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Elasto-plastic models of magma inflation**

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## Highlights

- Seismicity at Piton de la Fournaise displays a cup shape dipping 2 km below the eastern flank's surface,
- elasto-plastic models with topographic loading and magma inflation source test various rock frictions,
- a dike-like inflation source below the eastern flank produces a too shallow dipping shear zone,
- inflation of the magma reservoir at ca. 0 km depth produces a shear zone comparable to observations,
- the 3D kinematics of this shear zone indicate that it may not spark an imminent flank slide.

# What causes the persistent seismicity below the eastern flank of Piton de la Fournaise (Réunion Island) ? Elasto-plastic models of magma inflation

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## Abstract

Identifying the causes of flank destabilization of active volcanic edifices is key to prevent catastrophic events. The persistent seismicity recorded below the eastern flank of Piton de la Fournaise shield volcano (Réunion Island), both in between and during eruptive events, may give indications on the mechanical stability of this edifice. Whether this asymmetric "cup" shaped seismicity is linked to magma injections and whether it sparks a gravitational flank slide motivates this study. Here we model the elasto-plastic behavior of this volcanic edifice at crustal scale, with the 3D finite-element code Adeli. First, we test the influence of tensile failure, recently implemented in combination to a Drucker-Prager shear failure criterion; a pressurized cavity below a flat top surface triggers shear failure in general, with tensile failure restricted to the surface and cavity tip. Then we include the topography of Piton de la Fournaise in the gravity field. Considering first only elasticity, deviatoric stresses attain about 35 MPa below the volcanic edifice and displacements are maximum in the horizontal east-west direction, reaching 30 m near sea-level. Introducing plastic behavior produces a rather symmetric cup shape plastic domain around the volcano's summit, that extends at depth with reducing bedrock *effective* friction (which acts as a proxy for reduced standard friction due to pore fluid pressurization). An asymmetric listric shear zone develops down to -3 km (bsl) only if the tensile strength, cohesion and friction angle are set as low as 1.5 MPa, 3 MPa and 3°, respectively; these values hence provide a lower bound for the edifice's effective strength. The second part of this study explores the influence of an internal overpressure, which is either applied as a vertical inflation source located about 500 m below the surface of the eastern flank, simulating a distal dike, or from a deeper ellipsoid simulating the magma reservoir located at depth ca. 0 km (near sea level) below the summit. The resulting strain pattern forms a cup-shaped shear zone dipping down below the eastern flanks of the edifice, reaching depth -2 km (bsl) if effective friction angle is  $\leq 5^\circ$ . Whereas the deep base of the dike and the eastern edge of the magma reservoir coincide geometrically in the models, the inflating dike produces a shear zone 1 km shallower than does the inflating magma reservoir, the latter coinciding better with the shape of the observed seismic cup.

Hence, we propose that this structure is a mechanical consequence of continuous magma supply in the reservoir, coherent with previous interpretations. This means that at least originally it did not need to form as a pre-existing weak zone or a magma-filled structure. However, this shear zone delimits an underlying domain in dilatation relative to a constricted hanging-wall; it may thus promote magma sills. It also branches to the surface with planar radial shear zones comparable to some observed eruptive fissures. The 3D kinematics of this shear zone does not rule out the possibility of a giant flank slide, although it does not appear today as imminent.

*Keywords:* volcano flankslides, elasto-plastic behavior, magma inflation, seismicity

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## 1. Introduction

Seismicity is a common feature of active volcanoes. It results from stress changes linked to magma pressurization in reservoirs or dikes, to gravitational instabilities and to the local tectonic activity. The Piton de la Fournaise shield volcano, la Réunion Island, displays a peculiar seismic pattern in its upper most 4 km and below the Enclos Fouqué present-day caldera (Fig. 1). This hotspot volcano produces a mean of 2 eruptions per year (Staudacher et al., 2009; Peltier et al., 2009; Roult et al., 2012) and is well monitored, making it a great natural laboratory to understand the interplay between eruption dynamics and the edifice's mechanical state. Recent eruptions are fed by a main shallow reservoir located approximately 1.5-2.5 km below the edifice's summit (Peltier et al., 2009; Di Muro et al., 2014), with magma migrating via localized dike injections that adopt vertical or inclined trajectories (e.g. Chevallier and Bachèlery, 1981; Bonali et al., 2011; Smittarello et al., 2019). Seismicity associated with these magma injections concentrates within a bulk volumetric domain about 1 to 2 km below the summit (Lengliné et al., 2016; Duputel et al., 2019, 2021). It superimposes on seismic activity in distal regions below the eastern flank of the volcano, which persists during pre-eruptive periods and bursts during magmatic intrusion events; a ca. 6 years record reveals a three-dimensional curved or *cup* shaped structure, dipping to the East down to -2 km below sea level, 5 km away from the summit (Fig. 1b, Duputel et al., 2021). Such flank seismicity has also been identified at other active volcanoes, like at Kilauea, Hawaii, where it is clearly associated with a deep tectonic decollement plane (Got et al., 1994; Poland et al., 2017). However, at Piton de la Fournaise, although N120 oriented fault lineaments have been identified consistent with regional-scale oceanic fractures (Michon et al., 2009), regional geophysical surveys (Gailler et al., 2018) and airborne MT surveys (Dumont et al., 2019) confirm that flank seismicity at Piton de la Fournaise lacks a strong control from active tectonics.

This distal, persistent seismicity in which we are interested in here, is actually observed since the installation of the first dense seismic recording network, thus since at least ca. 30 years (Hirn et al., 1991). A number of studies have explored the relation between magmatic injections patterns, surface motion and

25 seismicity at Piton de la Fournaise (e.g. Peltier et al., 2009; Famin and Michon, 2010; Got et al., 2013;  
26 Michon et al., 2015; Smittarello et al., 2019) indicating that this seismogenic domain may be a weakened,  
27 'damaged' volume or/and a zone of magmatic fluid circulation or storage. The interplay between magmatic  
28 injections and the continuous motion of the eastern flank, which slips by a few cm/yr and up to tens of  
29 cm during volcanic crises (Bachèlery, 1981; Brenguier et al., 2012; Got et al., 2013; Peltier et al., 2015;  
30 Froger et al., 2015) is still debated. More than 500 km<sup>3</sup> of avalanche debris cover the submarine flanks  
31 of the Island (Oehler et al., 2008), which indicates regular edifice flank destabilizations and motivates the  
32 need to assess the meaning of this seismicity in terms of flank slide hazards. On the other hand, modelling  
33 studies showed the key role of edifice's strength in generating volcano flankslides, and the effect of strength  
34 reduction induced by hydrothermal fluid flow forced by magmatic injections (Iverson, 1995). However it was  
35 also shown difficult to reproduce deeply seated flankslides (at depths greater than ca. 1 km depth), because  
36 this requires extreme magma overpressure or an extremely weak decollement plane (Reid, 2004; Morgan and  
37 McGovern, 2005b; Apuani and Corazzato, 2009).

38 At Piton de la Fournaise and in continuity with previous studies that investigated the source(s) and the  
39 mechanical triggers of observed deformation (Cayol and Cornet, 1998; Fukushima et al., 2005, 2010; Peltier  
40 et al., 2006, 2008; Michon et al., 2009; Got et al., 2013; Tridon et al., 2016; Smittarello et al., 2019; Beauducel  
41 et al., 2020), here we explore the mechanical state of the edifice considering its crustal scale, and test whether  
42 the persistent seismicity pattern can be reproduced. Therefore we design 3D (three-dimensional) numerical  
43 models that account for the gravitational load of an edifice behaving elasto-plastic and affected by the  
44 overpressurization of a magma reservoir or a dike. While the construction of a volcanic edifice obviously  
45 results from the progressive accumulation of rock mass over hundred thousands of years by punctual magma  
46 injections, options to reproduce the appropriate stress buildup are limited (e.g. Apuani et al., 2005; Morgan  
47 and McGovern, 2005a). While one view point treats the stress field as isotropic (Cayol and Cornet, 1998),  
48 here we choose the other view point in which the edifice's topographic load is 'suddenly' imposed within the  
49 gravity field. The study aims at bracketing the potential influence on present day deformation of gravity,  
50 with and without magma pressurization, acknowledging that reciprocally, many studies have already shown  
51 how the edifice's load plays a key role in orienting the trajectory of magma towards the surface (Watanabe  
52 et al., 2002; Hurwitz et al., 2009; Pinel and Jaupart, 2005; Pinel et al., 2010). At first order, we choose  
53 not to take into account other causes of deformation related to pre-existing heterogeneities, faults and deep  
54 plutonic bodies (Michon et al., 2015; Gailler et al., 2018), chemical reactions and hydrothermal alteration  
55 (e.g. Barde-Cabusson et al., 2012; Boudoire et al., 2017; Dumont et al., 2019). However our results will drive  
56 us to discuss these factors, since they are all interlinked within the multi-scale dynamics of any volcanic  
57 system.

58 After a summary of the state of knowledge at Piton de la Fournaise, Section 3 below presents our  
59 numerical approach, the FEM method Adeli, which has been applied to a variety of geodynamic contexts

60 for years (Hassani et al., 1997; Gerbault et al., 2018). In preamble we present a newly implemented tensile  
61 failure criterion and illustrate its potential influence on our specific volcanic setting. First tests display  
62 stresses and deformation resulting from a magmatic reservoir of comparable depth and size to that inferred  
63 below Piton de la Fournaise, considering separately, the influence of the inflation source’s geometry, the  
64 bedrocks’ strength, gravity alone or topography alone; these results illustrate the relative influence of each  
65 factor. In section 4 we illustrate how stress and deformation patterns are affected by the equilibration of  
66 topography considering elastic and then elasto-plastic behavior. In section 5 we look at the influence of a  
67 magma inflation, either offset below the eastern flank of the volcano simulating a distal dike injection, or  
68 centered below the summit at ca. 2.5 km depth simulating the magma reservoir. Finally we compare the  
69 resulting deformation patterns with observations and previous works, commenting on the volcano dynamics.

## 70 **2. Piton de la Fournaise, a summary of the state of knowledge**

71 Piton de la Fournaise is the latest active volcanic manifestation along the track of La Réunion hotspot.  
72 It is a 0.5 Myrs old (McDougall, 1971; Gillot and Nativel, 1989), shield volcano culminating at 2632 meters  
73 and built on the eastern side of the older Piton des Neiges volcanic edifice (5 Myr old; Gillot et al., 1994).  
74 Its surface morphology is marked by the presence of three nested rims, the calderas of Rivière des Remparts,  
75 Plaine des Sables, and the youngest Enclos Fouqué with a fully developed horse-shoe shape opened to the  
76 East on the Indian Ocean (Fig. 1).

77 Ninety-five percent of the eruptions of the last three centuries occurred within the Enclos Fouqué (Chevrel  
78 et al., 2021), which also hosts a 400 m-high, 3-4 km-wide central cone. The April 2007 Dolomieu caldera  
79 collapse was coeval to the largest historical eruption at Piton de la Fournaise (e.g. Michon et al., 2009).  
80 According to Michon et al. (2015), previous volcanic centers concentrate within 4 other main domains  
81 besides the Enclos Fouqué. Two domains were active from 60-30 ka, the southern volcanic zone (SVZ), and  
82 the NW-SE rift zone linking the N120 axis linking the Piton des Neiges and Piton de la Fournaise summits.  
83 This NW-SE, N120 oriented rift zone (the "Plaine des Cafres" area) stands as a main tectonic feature  
84 still hosting eruptive vents, and is believed to be an inherited structure (a fracture zone) cutting through  
85 the whole oceanic crust (Chevallier and Bachèlery, 1981; Michon et al., 2015). Cross-analysis of geophysical  
86 data, geochemistry and volcanic cone morphometry shows that volcanism at the Plaine des Cafres originates  
87 from the deep magmatic plumbing system of Piton de la Fournaise (Boudoire et al., 2017).

88 Eruptive fissures cover the entire volcanic area, and many concentrate in two NE-SE-oriented fracture  
89 zones branching on the central cone, forming the typical "Rift Zones" identified in many volcanic complexes  
90 (e.g. Canaries, Hawaii, Etna, Michon et al., 2015): these are believed to develop in relation to the mechanical  
91 disequilibrium between the "mobile" side of the edifice, open to the ocean (the eastern flank here) and  
92 the "locked" side shouldering on the island’s interior (to the west). This disequilibrium is maintained by

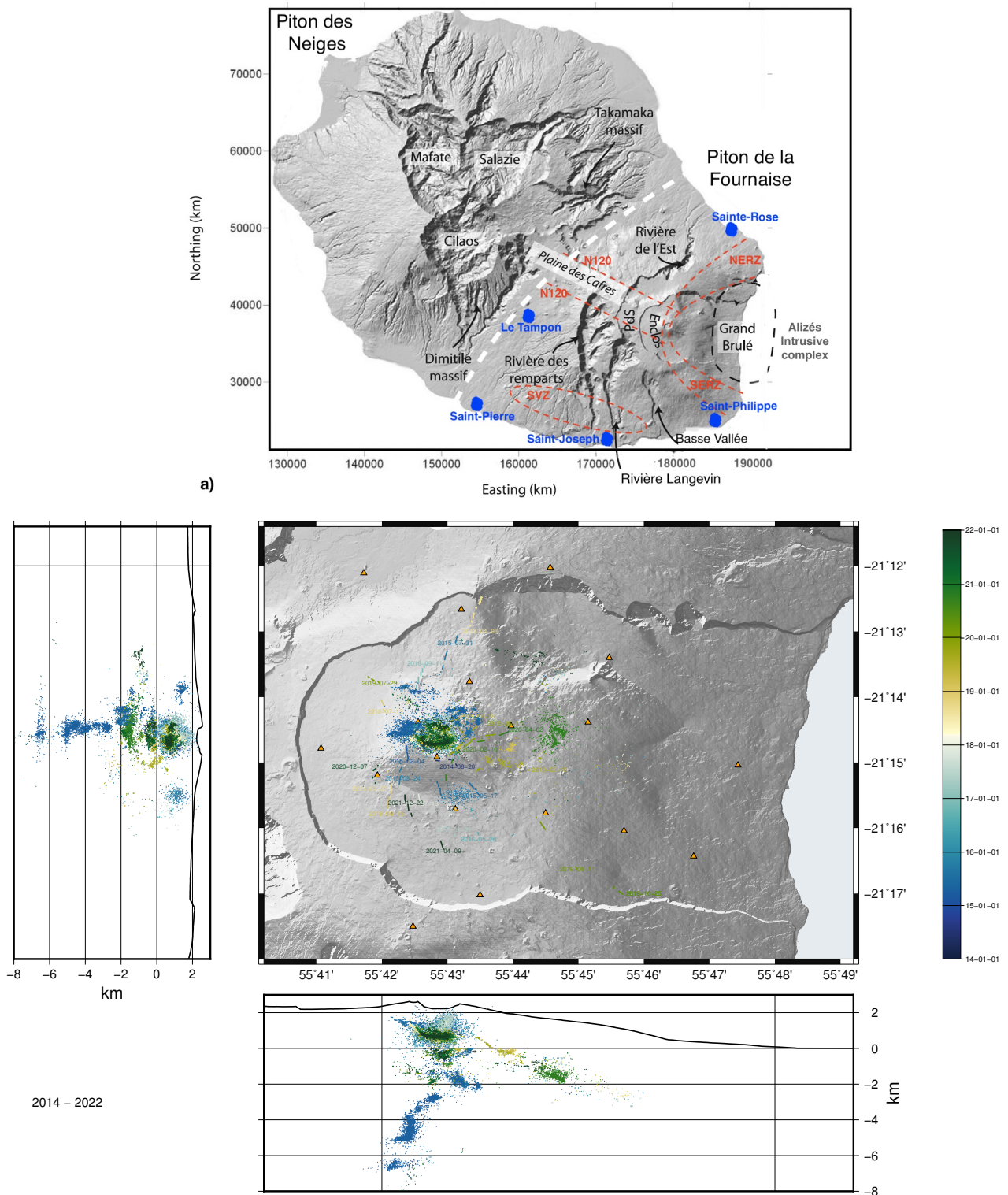


Figure 1: The Piton de la Fournaise volcano occupies the Southern part of Réunion Island: a) Rift zones (NERZ, SERZ and N120) and specific locations names (towns in blue). PdS: Plaine de Sables; SVZ: Southern Volcanic Zone. b) topography of the Enclos Fouqué and earthquake locations between February 2014 and June 2021 in plane view and along north-south and east-west profiles (OVPF, Lengliné et al., 2016; Duputel et al., 2019). FOAG GPNP and FJAG are GPSG stations (triangles).

