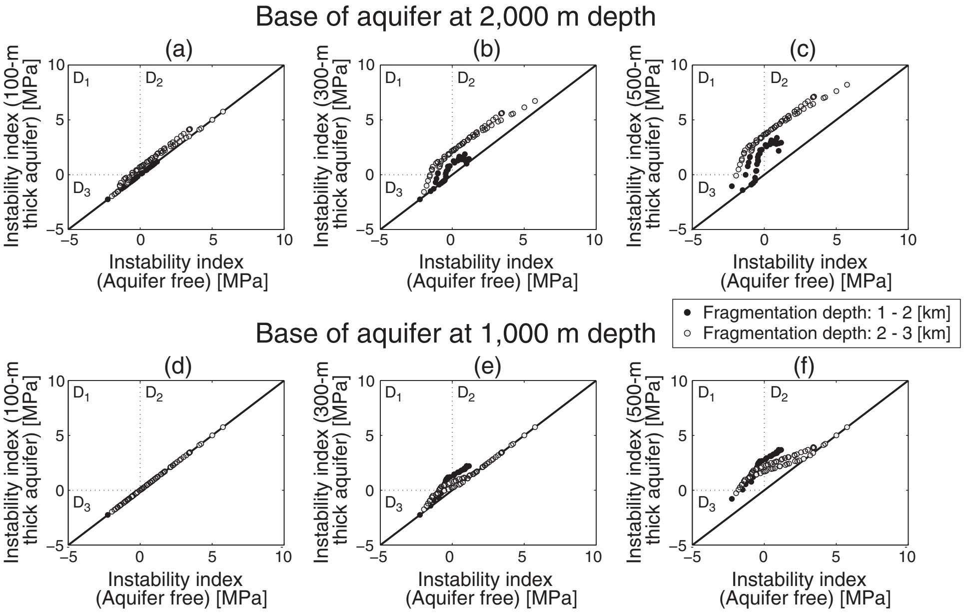

Fig. 4. – Relation between the instability indexes of aquifer-free conduits (x-axis) and results related to the presence of unconfined aquifers (depths and thicknesses are indicated in titles and y-axis), using Mogi-Coulomb collapse criterion. D_1: domain of mechanical stability for aquifer-free simulations and mechanical instability for simulations with shallow aquifers. D_2: domain of mechanical instability for both sets of simulations. D_3: domain of mechanical stability for both sets of simulations.

limited consequences on conduit dimensions. Because of the strong relation between conduit radius and mass discharge rate ($R^4 \propto$ MDR), the substrate characteristics would systematically influence the typical eruption rates of explosive eruptions and thus it could control other important eruptive parameters, such as column height and dispersal power of the pyroclasts [1].

The presence of unconfined aquifers is an additional controlling factor of volcanic conduit stability. Since pore pressure increases the minimum pressure for avoiding conduit collapse, aquifers tend to produce a significant destabilizing effect in the conduit, and collapse conditions are expected to be concentrated around shallow aquifers when they are present. Accordingly, phreatomagmatic interaction would be commonly related to the inclusion of relatively high volumes of conduit fragments in the erupted mixture, which is consistent with the presence of lithic fragments in many pyroclastic deposits with evidences of magma-water interaction [25, 26]. Moreover, because aquifer pressure is considered in the formulation of both collapse criteria, confined aquifers are expected to produce an even higher destabilizing effect. On the other hand, since collapse conditions are expected to be favored by narrow conduits [8], the presence of shallow aquifers could represent a relevant conduit enlargement catalyst during the onset phases of volcanic eruptions, as suggested by the occurrence of phreatomagmatic interaction during the opening stages of many eruptions [24, 27].

5. – Concluding remarks

Based on numerical modelling, I studied the factors which control volcanic conduit stability, with a clear focus on the role of the country rock mechanical parameters and the presence of unconfined aquifers. This study highlights that:

a) Country rock mechanical parameters are non-negligible factors for evaluating conduit wall collapse conditions. Indeed, friction angle and cohesion present a significant influence on conduit stability, and thus on the expected dimensions of the conduit.

b) Since the presence of unconfined shallow aquifers produces important destabilizing effects, phreatomagmatic interaction would be likely related to volcanic conduit erosion by walls collapse, and the inclusion of lithic fragments in the erupted mixture.

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