93 repeated magma injections and eruptions, with the eastern side of Piton de la Fournaise undergoing a  
94 continuous eastward displacement of a few cm/yr (Bachèlery, 1981; Brenguier et al., 2012; Peltier et al.,  
95 2015), transiently rising up during major crises, up to 1.4 m in 2007 (e.g. Froger et al., 2015). Volcanic  
96 eruptions along these NE (ca. N25) and SE (ca. N155) Rift Zones and outside the Enclos Fouqué, are  
97 reported to have been mostly active from ca. 5 ka to 2.8 ka (Michon et al., 2015, and references therein).  
98 With rare eruptions outside the Enclos Fouqué, a spatial alternation is observed in eruptions locations  
99 between the SE and the NE rift zones inside the Enclos Fouqué, especially since 2007 (Dumont et al., 2022).  
100 Michon et al. (2015) proposed a switching mechanism of the tensile stresses orientation between these rift  
101 zones and the eastward motion of the volcano’s eastern flank, coeval with magma propagation at depth from  
102 vertical -dike- injections to shallower -sill- intrusions.

103 Furthermore, the fissures and fractures network in the vicinity of the central cone were categorized into  
104 3 main groups by Michon et al. (2009): ca. N20 and ca. N65 oriented eruptive fissures opened perpendicular  
105 to the slope, concentric fractures parallel to the Bory and Domolieu crater scarps, and linear flank structures  
106 cross-cutting several geological units (Fig. D.1). It is debated whether some of these deformation zones are  
107 R’ shear structures associated with the eastern flank slump motion or instead, structural features associated  
108 with the vertical plug exerted by magma intrusion (Carter et al., 2007; Michon et al., 2009).

109 The magma that feeds present-day eruptions originates from an aseismic, partially molten horizon cen-  
110 tered below the central cone, at a depth of about 2 km below the summit (Peltier et al., 2009; Di Muro  
111 et al., 2014; Lengliné et al., 2016). This horizon is referred to as the *shallow* magma reservoir. Dikes are  
112 identified to rise from this horizon and propagate towards the surface. At greater depth, seismicity initiates  
113 from a ca. 20-30 km depth in a N20 oriented domain set in between the Piton des Neiges and Piton de  
114 la Fournaise, then rises up from 20 to 10 km depth generally along the N120 NW-SE rift zone, to focus  
115 nearly below the central cone at ca. 10 km depth (Michon et al., 2015; Duputel et al., 2021). Between 1998  
116 and 2007, surface displacements occurred by cycles, after many summit-proximal eruptions during which  
117 the E-W component of the horizontal stress would increase (Peltier et al., 2008; Got et al., 2013). This was  
118 understood as a process of stick-slip elasto-plastic displacement of the eastern flank in response to pressur-  
119 ization of the shallow magma reservoir that led to major distal eruptions (Got et al., 2013). Densification  
120 of the seismometers network from 2013 allowed to improve seismicity location. While earthquake location  
121 techniques are strongly dependent on the choice of a velocity model (Lomax et al., 2000), the persistent  
122 seismicity that occurs offset with respect to the central cone is currently shown to display an inclined trend  
123 eastward 2 km below sea level (*bsl*) below the eastern flank, with slightly shallower south and northern edges.  
124 Hence its ”cup” shaped designation. Enhanced during magma injection events, it also persists in between  
125 them (Figs. 1b, D.2, Duputel et al., 2021).

126 The goal of the present study is to analyze how the observed persistent seismicity pattern may be linked  
127 to the typical topography of Piton de la Fournaise and to dike injection or inflation of the shallow magma



128 reservoir. We will not incorporate the effect of deeper magma reservoirs at ca. 8 km and 20 km depth *bsl*  
129 (Prôno et al., 2009; Di Muro et al., 2014; Lengliné et al., 2016), nor will we test the role of pre-existing weak  
130 faults or intrusion zones such as did Michon et al. (2009) and Chaput et al. (2014). Although these studies  
131 will be mentioned again when discussing our results, here instead, we ask whether it is possible to *form* a  
132 deformation zone similar to the recorded seismic cup pattern *above* ca. -4 km depth, in relation to its steep  
133 asymmetric topography and standard magma injection events. Is there a peculiar state of stress associated  
134 with gravitational loading, or is it necessary to invoke pre-existing heterogeneity zones? Is the persistent  
135 seismic "cup" pattern a rather passive feature or instead a potentially active destabilizing, large-scale shear  
136 zone? Is it activated with the complementary load exerted by repeated magma reservoir inflation or instead  
137 by dike injections?

### 138 3. Numerical method, model setup and preliminary tests

#### 139 3.1. ADELI: a standard FEM for elasto-plastic modelling

140 Adeli is a Finite Element method (FEM) that resolves the quasi-static equation of motion by using  
141 the numerical relaxation method (Cundall, 1988). This time-explicit method was shown to handle well the  
142 initiation and propagation of brittle elasto-plastic shear zones throughout the crust (Poliakov et al., 1993;  
143 Gerbault et al., 1998). Adeli has been used for decades to model various elasto-visco-plastic rheologies in  
144 geodynamics and volcanology (Hassani et al., 1997; Chéry et al., 2001; Got et al., 2008; Cerpa et al., 2015;  
145 Gerbault et al., 2018). Details on the numerical method can be found in these publications and in Appendix  
146 A, and a repository link is provided in the *Code and Data Availability* section.

#### 147 3.2. Combining shear and tensile failure for an elasto-plastic rheology

148 Here, we use non-associated Drucker-Prager elasto-plasticity combined with a tensile failure criterion.  
149 Tensile failure was not accounted for in Adeli until 2019, and is now implemented based on the approach  
150 described in Itasca Flac's manual; details are provided in Appendix A. While the Drucker-Prager criterion  
151 depends on the material cohesion  $C$  and friction angle  $\varphi$ , tensile failure is assumed to depend on a critical  
152 mean pressure threshold  $p_t$ . Assuming constants  $\alpha = \frac{6 \sin \varphi}{3 - \sin \varphi}$ ,  $p_0 = \frac{C}{\tan \varphi}$ , the domain of admissible stresses  
153 is delimited by a truncated cone in the stress space (Fig. 2), defined by the Drucker-Prager yield envelope  
154 ( $f_s$ ) and the tensile yield envelope ( $f_t$ ), assuming  $p_t \leq p_0$  (we use further  $T = p_t$  for conveniency):

$$\begin{cases} f_s(\boldsymbol{\sigma}) = J(\boldsymbol{\sigma}) + \alpha(p - p_0), \\ f_t(\boldsymbol{\sigma}) = p - p_t, \end{cases} \quad (1)$$

155 where  $p = \text{tr}(\boldsymbol{\sigma})/3$  is the mean pressure and  $J_2(\boldsymbol{\sigma}) = \sqrt{3/2}\|\boldsymbol{s}\|$  is the second invariant of the deviatoric  
156 stress  $\boldsymbol{s} = \boldsymbol{\sigma} - p\mathbf{I}$ . Strain invariants are defined similarly with respect to the strain tensor  $\boldsymbol{\varepsilon}$  and will be  
157 displayed for the models below (cf. **Appendix A**):

- the total shear strain  $J_2(\boldsymbol{\varepsilon}) = \int_0^t \sqrt{\frac{2}{3}} \|\dot{\boldsymbol{\varepsilon}}\| dt$ , and the effective plastic shear strain  $\varepsilon_p(t) = \int_0^t \sqrt{\frac{2}{3}} \|\dot{\boldsymbol{\varepsilon}}_p\| dt$ ,
- the mean strain is the tensor's trace  $I_1(\boldsymbol{\varepsilon}) = \text{tr}(\boldsymbol{\varepsilon})$ , which displays dilatational zones when positive,
- the shear strain component  $\varepsilon_{zx}$ , acts along the vertical direction  $z$  (negative downwards, origin at sea level), and the eastward direction  $x$ ,
- differential values are sometimes plotted, subtracted from values prior to magmatic pressurization.

Note that the convention here is that compressive stress is negative. A Table summarizing the meaning of parameters and symbols can be found in **Appendix A**. Two benchmarks are presented in **Appendix B** to validate the implementation of tensile failure: uniaxial traction and compression of a pierced plate. Whereas the first case displays analytical solutions the second one does not, and we welcome the community to share benchmarks for such implementation.

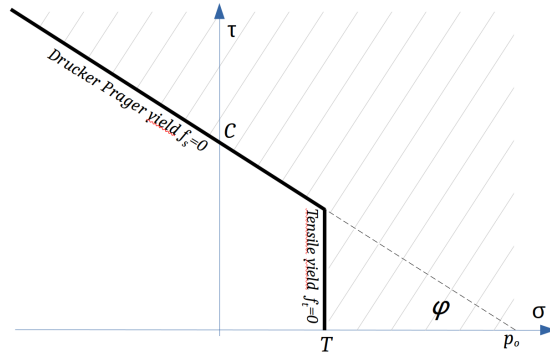


Figure 2: Combined shear and tensile yield envelopes in the first and second stress invariants space  $(\sigma, \tau)$  (modified from Itasca FLAC user manual, parameters from eq. 1).  $T = p_t$  is the tensile strength,  $C = p_0 / \tan(\varphi)$  the cohesion, and  $\varphi$  the friction angle. The shaded domain delimits the prohibited stress field (elastic behavior occurs below the yield envelopes).

### 3.3. Shear and tensile failure around an inflating cavity, no topography

We start our modelling approach with a standard configuration used to model magma reservoir inflation below a flat surface (e.g. Sartoris et al., 1990; Trasatti et al., 2003; Bonaccorso et al., 2005; Currenti and Williams, 2014; Gerbault et al., 2018). Our three-dimensional (3D) setting is similar to that adopted by Gerbault et al. (2018) for an elasto-plastic medium, with the addition of a tensile failure criterion as described above. The inflating source is defined as an ellipsoid cavity of geometry similar to that inferred for the shallow reservoir below Piton de la Fournaise (cf. section 2): its center is located at  $z = -2$  km (vertical axis negative downward), its Y and Z semi-axis are equal to 0.5 km, and its X semi-axis is equal to 0.75 km, hence elongated in the East-West orientation later on. The lateral borders are set free-slip whereas the top surface is set stress free. A step-wise increasing pressure is applied at the reservoir's walls so that stresses and deformation then propagate progressively throughout the domain. On the appropriateness of applying an overpressure rather than a displacement, the reader can refer to (e.g. Sartoris et al., 1990). Note also

180 that only a quarter of the model domain is considered because of radial symmetry, saving computational  
 181 cost: the modeled domain is a cube of edge length 50 km and mesh resolution reaches 75 m at the cavity  
 182 walls.

Model name	Fig.	Source axes/depth (km)	Tensile and shear strengths	Gravity	Topo	Surface Disps (m)
M1	3	I2: 0.75-0.5-0.5 / -2	$T, C = 1, 5 \text{ MPa}, \varphi = 3^\circ$	OFF	0	$U_x=0.027 \ U_z= 0.083$
M2	3	I2: 0.75-0.5-0.5 / -2	$T, C = 1, 5 \text{ MPa}, \varphi = 3^\circ$	ON	0	$U_x=0.022 \ U_z= 0.068$
M3	3	I3: 1.5-0.5-0.5 / -2	$T, C = 1, 5 \text{ MPa}, \varphi = 3^\circ$	OFF	0	$U_x=0.045 \ U_z= 0.170$
M4	3	I3: 1.5-0.5-0.5 / -2	$T, C = 1, 5 \text{ MPa}, \varphi = 3^\circ$	ON	0	$U_x=0.040 \ U_z= 0.142$
M5	4	I1: 0.06-0.5-0.5 / -1	$T, C = 3, 5 \text{ MPa}, \varphi = 3^\circ$	OFF	PdF	$U_x=0.043 \ U_z= 0.090$
M6	4	I1: 0.06-0.5-0.5 / -1	$T, C = 3, 5 \text{ MPa}, \varphi = 15^\circ$	OFF	PdF	$U_x=0.032 \ U_z= 0.060$
M7	4	I2: 0.75-0.5-0.5 / 0.	$T, C = 3, 5 \text{ MPa}, \varphi = 3^\circ$	OFF	PdF	$U_x=0.039 \ U_z=0.072$
M8	4	I2: 0.75-0.5-0.5 / 0.	$T, C = 3, 5 \text{ MPa}, \varphi = 15^\circ$	OFF	PdF	$U_x=0.022 \ U_z=0.045$

Table 1: Models testing independently the influence of gravity, topography, strength and source geometry. First four cases with a flat surface test gravity and the inflating source geometry (semi-axis  $a_X$  varies for I1,I2,I3). I2 geometry is similar to that of the reservoir below Piton de la Fournaise ('PdF'). Next four cases illustrate the influence of PdF topography without gravity, for distinct source geometries and bedrock strength (tensile strength  $T$ , cohesion  $C$  and friction angle  $\varphi$ ). Young's modulus in all cases is 10 GPa. The maximum surface displacements (last column) are for an overpressure  $DP = 10 \text{ MPa}$ .

183 Since the influences of inflating source geometry and gravity on elasto-plastic deformation were discussed  
 184 in the studies cited above, here we only recall key results in the framework of Piton de la Fournaise. The  
 185 influence of the source's elongation is readily explained with the increasing vertical stretching at its tips  
 186 upon inflation at the walls, which facilitates tensile failure there. The influence of gravity in turn, appears in  
 187 the normal stress acting on potential failure planes : the deeper the overpressure source, the more negative  
 188 the mean stress, away from the tensile threshold. But if the rock mass is considered undrained, then fluid  
 189 overpressure cancels out the normal component of the stress field. This key role of interstitial fluids was  
 190 first expressed by Terzaghi (1943) and King Hubbert and Rubey (1959), with pore pressure ( $p_f$ ) written  
 191 proportional to the overburden weight ( $\rho \cdot g \cdot z$  at depth  $z$ ). Hence, observations of hydrostatic and sometimes  
 192 lithostatic fluid pressures in deep wells worldwide have led to the understanding that rocks strength can  
 193 be reduced in the first couple of kilometers depth (e.g. Suppe, 2014). One can then either assume that  
 194 gravity cancels out or that the "effective" friction is low. The frictional yield can then be expressed with the  
 195 effective friction ( $\varphi$ ) instead of the intrinsic friction ( $\phi$ ), so that  $\tan \phi \cdot (\sigma_n - p_f) \sim \tan \varphi \cdot \sigma_n$ . Recall that  
 196 this influence of fluid overpressure on effective strength was also the argument used by Iverson (1995) and  
 197 Reid (2004) to increase the depth at which rock wedges may destabilize (hydrothermal fluid overpressure  
 198 would propagate from magmatic sources).

199 To assess these effects, here we display a first series of four models, with two inflating source geometries  
 200 and with gravity turned "on" or "off". The bedrock has an elasto-plastic rheology with parameters  $E = 10$   
 201 GPa,  $T = 1 \text{ MPa}$ ,  $C = 5 \text{ MPa}$  and friction angle  $\varphi = 3^\circ$  (Models M1 to M4, Table 1). Figure 3 summarizes

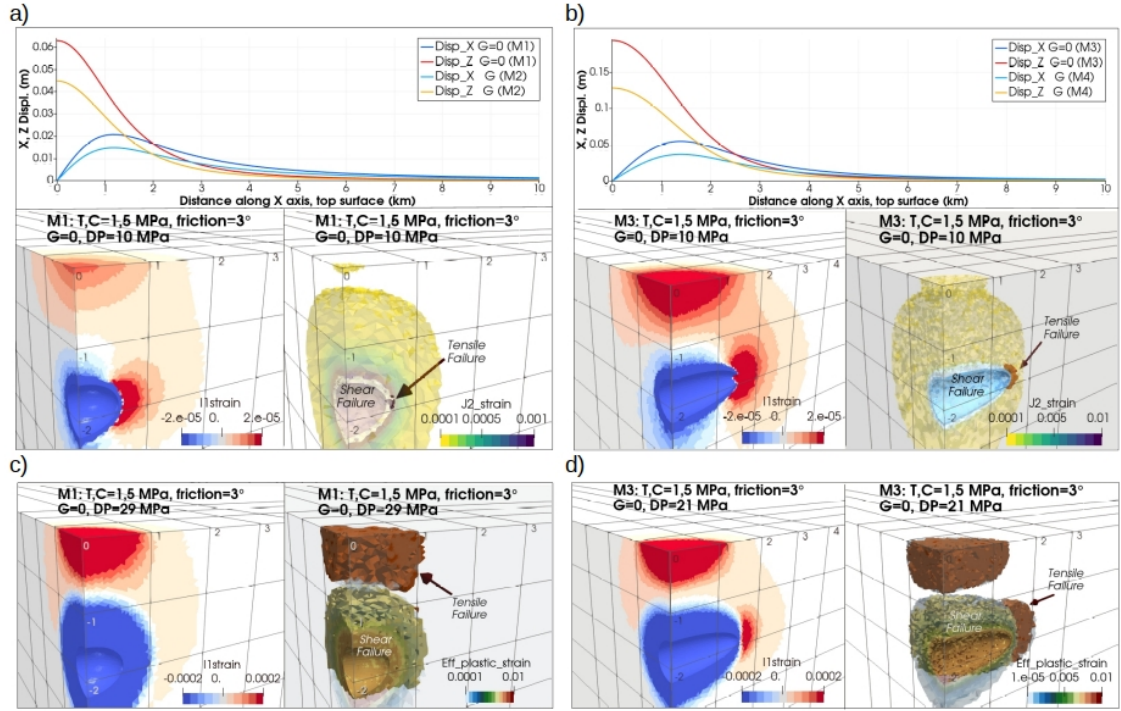


Figure 3: Inflation of a magma cavity below a flat surface in elasto-plastic bedrock, for an overpressure  $DP = 10$  MPa: **a)** for an elliptical magma source with semi-axes  $a_Z = a_Y = 0.5$  km,  $a_X = 0.75$  km (model M1). **b)** for an elongated source with horizontal axis  $a_X = 2$  km (model M3). Figures display 3D views of the total shear strain and the effective plastic strain (top-left) and the mean strain (bottom-left, red for dilatation and blue for constriction). Note that tensile failure only occurs at the tip of the elongated source (b). To the right, vertical ( $z$ ) and horizontal ( $x$ ) displacements at the surface, with the additional cases with gravity "turned on" (M2 in a, and M4 in b), and  $x$  and  $z$  displacements on a vertical section along plane  $Y=0$ . **c-d)** Same models once overpressure exceeds 29 MPa for M1(c) and 21 MPa for M3(d): the mean stress to the left, and domains undergoing shear (yellow) or tensile (brown) failure modes to the right. Parameters given in Table 1.

202 the results for an overpressure  $DP = 10$  MPa :

- 203 • The deviatoric stress decreases at a cubic rate with distance ( $1/r^3$ ,  $r$  the distance from the source,
- 204 Timoshenko and Goodier, 1951) so that failure only initiates in the immediate vicinity of the source
- 205 even at low strength Figs. 3a,b).
- 206 • The surface displacements with the elongated reservoir are almost twice those obtained with the more
- 207 spherical reservoir (models M1, M2 vs. M3, M4, Figs. 3).
- 208 • When gravity is accounted for, the deviatoric stress field needs to overcome a factor of the overburden
- 209 weight ( $\rho.g.z$ ) for failure to occur, hence no failure occurs at  $DP=10$  MPa. Hence models with gravity
- 210 "on" display similar patterns to models without gravity, and there is no point in displaying them. Only
- 211 the surface displacements are  $\sim 15$  % lower than without gravity (due to lack of plastic behavior).

- 212 • "Without" gravity, the elongated reservoir develops greater tensile stresses at its long axis tip, because  
 213 the exerted pressure on the walls tends to stretch them vertically. Tensile failure initiates there (Fig.  
 214 3b). The mixed tensile and shear failure mode that appears at the sharp intersection corner between  
 215 the two yield envelopes (**Appendix A**), is not captured here because of both too low mesh resolution  
 216 and low temporal sampling frequency.
- 217 • Brittle failure expands throughout the crustal domain: in M1 tensile failure barely initiates at the very  
 218 tip of the longest lateral edge (red zone in Fig. 3a). With increasing overpressure it mainly develops at  
 219 the surface above 1 km depth, while shear failure dominates around the reservoir (yellow zones in Fig.  
 220 3c). In contrast in M3, tensile failure initiates and propagates from the tips as a ring-shaped front,  
 221 replaced by shear failure with increasing overpressure (Figs. 3b, d). Failure domains at the source's  
 222 edge and near the surface eventually connect with increasing pressure (cf. Gerbault et al., 2012), but  
 223 only once  $DP$  exceeds 21 and 29 MPa for geometries I3 and I2, respectively.

#### 224 3.4. Building a numerical model for Piton de la Fournaise

225 We present now models that account for the relief at Piton de la Fournaise. Therefore, the mesh is built  
 226 using the *GMSH* software (Geuzaine and Remacle, 2009), for a model domain 42 km wide in both X and  
 227 Y directions, pointing eastward (X) and northward (Y) respectively. The vertical Z direction originates at  
 228 sea level and points negative downwards. Thickness is constrained by the depth to the Moho, which varies  
 229 between 14.5 km in the eastern border of the model domain to a maximum of 17.5 km in its south-western  
 230 corner (Gailler et al., 2018). Surface topography is implemented at the top surface so that the volcano  
 231 summit stands at coordinate  $X_o = 20$  km,  $Y_o = 25.8$  km. As in the previous models, lateral borders are  
 232 set free-slip while the top surface is set stress free.

233 The base of the model is set motionless, a boundary condition that might be questioned: fixing the  
 234 Moho's base corresponds to assuming that the mantle underneath is infinitely rigid and compensates the  
 235 surface topography. Actually some magmatic fluids from the mantle below might locally release the rocks  
 236 strength and impose instead viscous behavior over a certain breadth. Past tomographic studies including P  
 237 or S velocity models or both (Driad, 1997; Hirn et al., 1999; Gallart et al., 1999; Fontaine et al., 2015) have  
 238 mentioned the possible presence of magma at the Moho. This is interesting information because it questions  
 239 the kinematic status at this boundary; indeed, underplated low viscosity magma in sufficient quantity may  
 240 allow for lateral motion over a broad wavelength due to the search for isostatic reequilibration along the  
 241 Moho's slope. The detection of this motion by instruments is hindered by its large wavelength, much larger  
 242 than the Island's size. Hence in the frame of the present work, we do not consider this factor. Our choices  
 243 of rheological parameters are justified by the following arguments:

- 244 • Young's modulus: at Piton de la Fournaise, several studies assume  $E = 5$  GPa (Cayol and Cornet,

1998) in order to fit the observed surface displacements with reasonable overpressure values. This also corresponds with Heap et al. (2019)’s proposition based on a review of volcanic rock properties worldwide. However, greater values were considered by Chaput et al. (2014) (70 GPa) and Got et al. (2013) ( $E = 50$  GPa). Got et al. (2013) assumed that such a high Young’s modulus represented the intact, linear elastic part of the rock mass deformed at small strain, whereas most of the deformation was explained by larger plastic strain. Other authors such as Traversa et al. (2010) consider instead a Young’s modulus of 1 GPa, but they explore the first kilometer where dikes intrude near the surface. Therefore here, we opt for an intermediate value of 10 GPa for the entire crustal domain. More advanced models seeking accurate fit with data should obviously account for a depth dependent  $E$ , which should best rely on data-based correlations between seismic velocity and density (e.g. Brocher, 2005).

- Shear and tensile strength: these parameters are poorly constrained. For a wide range of rock types, i.e., altered vs. intact domains, hydrated vs. dry domains, superficial vs. crustal scale domains, tensile strength  $T$  generally varies between 1 and 5 MPa, cohesion  $C$  between 1 and 20 MPa, and friction between  $0^\circ$  and  $40^\circ$ , with low values corresponding to an *effective* value that accounts for pore fluid pressure (Cocco and Rice, 2002; Suppe, 2014; Villeneuve et al., 2018; Heap et al., 2020), see also discussion in Ginouves et al. (2021). While tension and cohesion control the stress thresholds over the first km below the top surface, friction becomes the main control parameter at greater depths. Saffer and Marone (2003) and Collettini et al. (2019) reviewed how fault zones display fluid-assisted reactions at the grain-scale as a general weakening mechanism in a variety of contexts, which lead to interconnected phyllosilicate-rich fault zones and can result in *effective* frictions as low as  $\mu = \tan(\varphi) = 0.1$  ( $\varphi \sim 7^\circ$ ). Recall also that a reduced effective friction was invoked to result from the propagation of overpressurized fluids throughout the rock mass below sloped wedges (Iverson and Reid, 1992); similarly here we will see that friction directly shapes the extent of plastic yielding throughout the volcanic edifice. Instead of displaying a cumbersome catalog of tests, we selected here three typical *effective* friction angles to test,  $\varphi = 3 - 5 - 10^\circ$ .

### 3.5. Stress and deformation with topography and no gravity

In seeking the role of topography, we first illustrate how the Piton de la Fournaise edifice impacts on the stress and strain fields induced by a magmatic inflation, without gravity. Gravity is added next.

Four cases displayed Fig. 4 illustrate the influence of the inflating source geometry (I1 vs. I2, models M5-6 vs. M7-8), and that of bedrock friction (models M5-7 vs. M6-8, Table 1). I1 cases describe a narrow vertical intrusion referring to a dike located 1 km east from the crater’s center, extending upwards over 1 km (geometry I1). Below, we will use indifferently the term ”intrusion” or ”injection” to describe the application of an overpressure at the walls of this modeled ”dike”, regardless of whether magma reaches the surface or

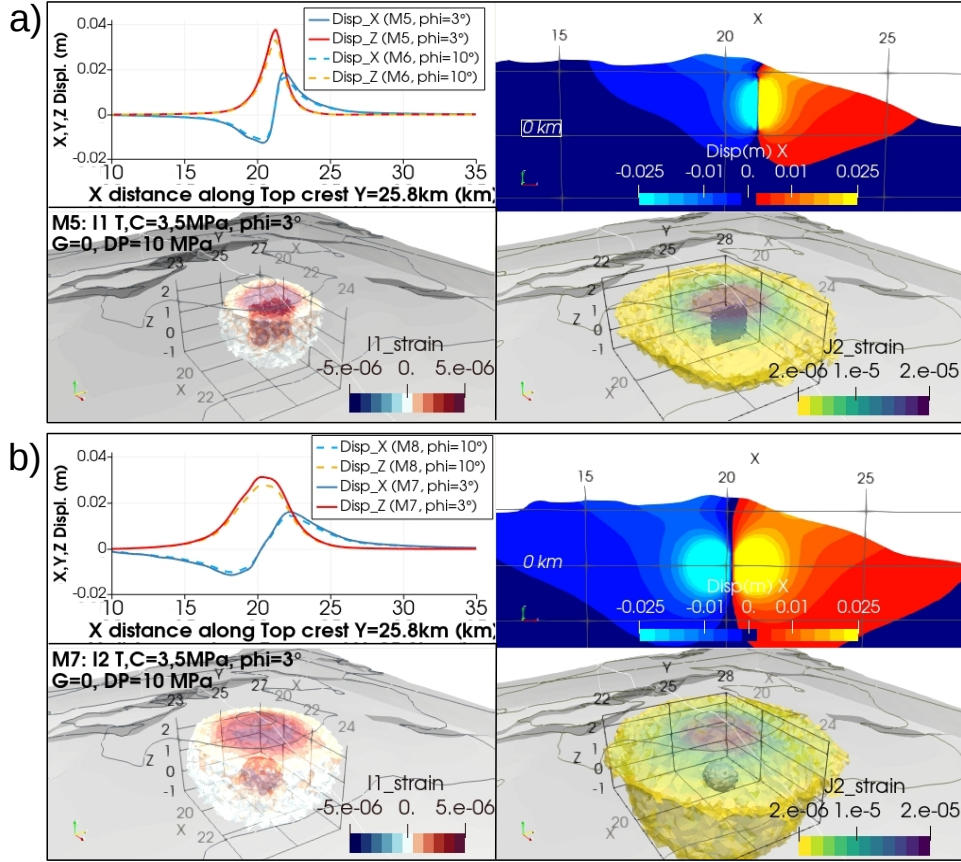


Figure 4: Inflation of a magma cavity with Piton de la Fournaise's topography and *no* gravity (models M5 to M8), overpressure. Displacements ( $x, z$ ) at the surface (top-right) and along a vertical profile oriented East-West (  $X$  direction, top-left). Bottom-left: the mean strain (dilatation in red), and bottom-right, the total shear strain isocontours. An overpressure  $DP = 10$  MPa is applied from a narrow dike (I1, **a**) or from an ellipsoidal reservoir (I2, **b**). Contour plots are presented for low friction models (M5, M7) while the surface displacements also display the *higher friction* cases (M6, M8). Parameters in Table 1.

not. As for I2 cases, they describe a magma reservoir located below the summit at center coordinate depth  $z = 0.5$  km and of ellipsoidal shape with semi-axes  $a_z = 0.5$  km,  $a_y = 0.5$  km,  $a_x = 0.75$  km (references in section 2, and Staudacher et al. (2009)). The results are summarized as follows for an applied overpressure  $DP = 10$  MPa:

- With this overpressure, plasticity only initiates in the vicinity of the magma reservoir walls, in both geometries I1 and I2 and for the lowest friction cases (M5 and M7). Greater friction cases remain elastic (M6 and M8).
- Because of this limited plasticity around the pressure source, displacements are not significantly impacted, barely 1 mm greater for low friction cases (M5 and M7) with respect to the more resistant cases (M6 and M8).

- 289 • Both inflation source geometries display similar displacement magnitudes but their extent varies: they  
290 extend over about 10 km for the dike (I1) and over almost 20 km for the reservoir (I2) (compare  
291 profiles Fig. 4a vs. 4b, top right). Stress and strain deformation isocontours are radial around the  
292 inflation sources, little impacted by the asymmetric topography at this scale.
- 293 • As of the influence of topography, we compare M7 - Fig. 4b- with M1 - Fig. 3a. We note that i)  
294 horizontal displacements have similar amplitudes but they expand along the eastern flank over an  
295 additional ca. 5 km with topography, ii) the vertical displacement in turn is reduced by about 2 cm  
296 at the summit and it also expands to the east over another ca. 5 km.
- 297 • The radial pattern of shear strain follows the circular shape of the Enclos Fouqué caldera (yellowish  
298 contours in Fig. 4), for values ranging between  $1.5 - 3.10^{-6}$ : this depression may thus consistently be  
299 interpreted as a mechanical consequence of cumulated micro-shear damage related to repeated magma  
300 inflation-deflation cycles (eg. Staudacher et al., 2009; Got et al., 2017).

#### 301 4. Accounting for gravity: stress and deformation related to topography only

302 Now, we "turn on" gravity to test the influences on stress and strain patterns, first of the bedrock's  
303 strength and second, of the geometry of the inflating source (cases I1 and I2 described in section 3). But  
304 a first pre-inflation stage has to be carried out without an inflating source so as to assess the edifice's  
305 equilibrium. Hence this section exposes the stress and deformation patterns produced when the medium  
306 "equilibrates" when topography alone is imposed. We assume at the onset of the runs that the stress field  
307 is isotropic, and we describe the results of four models that assume first an elastic, then an elasto-plastic  
308 bedrock (cf. Table 2).

##### 309 4.1. Topography, gravity, and elasticity

310 In model M00 assuming topography, gravity, and only elastic behavior, the resulting stress and defor-  
311 mation displayed Fig. 5 are consistent with analytical calculations on the back of an envelope: the weight  
312 of a vertical column at the edifice's summit generates  $\sigma = \rho.g.\Delta z = 2500.10.2600 \sim 65$  MPa, which induces  
313 a maximum shear stress of about half, e.g.  $\tau \sim 33$  MPa. From standard 1D Hooke's law, this induces a  
314 deformation  $\varepsilon = \tau/E$ , which over the width  $L \sim 10$  km of the edifice leads to a displacement  $dl = L\varepsilon \sim 33$   
315 m. The 3D models here allow to understand where these maximum values are located spatially, and they  
316 are not located at the same place: the shear stress (equivalent to  $J_2(\sigma)$  in Fig.5a) is maximum immediately  
317 below the edifice summit ( $J_2 \sim 35$  MPa) while horizontal displacement is maximum ( $\sim 29$  m) further along  
318 the eastern flank near the shore-line.



Model name	Fig.	Plastic strength	Inflation	Surface Disps (m)	Deformation style
<i>M00</i>	5,C.1	Elastic E=10 GPa	-	U <sub>x</sub> =27m U <sub>z</sub> =-12m	diffuse, broad
<i>M01</i>	6,C.2	$T, C = 1.5, 3$ MPa, $\varphi = 3^\circ$	-	U <sub>x</sub> =300m U <sub>z</sub> =-200m	listric
<i>M02</i>	6, C.1	$T, C = 3, 5$ MPa, $\varphi = 3^\circ$	-	U <sub>x</sub> =15m U <sub>z</sub> =-23m	broad > 5km
<i>M03</i>	6	$T, C = 3, 5$ MPa, $\varphi = 5^\circ$	-	U <sub>x</sub> =10m U <sub>z</sub> =-10m	broad~ 5km
<i>M04</i>	6, C.1	$T, C = 3, 5$ MPa, $\varphi = 10^\circ$	-	U <sub>x</sub> =2m U <sub>z</sub> =-2m	shallow < 0.5 km
<i>M11</i>	7,C.3	Elastic E=10 GPa	Dike I1	U <sub>x</sub> =0.015m U <sub>z</sub> =0.03m	spike, $dz > dx$
<i>M12</i>	7,C.3,C.5	$T, C = 3, 5$ MPa, $\varphi = 3^\circ$	Dike I1	U <sub>x</sub> =0.02m U <sub>z</sub> =0.02m	asymmetric $dz \sim dx$
<i>M13</i>	7,9,C.3	$T, C = 3, 5$ MPa, $\varphi = 5^\circ$	Dike I1	U <sub>x</sub> =0.02m U <sub>z</sub> =0.015m	asymmetric $dz < dx$
<i>M14</i>	7,C.3,C.5	$T, C = 3, 5$ MPa, $\varphi = 10^\circ$	Dike I1	U <sub>x</sub> =0.015m U <sub>z</sub> =0.03m	spike, $dz > dx$
<i>M21</i>	8,C.4	Elastic E=10 GPa	Reservoir I2	U <sub>x</sub> =0.013m U <sub>z</sub> =0.03m	symmetric + uplift
<i>M22</i>	8,C.4	$T, C = 3, 5$ MPa, $\varphi = 3^\circ$	Reservoir I2	U <sub>x</sub> =0.025m U <sub>z</sub> =-0.03m	broad + subsides
<i>M23</i>	8,9,C.4,C.5	$T, C = 3, 5$ MPa, $\varphi = 5^\circ$	Reservoir I2	U <sub>x</sub> =0.027m U <sub>z</sub> =-0.03m	broad + subsides
<i>M24</i>	8,9,C.4,C.5	$T, C = 3, 5$ MPa, $\varphi = 10^\circ$	Reservoir I2	U <sub>x</sub> =0.013m U <sub>z</sub> =0.03m	symmetric + uplift

Table 2: Models accounting for both topography and gravity. The first four M0x models are without source inflation. The next series test variable source geometries (I1 and I2) and bedrock strength: tensile strength  $T$ , cohesion  $C$  and -effective- friction angle  $\varphi$ . The resulting surface displacements are provided for an overpressure  $DP = 10$  MPa. See text for details.

319 Here, Young’s modulus  $E=10$  GPa was assumed. Naturally, multiplying  $E$  by 2 leads to displacement  
320 magnitudes divided by 2, hence absolute values should be taken with caution, since in the *-real-* Piton de la  
321 Fournaise, values of the Young modulus likely vary significantly with depth (cf. Discussion).

322 Moho depths vary at the base the model domain: values range from 17.5 km depth in the south-western  
323 corner to 14.5 km in the north-eastern corner (Gailler et al., 2018). A model with a flat Moho was tested  
324 in comparison (not shown here); it produces similar displacement magnitudes but  $X$  and  $Z$  displacements  
325 maxima at the surface are shifted eastward by about 4 km.

326 This model also illustrates the inherent flaws that appear when one tries to model the mechanical state of  
327 such a volcanic edifice; assuming that topography generates an isotropic stress field (eg. Cayol and Cornet,  
328 1998) or that gravity does not control deformation (eg. Gudmundsson, 2006) contrast with our results.  
329 Nevertheless, for equilibrium to be maintained over time with this topography requires additional loading of  
330 some sort, e.g. magmatic overpressurization from below, exactly where high stress and strain concentrate.  
331 Here we do not state that these models represent the present day stress and deformation fields at Piton de  
332 la Fournaise, but we believe that they allow to bracket the potential influence of gravity.

#### 333 4.2. Topography, gravity, and plasticity

334 Now we aim at quantifying the influence of a more realistic brittle behavior when Piton de la Fournaise’s  
335 topography is embedded in the gravity field. To do this, we use the numerical solution obtained above with  
336 only elastic behavior as input, and we “turn on” plasticity. Four models allow to test distinct yield strengths  
337 (models M01 to M04, Table 2) and to assess to which extent can the edifice domain undergo plastic failure

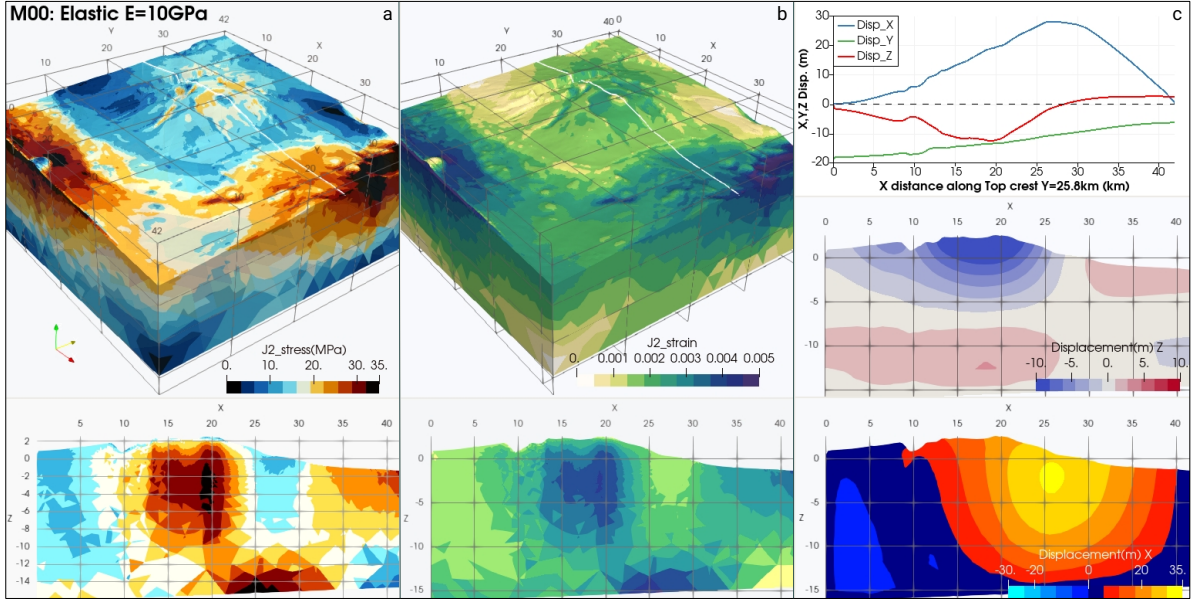


Figure 5: Model M00 considering the topography of Piton de la Fournaise, assuming elasticity in a gravity field. The resulting second invariant of the deviatoric stress,  $J_2(\sigma)$ , (a) top-3D and bottom-2D views) reaches 35 MPa immediately below the volcano's summit. Shear deformation (b) follows the same pattern with magnitudes ca.  $10^{-3}$ . Displacements (c) display maximum subsidence ( $z$  component) at the summit, and horizontal motion in the east-west direction that is maximum near the coastline ( $X \sim 26$  km), with 28 m at the surface (top right plots display the  $x, y, z$  components along axis  $Y = 25.8$  km).

338 as it 'returns' to equilibrium. The resulting deformation from these models is displayed in Figure 6, while  
 339 the resulting stress field is displayed in Appendix Figure C.1. Several features are noted:

- 340 • In the weakest model (M01, Fig. 6a), the entire edifice fails and forms a clear large scale, listric shear  
 341 zone encompassing the western edge of the Enclos Fouqué down eastward to the shore line. Shear  
 342 deformation magnitudes are greater than 0.1, vertical and horizontal displacements achieve several  
 343 hundreds of meters, and we note uplift to the east below the coastline in  $X \sim 31$  km (in red). We are  
 344 clearly seeing here the general collapse of the edifice.
- 345 • Only doubling the value of tensile strength ( $T$ ) and cohesion ( $C$ ) impedes this drastic topographic  
 346 collapse (M02, Fig. 6b). Shear deformation is reduced by an order of magnitude, with displacements  
 347 of only few tens of meters. Plastic shear failure covers an area of about 10 km around the summit  
 348 (exceeding the western limit of Enclos Fouqué), reaching about  $z = -4$  km depth. It is greatest along  
 349 a north-west south-east axis passing by the summit and along the coastlines.
- 350 • When the friction angle is further increased from  $3^\circ$  to  $5^\circ$  (M03, Fig. 6d), deformation magnitudes  
 351 and displacements are both reduced by another factor 2, but plasticity still occurs over about 1 km  
 352 below the summit area.

- 353 • In the 'strong' model with friction angle set to  $10^\circ$  (M04, Fig. 6c), plastic deformation is again reduced  
 354 by an order of magnitude and only affects the upper  $\sim 500$  m below the summit area. Displacements  
 355 achieve only a couple meters. Despite these huge differences in amplitudes, the displacements in models  
 356 M02-M04 adopt a similar pattern that extends along the eastern flank of the edifice.

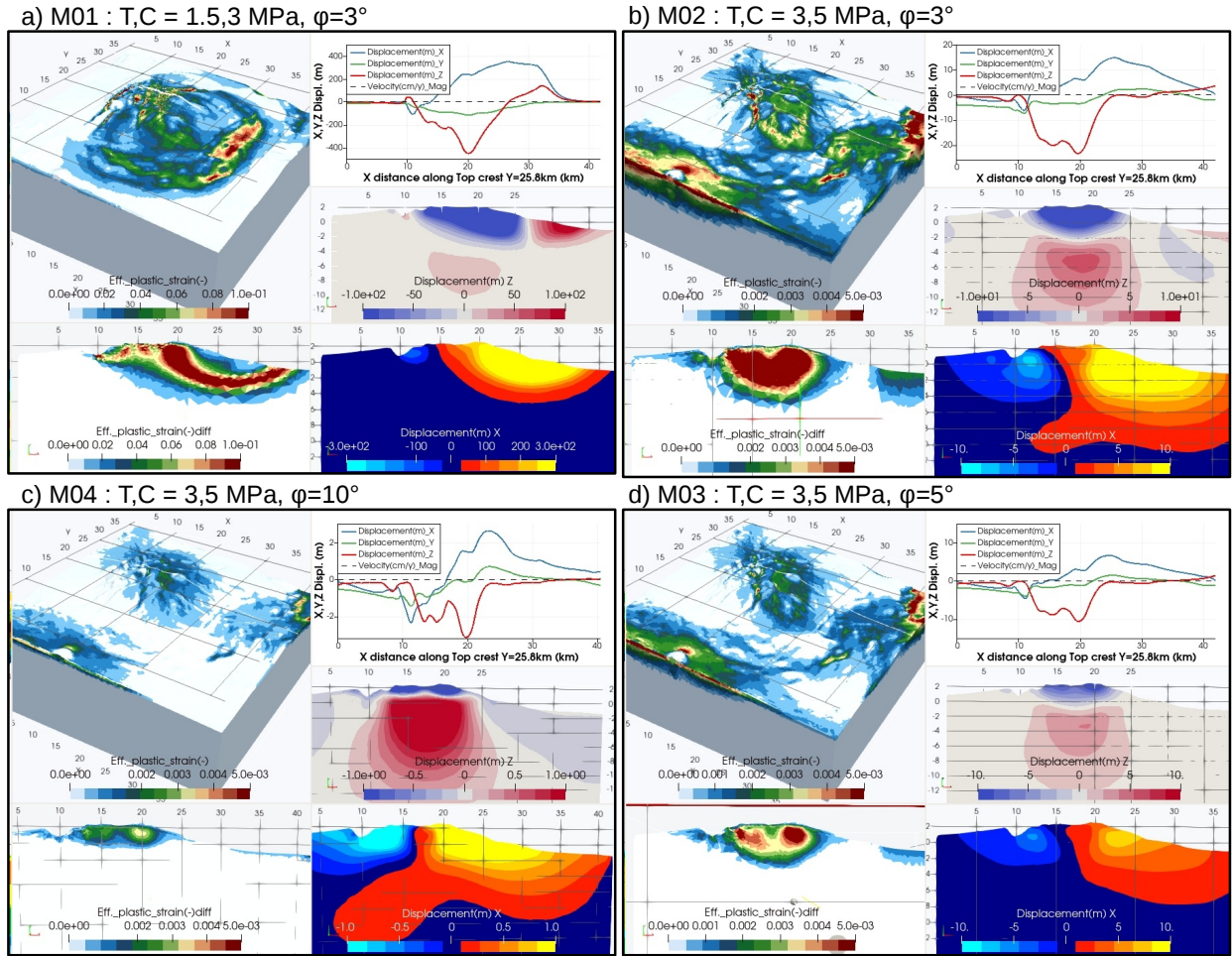


Figure 6: Modeled deformation due to topographic loading only, testing four distinct elasto-plastic strengths. **a)** case M01, with  $T = 1.5$  MPa,  $C = 3$  MPa,  $\varphi = 3^\circ$ , **b)** case M02, with  $T = 3$  MPa,  $C = 5$  MPa,  $\varphi = 3^\circ$ , **d)** case M03, with  $T = 3$  MPa,  $C = 5$  MPa,  $\varphi = 5^\circ$ , **c)** case M04, with  $T = 3$  MPa,  $C = 5$  MPa,  $\varphi = 10^\circ$ . Left column : the effective plastic shear strain ( $\varepsilon_p^{dev}$ ) in 3D (top) and in 2D vertical section along  $Y=25.8$  km (bottom). Note two orders of magnitude difference in scale with case (a). Right column : the displacement components (in addition to the elastic solution, Fig. 5). At the surface along axis  $Y=25.8$  km (up-right) and for components  $z$  (vertical, middle) and  $x$  (east-west, bottom). Note again the different magnitudes.

357 While it has become customary to relate modeled plastic strain to seismic behavior (e.g. Sibson, 1994; Chéry  
 358 et al., 2001; De Barros et al., 2019), this requires assuming a relationship between a certain amount of (shear  
 359 or volumetric) strain to seismicity. However, this assumption remains empirical, very scale-dependent, and to  
 360 our knowledge there are no critical intensity values that can be assimilated to seismic behavior unequivocally.

361 Nevertheless, geometrical patterns can be compared. Hence, when asking whether the observed cup shape  
362 seismicity observed at Piton de la Fournaise is caused by the yielding of the rock mass in relation to its  
363 topography only, we analyze the plasticity pattern obtained in the models above and observe that :

- 364 1. obviously the listric shear zone obtained in the weakest model (M01) reminds of the observed seismic  
365 cup shape. But this result means that if that was the real state of Piton de la Fournaise, it would not  
366 be able to maintain itself at the height at which it stands today. Hence, as this model provides an  
367 extreme solution of what would happen if the volcano was to destabilize entirely, it tells us that the  
368 general strength of the edifice has to be higher than what is assumed there. Furthermore Appendix  
369 Fig. C.2 shows that this listric trend does not fit the straightness of the persistent seismicity.
- 370 2. The other model cases with greater strength produce reduced magnitudes of deformation (by one to  
371 two orders), down to depths directly linked with the friction angle. This deformation pattern is rather  
372 symmetric around the summit and also trends down slope along a south-east orientation (see Fig. 6b  
373 and Fig. 6d in three dimensions). In contrast the observed seismicity cup rather trends plain east.  
374 Hence this deformation pattern does not fit the observed persistent seismicity.

375 For these two reasons, we conclude that topography alone cannot explain the seismicity *cup* observed at  
376 Piton de la Fournaise. Therefore next, we simulate magma inflation processes to assess their influence on  
377 the overall stress and strain patterns.

## 378 5. Influence of magma inflation geometry and bedrock rheology

379 Now we investigate how magma overpressure affects the "preloaded" stress and deformation patterns  
380 (obtained in the previous section). Therefore we consider the two different pressure sources considered in  
381 section 3, first the "vertical and narrow" one that represents a vertical dike injected 1 km east from the  
382 summit, termed I1, and second, the "wide and deep" ellipsoid source [centered at coordinate depth  \$z = 0.5\$](#)   
383 [km, that represents](#) the magmatic reservoir. The aim is to identify which one of these two sources produces  
384 deformation patterns that could best be linked to the observed seismicity.

### 385 5.1. Influence of a narrow vertical, distal intrusion

386 We model the impact of a narrow vertical inflation below the eastern flank of Piton de la Fournaise, that  
387 may be [attributed to a dike](#) that feeds distal eruptions in association with eastward motion (e.g. Peltier  
388 et al., 2009; Got et al., 2013). Got et al. (2013) showed with 2D numerical models that elasto-plastic behavior  
389 can amplify and localize deformation with respect to elastic behavior, then explaining GPS values of several  
390 tens of centimeters measured during eruptive crises. Our aim here is not to reproduce nor fit exactly such  
391 data, but rather to display in 3D the typical deformation pattern induced by such an injection.

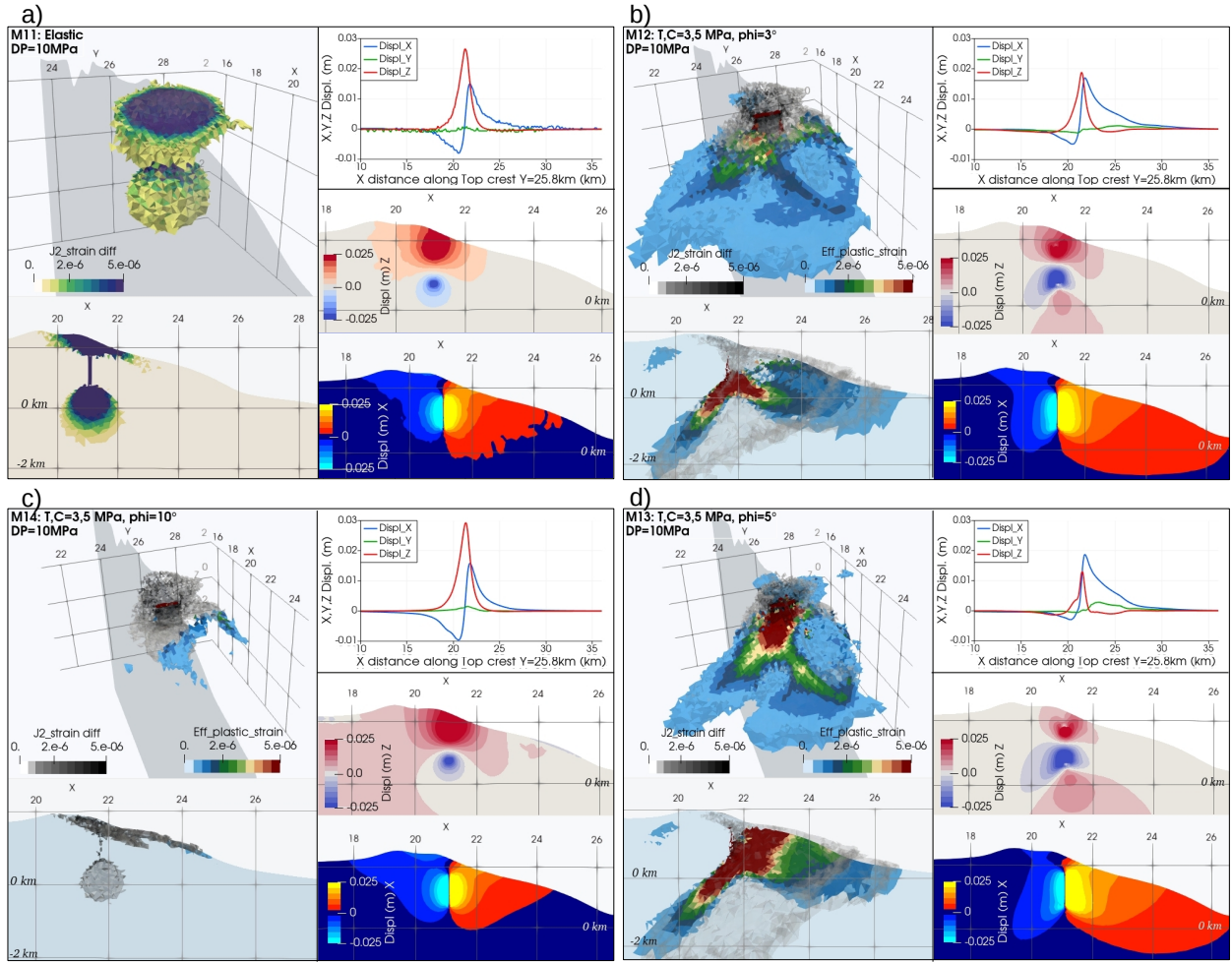


Figure 7: Models of a vertical injection (I1) below the eastern flank of the volcano, with 4 distinct elasto-plastic strengths: **a)** elastic (M11), **b-c-d)** elasto-plastic with tensile threshold  $T = 3$  MPa, cohesion  $C = 5$  MPa and friction  $\varphi$  equal to  $3^\circ$  (b),  $5^\circ$  (d),  $10^\circ$  (c). For each cases the left column displays 3D and 2D views of the effective plastic strain superimposed on the total shear strain (colored and grey colorbars, respectively). Displacements are shown on the right : top panel for the top surface, middle and bottom panels for components Z and X, respectively. Note the distinct patterns in the weak (b,d) and strong (a,c) cases. Plots display differences with the pre-inflation step.

392 The injection I1 is designed to initiate below the surface with a base set at depth  $z = 0.75$  km. It  
 393 extends vertically for 1 km and strikes north-south, 1 km east from the volcano's summit (I1 is a meshed  
 394 parallelepiped). An incremental overpressure ( $DP$ ) is applied at the walls of this structure, superimposed  
 395 on the mechanical state obtained in the previous 'pre-inflation' stage. We define four models to test distinct  
 396 bedrock strength: M11 is elastic, M12 and M13 have a weak bedrock friction ( $\varphi = 3^\circ$  and  $5^\circ$ ) and M14 has  
 397 a stronger bedrock friction ( $\varphi = 10^\circ$ ).

398 Figure 7 shows that the resulting deformation pattern expands from the inflation source outwards to  
 399 the surface, mobilizing portions of the eastern flank. It can differ from the previous tests without either

400 topography or gravity :

- 401 • The model with elastic rheology (Fig. 7a, M11) shows that shear strain develops radially around  
402 the upper and lower tips of the dike. The free surface above the dike dilates, with vertical uplift  
403 (maximum 3 cm) and slightly greater horizontal displacement to the east than to the west because of  
404 the asymmetric topography (maximum 1 cm). These patterns resemble the models without gravity,  
405 Fig. 4a (M5, M6). Complementary plots are displayed in Appendix Figure C.3.
- 406 • In models M12 and M13 with a weak bedrock friction (Figs. 7b,d), plastic deformation (effective  
407 plastic strain) develops maximum at the base of the dike intrusion near  $z = 0$  km depth, and expands  
408 sideways forming an inclined "curve" down to  $z \sim -1$  km along the edifice's eastern flank, which then  
409 rises back up to the surface just above the coastline at  $X \sim 26$  km. When looking from above, radial  
410 shear zones oriented south-east north-east join back down slope in  $X \sim 26$  km, connecting with the  
411 shear zone 2 km underneath. Near the summit and above the dike, the bedrock domain cannot develop  
412 much additional failure since it already failed in the 'pre-inflation' stage. Dilatation above the dike is  
413 narrower than in the elastic case, uplift is diminished but horizontal motion expands along the eastern  
414 flank and increases (maximum 2 cm).
- 415 • Model M14 with a greater bedrock friction displays an evanescent plastic domain, restricted to the  
416 dike's upper tip and the first ca. 100 m depth along the eastern flank. No sub-horizontal structure  
417 appears below the eastern flank (Fig. 7c). Surface displacements are similar to the elastic case.
- 418 • Displacements differ in both sets of weak and strong models: horizontal displacement is greater and  
419 more distributed over the extent of the eastern flank in the low friction models (M12 and M13) in  
420 contrast to the resistant models. These results are consistent with the patterns measured at Piton de  
421 la Fournaise in association with distal injection events (e.g. Got et al., 2013; Smittarello et al., 2019),  
422 noting that magnitudes differ with these studies due to distinct choices of  $E$  and  $DP$  (cf. test with  
423  $E = 50$  GPa displayed in Appendix E.1).

## 424 5.2. Influence of a "central-ellipsoid" magma reservoir

425 Now we aim at quantifying the deformation induced by a deeper and elliptical magma reservoir, as  
426 revealed by numerous studies at Piton de la Fournaise over the years (e.g. Peltier et al., 2015). Its shape  
427 and location are subject to debate, but the consensus is a center depth around coordinate  $z = 0.5$  km and  
428 an east-west major axis extending for a bit more than 1 km. This geometry I2 (similar to the one defined  
429 in section 3) is included as a meshed ellipsoid in models M21 to M24 (Table 2).

430 An incremental overpressure applied at the walls of this reservoir produces stress and strain that are  
431 displayed in Figure 8 for  $DP = 10$  MPa. These patterns resemble those produced by the distal vertical

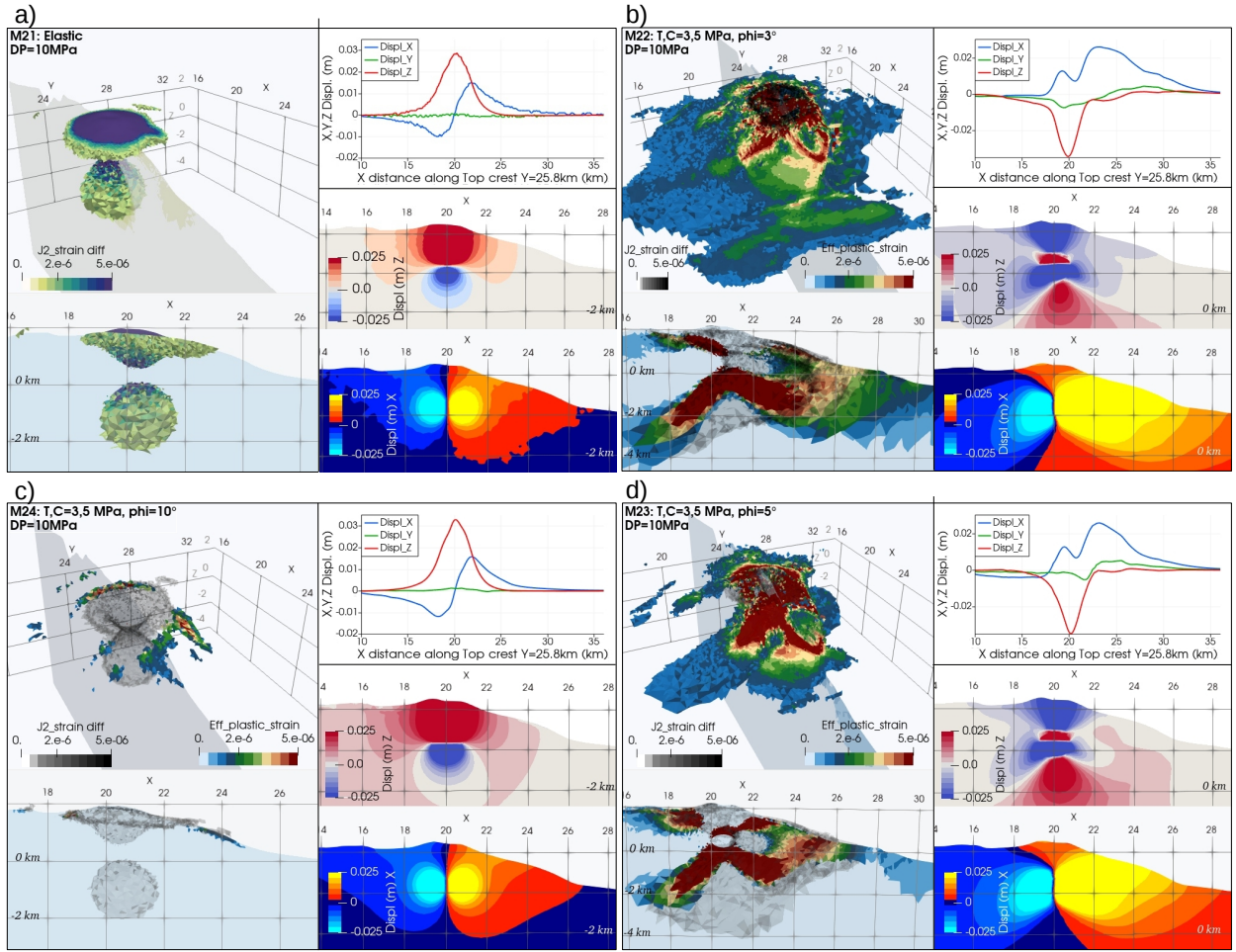


Figure 8: Models with an inflating magma reservoir (I2). Four cases with variable bedrock strength: **a)** elastic (M21), **b-c-d)** elasto-plastic with tension and cohesion  $T, C = 3, 5$  MPa and friction  $\varphi$  equal to  $3^\circ$  (b),  $5^\circ$  (d) and  $10^\circ$  (c). Left: 3D and 2D views of the effective plastic strain superimposed on the total shear strain (colored (a) and grey (b-c-d) colorbars). Right: the displacements (top are surface curves, middle is vertical Z component, bottom is horizontal X component). Note the distinct patterns in the weak (b,d) and strong (a,c) cases. Plots and displacements are measured from the onset of inflation.

432 intrusion models : the displacement magnitudes are similar, the plastic strain is asymmetric with isocontours  
 433 dipping along the eastern flanks of the volcano. As we note that the eastern edge of the modeled magma  
 434 reservoir (I2) coincides with the deepest portion of the modeled dike intrusion (I1), we identify that this  
 435 specific area of overpressure source, common to both geometries, controls the observed surface deformation  
 436 patterns below the eastern flank. Further remarks can be made:

- 437 • the total shear strain contours occupy at the surface a similar breadth to that of the circular boundary  
 438 of the Enclos Fouqué heights (similarly to models without gravity, Fig. 4b). Most of the shear strain is  
 439 plastic when friction  $\varphi \leq 5^\circ$ , and it expands along the volcano's east and south-east flanks. An "arm"

440 of plasticity develops south-east, indicating that this domain might present some structural fragility  
441 (top 3D views in left columns of Figures 8a and Appendix C.4).

442 • Here again the maximum depth of the plastic domain depends on the bedrock's frictional strength:  
443 it barely affects a few hundred meters depth if the friction angle is  $10^\circ$  or more (model M24), but it  
444 reaches  $z \sim -2$  km if the friction angle is in the range  $3-5^\circ$  (models M22, M23).

445 • Figs. 8b,d show that radial "eccentric" shear zones develop at the surface from the edifice's summit  
446 down east- and south-wards, forming the typical 3D patterns that have been observed and modeled  
447 elsewhere resulting from brittle material being indented from below (Nádai, 1963; Ernst et al., 1995;  
448 Holohan et al., 2013; Gerbault et al., 2018). Hence these modeled structures might offer a complemen-  
449 tary explanation to the interpretation of radial and oblique eruptive fissures or fault zones reported at  
450 Piton de la Fournaise (e.g. Michon et al., 2009, Appendix D.1). This will be further discussed below.

451 • The domain immediately above and about 2 km around the summit (e.g. the central cone), displays a  
452 distinct state of stress depending on bedrock strength; dilatation and uplift occurs when the bedrock  
453 is strong (models M21, M24, Figs. 8a,c, C.4), following standard elastic behavior. In contrast, a  
454 more complex pattern of alternating levels of dilatation and constriction develops when the bedrock  
455 is weak (models M22, M23, Appendix Fig. C.4a,b), and the summital area subsides. This occurs  
456 because the bedrock fails plastically there, in between the reservoir's roof and the top surface, leading  
457 to coeval uplift and collapse (like an extrado). Note that the models provide an 'integrated' picture of  
458 the edifice's response to pressurization. In contrast at Piton de la Fournaise, the central cone records  
459 surface uplift -or no significant vertical motion- during reservoir pressurization, and subsidence after  
460 eruptions. This discrepancy between modeled deformation with observations indicates that other  
461 processes than those modeled here also contribute in sustaining the cone (such as repeated magma  
462 input).

463 • Note also that this summit area forms at depth a cone of deformation isolated from the rest of the  
464 edifice; in the case of weak bedrock it is bounded by shear zones branching to the center of the magma  
465 reservoir. They emerge to the surface to the west in the Plaine des Cafres and to the east at  $X \sim 22.5$   
466 km; comparison with observations is discussed below. Such 'shallow' landslides require a more precise  
467 geotechnical study.

468 • Another point to discuss further concerns the modeled failure modes : Figs. C.4 show that shear  
469 failure is again, the dominant mode of failure over the entire plastic domain, except in the near surface  
470 few hundred meters to the west of the volcanic edifice, upstream of the Rivière de l'Est to the north  
471 and upstream of the Remparts and Langevin river canyons, where tensile failure also occurs (when  
472  $\varphi \leq 5^\circ$ ).



473 *5.3. Relating the modeled deformation field and the observed seismicity below the Eastern flank*

474 In the light of the above models, we superimpose the modeled strain patterns and the observed seismicity  
475 pattern, Figure 9. The differential effective plastic strain and the  $xz$  component of the strain tensor are both  
476 plotted for models M12 and M22. Clearly, the distal injection model (M12) produces a curved shape shear  
477 zone below the eastern flank of Piton de la Fournaise that is shallower than the observed seismicity cup by  
478 about 1 km. The magma reservoir inflation model in turn (M22) produces a shear zone whose maximum  
479 isocontours coincide well with the seismic cup. We add the following comments:

- 480 • Our modeled plastic shear strain along this  $z \sim -2$  km depth horizon testifies of a process of localized  
481 brittle shear failure, supporting the notion of a localized "fault-zone" drawn by the cup-seismicity  
482 below Piton de la Fournaise (cf. events depth located by OVPF as red circles in Fig. 10). Our  
483 representation of the  $xz$  strain component indicates a more specific orientation of shearing in these  
484 directions, consistent with an eastward down-sliding component of the hanging-wall portion of the  
485 edifice's flank.
- 486 • The domain embedded by the shear strain "cup" can be considered to deform aseismically, eg. by  
487 creep (e.g. Poland et al., 2017; Villeneuve et al., 2018; Got et al., 2019; De Barros et al., 2019). Note  
488 that seismicity actually does not necessarily occur in damaged domains but rather at its boundaries  
489 with surrounding intact rock mass where there are still cohesive bonds to break; in that sense, the  
490 seismic "cup" can draw this contour boundary between intact material at depth and already damaged  
491 (e.g. 'broken') material near the surface.
- 492 • The observed seismicity cluster at the deepest end at  $z \sim -2.5$  km and  $x \sim 25$  km (C3 in Fig. 1b)  
493 correlates with the area in our models where the shear zone 'rotates' from down-east dipping back  
494 up-to-the-east. We note that the strain magnitude significantly reduces in this eastward up-dipping  
495 portion, which can be linked with the lack of seismicity observed further to the east. This observed  
496 seismic cluster stands "upstream" from the Alizés grabboic body that was identified from MT and  
497 gravity studies (Gailler et al., 2018, , Fig. 1a).
- 498 • The observed seismicity clusters to the south ( $z \sim -1.5$  km and  $y \sim 26$ , C2) km and to the east  
499 ( $z \sim -2.5$  km, C3, Fig. 1b) could result from locally altered rock domains or a fault zone. Dumont  
500 et al. (2019) measured MT anomalies above these seismic clusters (investigation depth 1 km) which  
501 would coincide with a N65 fault lineament (Michon et al., 2009). While a pre-existing fault zone  
502 is a possibility, our models only indicate that shear strain there may result from the edifice's flank  
503 dynamics and not necessarily from a pre-existing fault.
- 504 • West from the summit and deeper than  $z = -4$  km, the observed seismicity seems to link with the  
505 modeled west-down-ward dipping branch of shear strain that results from inflation of the magma

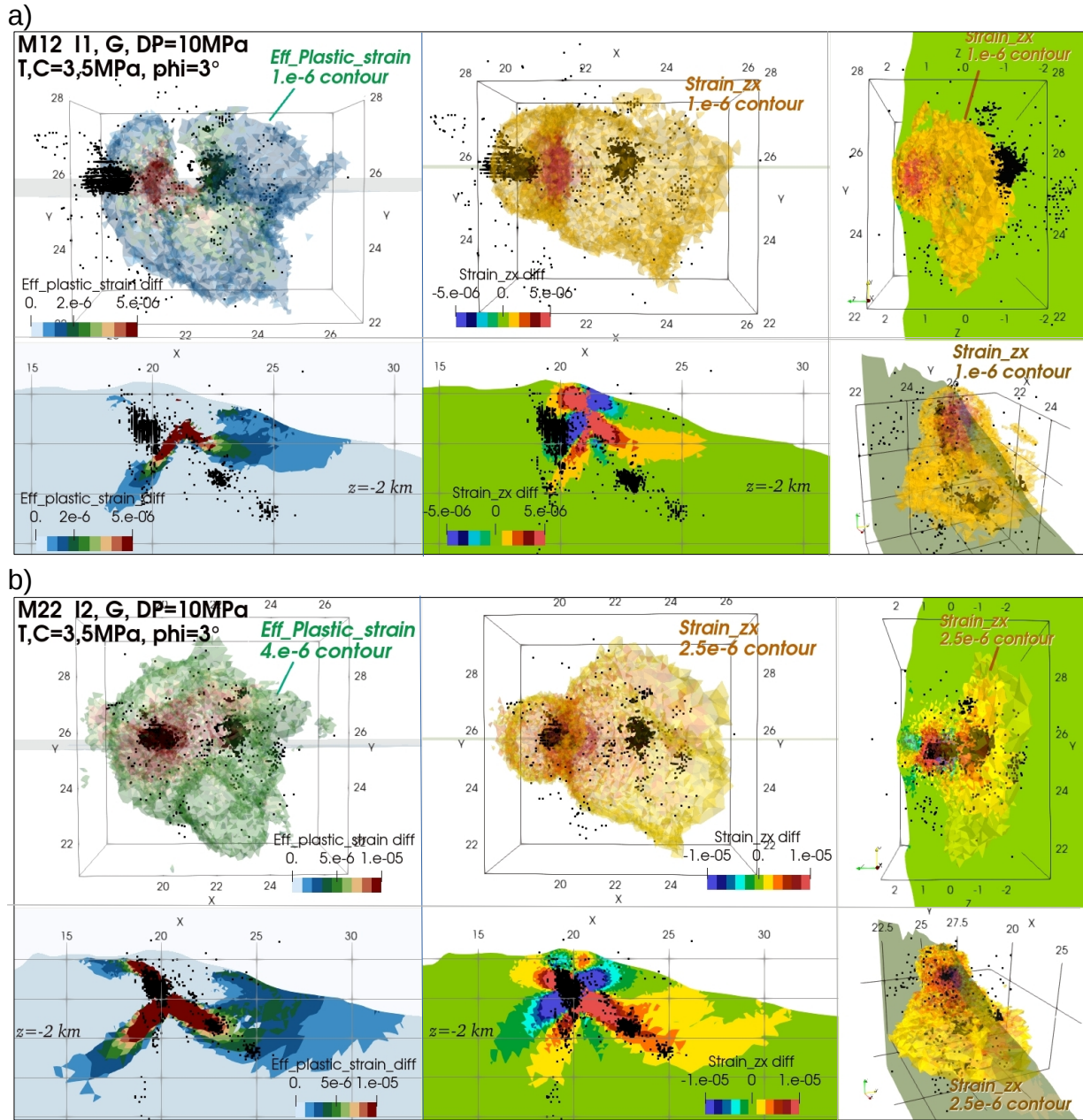


Figure 9: Comparison of the observed seismicity pattern at Piton de la Fournaise (black dots) with the contours of shear deformation obtained numerically in two distinct models. In the column to the right, the effective plastic strain, and to the left, the  $zx$  shear strain component. Views are displayed similarly to Fig. 1b, in top view and along profiles in the east-west and north-south direction. a) model M12 with a vertical distal injection: high strains remain above ca.  $z=-1$  km depth below the eastern flank. b) model M22 with an inflating magma reservoir: the dipping shear zone coincides now better with the observed cup-shape seismicity.

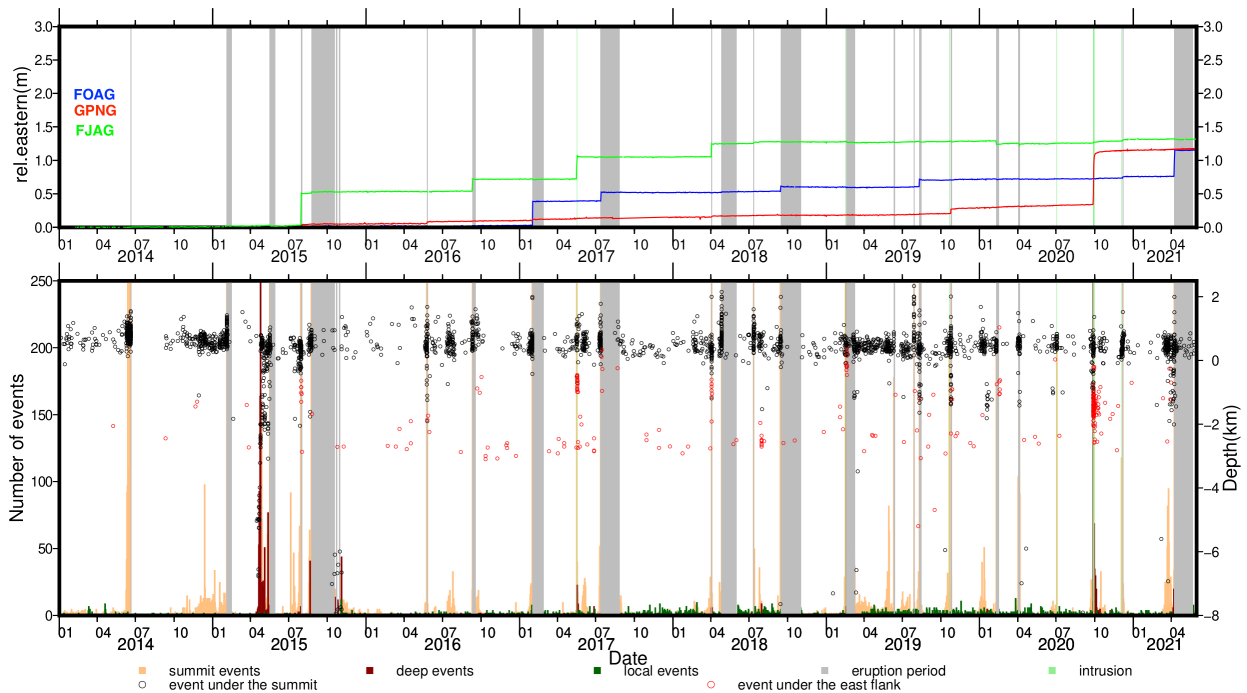


Figure 10: Temporal record of flank motion, seismicity and eruptive activity at Piton de la Fournaise from 2014 to 2021 (OVPF). **a)** Eastern displacements at three GPS stations (FOAG, GPNG, FJAG) located in Fig. 1. **b)** Daily seismicity rate and earthquake depth. Events below the summit are shown with black circles and earthquakes under the east flank are shown in red. Shallow and deep seismicity rates are shown in orange and brown, respectively. Eruptive activity is marked as grey bands.

506 reservoir. Note that this deformation branch in the models does not develop with high rock strength,  
 507 which is consistent with the idea that the crust becomes more resistant with depth. However localized  
 508 weakening by hydro-magmatic fluid flow upon injection may produce seismicity (e.g. White et al.,  
 509 2011; De Barros et al., 2019), and in fact this deep pattern of nearly vertical seismicity is interpreted  
 510 as related to magmatic fluids migrating out from the deeper reservoir at ca.  $z \sim 8$  km depth (e.g.  
 511 Battaglia et al., 2005; Michon et al., 2015; Lengliné et al., 2016). We actually note a difference in dip  
 512 of about  $10^\circ$  between our modeled shear zone and the observed near vertical seismicity trend. Our  
 513 models simply indicate that either way the dynamic transfer of magma from a reservoir at ca. 8 km  
 514 depth up to the '0-km-depth' reservoir is kinematically consistent with shear deformation along this  
 515 trend.

- 516 • Our models indicate the development of active conjugate shear zones that form a "cross" centered on  
 517 the magma reservoir and that accompany its inflation cycles; they witness the 'gravitational' interplay  
 518 of magma inflation and the inclined eastern flank. These shear zones also developed in previous models  
 519 (Gerbault et al., 2012, 2018; Holohan et al., 2013, with flat free top surfaces), (Got et al., 2013, or

520 not). Note then how the three-dimensional structures are organized: while the summit area is uplifting  
521 or subsiding depending on the magma reservoir’s pulsating inflation cycle, the eastern side forms a  
522 material slice that is bordered by eccentric shear zones at the surface and which root at depth: their  
523 upper limit links on to the eastern upper branch of the cross-shape shear zone, and their lower limit  
524 links on to the east-down-ward dipping cross-shape shear zone down to ca. -2 km depth (e.g. our  
525 cup-shape shear zone). The models help us to understand the constrained kinematics associated to  
526 this 3D cup-geometry.

- 527 • Finally, in our models, the shear zone that we attribute to the observed cup seismicity is also a  
528 domain where the trace of the strain tensor switches from dilatational above, to constrictional below  
529 (differential values, Figs. C.4a,b). This is a typical feature of tectonic shear zones that delimit locations  
530 of stress rotation and display seismicity (e.g. Gerbault et al., 2003; Dorbath et al., 2008). This switch  
531 of the mean stress state in turn indicates that magmatic fluids coming from depth within the dilatation  
532 zone are impeded to travel further up because they encounter a constricted domain in the overburden  
533 (hanging-wall), hence, they remain stuck there. In comparison with the thermal models by e.g. Annen  
534 and Sparks (2002), we can say that this state of stress is consistent with magma stacking from below.

## 535 6. Discussion

### 536 6.1. Numerical assumptions and choice of parameters

537 A modeling study such as ours can never be exhaustive, and it is clear that accounting for the rheological  
538 heterogeneity of the crust at Piton de la Fournaise would allow to better fit a model of the mechanical state  
539 with various measured data (seismicity and GPS for instance). But uncertainties increase when having  
540 to assume the mechanical properties associated with heterogeneity. Our purpose here was to unveil the  
541 influence of first order parameters when considering the gravitational state of a homogeneous edifice, and  
542 yet a number of alternative assumptions deserve to be commented.

543 Whereas a volcanic edifice naturally results from potential energy minimization due to the progressive  
544 transfer of deep magmatic material to the Earth’s surface (during about 0.5 My in the case of Piton de la  
545 Fournaise), our models here were implemented with the sudden influence of topographic load, hence they  
546 produce an exaggerated deformation field. However, our comparisons between models accounting for gravity  
547 only, topography only, and then combined topography and gravity, show how the latter combination sheds  
548 light on the dynamic response of the volcanic edifice to magmatic inflation. Further comparison with other  
549 approaches is thus required to decipher real effects from artifacts:

- 550 1. We have assumed here a ”homogeneous” crustal medium to interpret the seismicity pattern below the  
551 edifice’s eastern flank, and we have found that the effective rock mass friction has to be rather close to

552  $3 - 5^\circ$  than to  $\geq 10^\circ$ , at least in its upper-most 4 km. While many studies have explored how elasto-  
553 plastic properties introduce non-linearity, generating rigid-like block motion bounded by shear zones  
554 (Gerbault et al., 1998, 2012), the spatial mechanical heterogeneity of crustal domains also complexifies  
555 the deformation signal upon application of a magmatic load (e.g. Trasatti et al., 2005; Gudmundsson,  
556 2006; Masterlark, 2007). At Piton de la Fournaise, both the elastic and plastic properties vary not only  
557 with depth but also most probably on inherited kilometric-size domains, identified from i) island-scale  
558 geophysical surveys, such as the central cone, the Piton des Sables and the Alizés bodies which were  
559 identified down to at least  $z = -4$  km depth (e.g. Gailler et al., 2018), and ii) morphological analysis of  
560 fissures and rift zones riddling the surface (e.g. Michon et al., 2009). These heterogeneities are expected  
561 to exert a first order control on deformation patterns and stress distribution throughout the edifice,  
562 with stiffer bodies storing larger deviatoric stress and reducing deformation amplitudes. Moreover,  
563 the boundaries of such heterogeneous domains constitute rheologically discontinuous "corners" where  
564 seismicity may be enhanced. For instance, the C4 seismicity cluster (Fig. 1b) may testify to a  
565 rheological boundary with the more rigid Alizés body. This body may actually block the propagation  
566 of the shear zone further to the East, hence act as a buttress that restrains the Eastern flank's motion.  
567 The presence of regional fractures or rift zones can also enhance seismicity locally as mentioned by  
568 Michon et al. (2015). Now that we understand what are the implications of considering a homogeneous  
569 medium, future models will need to confirm whether the observed seismicity actually illuminates  
570 "passive" rheological contrasts or instead, potentially "active", threatening large-scale flank motion.

- 571 2. In our models, the domain forming the magma source was considered elastic and of Young modulus  
572 equal to that of the surrounding bedrock; assigning it other properties can have some impact, and  
573 numerical tests -not shown here- show that considering an elasto-plastic intrusion modifies the deforma-  
574 tion patterns by about 10%, or that assuming a 10 times more compliant source (as Got et al., 2013)  
575 reduces the surface displacements by about a third. The internal thermodynamics can also induce  
576 visco-elastic behavior (Novoa et al., 2019). With lack of knowledge of how magmatic sources behave  
577 in reality, we can only warn here that the source's rheology also influences model-to-data matching.
- 578 3. Here, we have assumed that the dike injection was oriented fully north, following a simple orthogonal  
579 prolongation of the 2D model set up by Got et al. (2013). Other injection geometries can be tested,  
580 as has been done by previous studies for specific eruptive events (e.g. Fukushima et al., 2005; Michon  
581 et al., 2009; Smittarello et al., 2019; ?). Modifying the geometry of the inflating source in our models  
582 would allow comparing our stress and strain patterns with these studies and commenting about distinct  
583 loading assumptions. More specifically, the impact of a sill injection below the eastern flank could be  
584 further explored (cf. preliminary test in Appendix E.2).
- 585 4. Magmas come from the mantle, but we do not know at which rate and in which quantities they  
586 migrate from one level to the other. This magma input may occur by discontinuous pulses of small

587 quantities throughout the porous medium, eg. via porosity type waves (Havlin et al., 2013), or in larger  
588 quantities by transient motion that produce anomalies identified by geophysical surveys, at ca. 8 and  
589 20 km depths (Gallart et al., 1999; Fontaine et al., 2015; Gailler et al., 2018). Such magmatic transfer  
590 towards the surface is controlled by the regional stress field such as lithospheric flexure (Michon and  
591 Saint-Ange, 2008; Gerbault et al., 2017), which should be accounted for in future models.

592 5. Note that the overpressure that we chose to display,  $DP = 10$  MPa, corresponds, for a reservoir  
593 of size  $V_o \sim 1$  km<sup>3</sup> and a compressibility  $\beta = 3(1 - 2\nu)/E$ , to an erupted volume of the order of  
594  $dv/V_o = \beta DP \sim 0.0015$  km<sup>3</sup>. This value is comparable to estimates of erupted volumes of 0.001–0.013  
595 km<sup>3</sup> at Piton de la Fournaise, with about half ranging below 0.003 km<sup>3</sup> since 1992 (Roult et al., 2012).  
596 Similar magma overpressures of the order of 8 MPa have been proposed for dike injections (Fukushima  
597 et al., 2010) as well as for magma reservoir inflation (Peltier et al., 2008). Considering lower values  
598 of overpressure in our models actually has small impact that falls within the uncertainty range of  
599 other parameters over the scale of the volcanic edifice and crustal thickness. Traversa et al. (2010)  
600 proposed changes in magma reservoir overpressure of barely 2-3 MPa at Piton de la Fournaise, based  
601 on models of buoyancy driven dike propagation. However they considered a small shear modulus (1  
602 GPa) and low density of the central cone area. This difference in estimated overpressure with ours  
603 may be explained with the greater scale and simpler homogeneous medium that we consider here. It  
604 may also be reconciled if we consider that the source overpressure does not necessarily depart from an  
605 isostatic state of stress, but that instead it departs from a persistently overpressurized source, so that  
606 overall the pressure source would achieve ca. 10 MPa above the overburden weight (e.g. as we defined  
607  $DP$  here). Next generation models should also consider this point.

608 6. Additional tests not shown here with friction  $\varphi = 7 - 15^\circ$  develop characteristics closer to the strong  
609 cases ( $\varphi = 10^\circ$ ) than to the weak cases ( $\varphi = 3, 5^\circ$ ). This leads us to propose the critical value of  
610  $5^\circ$  as effective strength of the volcanic edifice down to about 5 km depth. While this value is close  
611 to estimates for Kilauea’s decollement zone (Morgan and McGovern, 2005a), the mechanisms at play  
612 explaining such low effective friction likely differ, since a specific weak tectonic zone was identified  
613 there. At Piton de la Fournaise in turn, we cannot rule out the existence of a paleo-surface composed  
614 of altered material, that would, locally, behave with such a weak effective friction. The alternative we  
615 advocate here invokes transient hydrothermal fluid pressurization associated with magma injections  
616 as proposed by Iverson (1995) and Reid (2004), and which dynamically reduces the effective normal  
617 stress throughout the domain, but not its intrinsic friction.

## 618 6.2. Implications on flank stability at Piton de la Fournaise

619 Now we discuss our results in terms of flank stability with respect to previous studies :

- 620 1. First looking at superficial structures, Merle et al. (2010) showed from field observations the strong  
621 action of erosion in excavating deep canyons in lava flow ancient calderas bordering the external slopes  
622 south-west of Piton de la Fournaise (along the rivers canyons des Remparts and Langevin). Two  
623 large landslides are documented to have occurred there about 300 kyr and 150 kyr ago, and which  
624 would have carried away the entire southern flank of the preceding caldera. We note that this area  
625 in our models still hosts large plastic deformation, related to its steep topography. It remains prone  
626 to destabilization, perhaps facilitating punctually, magma pathways to bypass the Enclos Fouqué's  
627 morphological boundary and erupt via this south-westward depression (Merle et al., 2010). Our other  
628 observation of tensile failure upstream of the Rivière de l'Est is consistent with the occurrence of  
629 recurrent episodes of failures in this area (OVPF monthly bulletin, ISSN2610-5101, 2020).
- 630 2. The altered and hydrated first hundred meters could have been accounted for with a softer rheology  
631 in our models, as they play an important role upon slope stability over that same thickness, and on  
632 the occurrence of phreato-magmatic eruptions. Instead here we focused on quantifying the effective  
633 friction, which controls the failure yield at greater depth. At Piton de la Fournaise, a recent airborne  
634 electromagnetic survey reveals the first ca. 500 m depth resistivity structure of the edifice (Dumont  
635 et al., 2019). It highlights the upwelling hydrothermal system below the craters, magma injection  
636 pathways and mapped fault structures. Assessing the mechanical state of this 'superficial' level requires  
637 to adjust tensile strength and cohesion at these depths, in a way similar to other studies of non-volcanic,  
638 altered slopes such as for instance the Clapière landslide in France (Bouissou et al., 2012).
- 639 3. Michon et al. (2009, 2015) carried an extensive analysis of the faults and fractures that cover the Piton  
640 de la Fournaise area, questioning the role of pre-existing preferential orientations on the trajectories of  
641 magma injection. On the origin of the radial eruptive fissures oriented ca. N150 and N55 (Fig. **D.1**),  
642 Carter et al. (2007) argued that these are fracture zones that accommodate the eastern flank sliding,  
643 whereas Michon et al. (2009) proposed a predominant control from magma injection from below. In  
644 our models here, we see that in either cases whether we account for a dike injection or inflation of  
645 the magma reservoir, eccentric (radial) shear zones develop at the surface of the model and merge  
646 downslope: these eccentric shear zones have a natural curved (radial) shape in 3 dimensions that  
647 results from the 3D geometrical setting, as already discussed in section 5.3.
- 648 4. Michon et al. (2009, 2015) also discussed the potential link of the NE-SE rift zones with the motion of  
649 the eastern flank, and proposed a dynamic switch mechanism of tensile stresses rotating from vertical  
650 with deep vertical intrusions in the NE-SE rift zones, to horizontal when the magma propagates as sills  
651 below the eastern flank (then acting as a decollement zone, cf. Chaput et al., 2014). Our models here  
652 reproduce shear strain along a SE orientation resembling the SE rift zone, but nothing to the NE. This  
653 may mean that we would have to account in our models for additional specific deep heterogeneities  
654 or injection sources located below this NE rift zone. In other words, while the NE rift zone does not

655 link with any modeled feature, the SE rift zone may be attributed to an arm of deformation acting  
656 as a geometrical "extension" of the eastern flank shear zone. Further investigations are needed to  
657 determine accurately the potential for flank instabilities and eruptions pathways in this southern area  
658 above Saint-Philippe town.

659 5. Rincón et al. (2018) showed with analogue modeling that distinct deformation patterns could be  
660 induced depending on the location of a deep magma injection : a basal injection at the center below  
661 the edifice's summit induces summit subsidence (as observed in our models here for cases I2) and minor  
662 lateral sliding of a flank, leading to a relatively stable mechanical state with no catastrophic eruptions.  
663 In contrast an injection offset from the summit can induce a large flank gravitational collapse, with  
664 potentially triggered eruptions if the flank-slide intersects the injected magma. Such a scenario at  
665 Piton de la Fournaise would probably be tracked by a seismic sequence propagating upwards below  
666 the eastern flank and from greater depth than what is observed today.

667 6. A number of studies since the 1990s have explored the concept of the "Factor of Safety" to assess the  
668 stability of volcanic edifice flanks (e.g. Iverson, 1995; Reid, 2004; Apuani and Corazzato, 2009). As  
669 mentioned in the introduction, studies concluded in general that only relatively superficial landslides  
670 < 500m thick could occur, more superficial than the ca. >2 km thick slice that would be mobilized if  
671 it rooted on the observed cup-shape seismicity at Piton de la Fournaise. While these studies assume  
672 low magma overpressure ( $\leq 3$  MPa) and high rock mass friction ( $\geq 30^\circ$ ), they invoke the key factor of  
673 rock mass effective strength reduction by transient thermally-pressurized fluid flow associated with a  
674 magma intrusion. Reid (2004) argued that the pressure wave propagates via the pores of the bedrock  
675 and cancels out the normal lithostatic stress component, hence reducing its effective friction. This  
676 would allow for destabilization of the flank slopes down deeper. Nevertheless in Reid's model, this  
677 pressure wave propagates rather quickly over a characteristic time of about 1 year. At Piton de la  
678 Fournaise, the persistent seismicity below the eastern flank has been recorded for much longer, ca. 30  
679 yrs (Hirn et al., 1991). Hence, if one considers that magma reservoir overpressure is persistent over  
680 time, then it may induce a permanent overpressurized fluid flow throughout the bedrock that weakens  
681 it on the long-term. Further modelling of this transient phenomena, coupled to the eastern flank  
682 motion, would be useful. Actually, the fact that we could assimilate the observed seismicity *cup* with  
683 a shear zone by considering effective bedrock frictions as low as  $3^\circ$  or  $5^\circ$  is coincidentally indicative of  
684 a reduction in effective strength at the edifice's scale on the long-term.

685 7. A large flank slide is expected to begin with motion and uplift at its toe extremity (Iverson and Reid,  
686 1992) (e.g. as is actually observed in Kilaua, Poland et al., 2017). Iverson and Reid (1992) showed that  
687 hydrothermal fluid flow actually accumulates there and has the strongest weakening effect, facilitating  
688 bedrock failure there. Such uplift is not measured by GPS on the eastern coastline of Piton de la  
689 Fournaise at present-day. In our models, only model M01 (Fig. 6a) with topography alone and



690 extremely weak bedrock displays such an uplift further to the east 5 km away below the coastline. Our  
691 other models with an inflating magma source do not produce an uplift (Figs. 7 and 8). The kinematic  
692 alternative is that flank sliding occurs horizontally along a flat lying decollement zone at depth  $z \sim -2$   
693 km extending further east below sea level : then horizontal motion would not necessarily have to be  
694 associated with toe uplift (e.g. Chaput et al., 2014). Measurements of slope motion offshore would  
695 help clarifying this point, but such data is not available yet.

- 696 8. Chaput et al. (2014) tested with numerical models the impact of a sill injected along a subhorizontal  
697 detachment identified to the north-east flank of the nearby Piton des Neiges. By assuming zero  
698 friction along this detachment plane and an overpressure of several MPa, they reproduced surface  
699 displacement patterns of several centimeters over a greater extent than if that detachment plane was  
700 frictional. Comparison to the measured surface displacements at Piton de la Fournaise led these  
701 authors to propose the existence of a magma-filled detachment zone below the eastern flank. They  
702 considered a bedrock with Young modulus 70 GPa, friction angle  $30^\circ$  and cohesion 4 MPa; it would be  
703 interesting to reassess these results with lower shear modulus and friction angle : the resulting surface  
704 displacements would overall be enhanced, hence the presence of frictionless magmatic material within  
705 the detachment might not be necessary. Such a decollement would then extend way down below sea  
706 level to the east, and as mentioned above, seismicity or ground motion should then be tracked there.
- 707 9. While our results show that the spatial distribution of seismicity can be explained by pressurization of  
708 the magma reservoir, they do not explain the temporal link between flank seismicity and the occurrence  
709 of lateral magma intrusions below the eastern flank (Figs. 10, D.2). At Kilauea and Etna volcanoes  
710 for instance, it was shown that fault slip under the edifice flank coincides with dyking episodes (Delaney  
711 et al., 1990; Puglisi et al., 2008). Famin and Michon (2010) also suggested the role of sill intrusions  
712 in inducing flank destabilization at the nearby Piton des Neiges. At Piton de la Fournaise, detailed  
713 analysis of lateral injections that triggered abundant seismicity under the eastern flank of Piton de  
714 la Fournaise in 2020 and 2021 appear essential to better decipher this relationship: are these lateral  
715 intrusions generating the seismicity at depth or is it the motion of the eastern flank that favors  
716 their emplacement there ? Our models here indicate at least that lateral intrusions are not required  
717 to trigger the observed seismicity below the Eastern flank (section 5.3). On the other hand, the  
718 temporal relationship between eastern flank seismic shear mobilization and reservoir inflation is hinted  
719 by typical observations indicating first, long-lasting inflation and seismicity increase below the volcano  
720 summit (linked to reservoir pressurization), then followed by short-term intense seismic swarms and  
721 preferential motion towards the Eastern flank (linked with final propagation of magma to the surface).

## 722 7. Conclusion

723 Our numerical models illustrate first that the topographic gradient has a first order control on the stress  
724 field and deformation patterns at Piton de la Fournaise. It mobilizes potential surface displacements over  
725 several tens of meters. A minimum *effective* strength is deduced (*effective* friction is distinguished here  
726 from standard friction), that indicates how the edifice’s shape can be maintained when not considering its  
727 anisotropic properties nor magma overpressure.

728 When exploring in a second step the influence of magma pressurization, the models show the development  
729 of a plastic shear zone of comparable cup-shape to that of the measured persistent seismicity along the  
730 eastern flank and dipping down to ca.  $z = -2$  km, when the inflating source has a similar shape to the  
731 inferred shallow reservoir identified below Piton de la Fournaise (e.g. an ellipsoid source located at ca.  
732  $z = 0$  km depth). In contrast a shallower vertical intrusion below the eastern flank of the edifice produces a  
733 shallower plastic shear zone, not exceeding  $z \sim -1$  km depth. Hence, we interpret the observed seismic *cup*  
734 as highlighting this persistent combination between gravitational and magmatic loading, without needing  
735 to prescribe any specific weakened behavior in this location. Furthermore in our models, increasing magma  
736 overpressure does not induce a large-scale flank-slide, indicating that this trigger alone, is not sufficient. The  
737 lack of observed uplift at the toe of the eastern flank supports this conclusion. We deduce that large-scale  
738 flank destabilization rooting at 2 km *bsl* would rather be triggered by another magma source specifically  
739 located below the eastern flank, a scenario not yet supported by present day observations.

740 Our models also indicate that the observed seismic cup is not necessarily a weakened structure storing  
741 magmatic fluids, although the low effective friction that was required to reproduce it calls for some hy-  
742 drothermal transient fluid flow (that reduces the effective normal stress and allows for shear failure in that  
743 location). This does not exclude previous suggestions that this persistent seismicity illuminates the bound-  
744 aries between altered and more rigid bodies at depth. While our models show that the depth of the plastic  
745 shear zone increases when the (effective) friction angle decreases, one should also bear in mind that the  
746 depth location of this seismic cup directly depends on the seismic velocities model (hence upon the Young’s  
747 modulus). In order to gain further insight on the stability of the eastern flank of Piton de la Fournaise,  
748 further geophysical studies are required to assess the mechanical properties of the edifice.

749  
750 *Code and data availability:* Seismic and GNSS data from Observatoire Volcanologique du Piton de la Fournaise  
751 are available on the volobsis website: <http://volobsis.ipgp.fr/>. Numerical models were achieved with the open-  
752 source code ADELI, which is available upon request to authors MG or RH, an old version with input files can be  
753 downloaded from <https://code.google.com/archive/p/adeli/>.

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991 **Appendix A. Numerical integration of the constitutive law**

992 The numerical integration of the elastoplastic Drucker-Prager constitutive model combined with a tensile failure  
 993 criterion is described here. For sake of simplicity only the case of infinitesimal deformations is considered, and more  
 994 details on the numerical method used in ADELI in the context of finite strain can be found in Chéry et al. (2001). A  
 995 standard version of the code (in french) remains available here, <https://code.google.com/archive/p/adeli/>, and  
 996 an updated version is available upon request (to MG or RH).

997 *Appendix A.1. Yield functions, plastic potentials and flow rule*

998 Following the general formulation given in Simo et al. (1988) for non-smooth multisurface plasticity and its  
 999 numerical implementation, we consider, as in the Itasca Flac's manual, the special case where the set of plastically  
 1000 admissible stresses is the truncated cone:

$$\Omega = \{\boldsymbol{\sigma} \in \mathbb{R}^6 \mid f_s(\boldsymbol{\sigma}) \leq 0\} \cap \{\boldsymbol{\sigma} \in \mathbb{R}^6 \mid f_t(\boldsymbol{\sigma}) \leq 0\}, \quad (\text{A.1})$$

1001 with  $f_s$  the classical Drucker-Prager yield function and  $f_t$  the tension yield function:

$$f_s(\boldsymbol{\sigma}) = J(\mathbf{s}) + \alpha(p - p_0), \quad f_t(\boldsymbol{\sigma}) = p - p_t, \quad (\text{A.2})$$

1002 where  $p = \frac{1}{3}\text{trace}(\boldsymbol{\sigma})$  is the mean stress,  $J(\mathbf{s}) = \sqrt{\frac{3}{2}}\|\mathbf{s}\|$  the equivalent stress,  $\mathbf{s} = \boldsymbol{\sigma} - p\mathbf{I}$  the deviatoric stress  
 1003 ( $\|\mathbf{s}\| = \sqrt{\mathbf{s}:\mathbf{s}}$ ),  $p_0 = c/\tan\varphi$ ,  $\alpha = 6\sin\varphi/(3 - \sin\varphi)$ ,  $c$  the cohesion,  $\varphi$  the friction angle and  $p_t$  is the tensile  
 1004 strength (it is assumed in the following that  $p_t \leq p_0$ , the classical Drucker-Prager criterion corresponding to the  
 1005 particular case  $p_t = p_0$ ). When isotropic hardening/softening phenomenon is considered,  $\varphi$  is a given function of  
 1006 the accumulated equivalent plastic strain  $\int_0^t \sqrt{2/3}\|\dot{\boldsymbol{\epsilon}}_p\|$  (Leroy and Ortiz, 1989).

1007 To complete the formulation the evolution of the plastic strain rate is given by the flow rule

$$\dot{\boldsymbol{\epsilon}}_p = \dot{\lambda}_s \frac{\partial g_s}{\partial \boldsymbol{\sigma}} + \dot{\lambda}_t \frac{\partial g_t}{\partial \boldsymbol{\sigma}}, \quad (\text{A.3})$$

1008 with  $g_s$  and  $g_t$  the two corresponding plastic potentials whose gradients are defined by :

$$\frac{\partial g_s}{\partial \boldsymbol{\sigma}} = \frac{3}{2} \frac{\mathbf{s}}{J(\mathbf{s})} + \frac{1}{3} \beta \mathbf{I}, \quad \frac{\partial g_t}{\partial \boldsymbol{\sigma}} = \frac{1}{3} \mathbf{I}, \quad (\text{A.4})$$

1009 where  $\beta = 6\sin\psi/(3 - \sin\psi)$  and  $\psi$  is the dilatancy angle (thus in this model the flow rule for tensile failure is  
 1010 associated while it is non-associated for shear failure unless  $\varphi = \psi$ ).

1011 In (A.3)  $\dot{\lambda}_s$  and  $\dot{\lambda}_t$  are two plastic multipliers which satisfy the complementary conditions:

$$\begin{aligned} \dot{\lambda}_s &\geq 0, & f_s(\boldsymbol{\sigma}) &\leq 0, & \dot{\lambda}_s f_s(\boldsymbol{\sigma}) &= 0, \\ \dot{\lambda}_t &\geq 0, & f_t(\boldsymbol{\sigma}) &\leq 0, & \dot{\lambda}_t f_t(\boldsymbol{\sigma}) &= 0. \end{aligned} \quad (\text{A.5})$$

1012 *Appendix A.2. Elastic predictor / plastic corrector algorithm*

1013 For materials with linear isotropic elastic response, the elastoplastic incremental constitutive law, splitted for  
1014 convenience in its deviatoric and volumetric parts, reads

$$\begin{cases} \dot{\mathbf{s}} = 2G(\dot{\mathbf{e}} - \dot{\mathbf{e}}_p), \\ \dot{p} = K(\dot{\bar{\epsilon}} - \dot{\bar{\epsilon}}_p) \end{cases} \quad (\text{A.6})$$

1015 with  $G$  and  $K$  the shear modulus and the bulk modulus, respectively,  $\dot{\mathbf{e}} = \text{dev}(\dot{\boldsymbol{\epsilon}})$  the deviatoric part of the total  
1016 strain rate tensor  $\dot{\mathbf{e}}$ ,  $\dot{\bar{\epsilon}} = \text{trace}(\dot{\boldsymbol{\epsilon}})$ ,  $\dot{\mathbf{e}}_p = \text{dev}(\dot{\boldsymbol{\epsilon}}_p)$  and  $\dot{\bar{\epsilon}}_p = \text{trace}(\dot{\boldsymbol{\epsilon}}_p)$ .

1017 Assuming a known constant strain-rate over the time step  $[t^n, t^{n+1}]$ , the integration of (A.6) using the implicit  
1018 backward Euler scheme provides

$$\begin{cases} \mathbf{s}^{n+1} = \mathbf{s}_e - 2G \Delta \mathbf{e}_p^{n+1}, \\ p^{n+1} = p_e - K \Delta \bar{\epsilon}_p^{n+1}, \end{cases} \quad (\text{A.7})$$

1019 where  $\Delta \mathbf{e}_p^{n+1} = \Delta t \dot{\mathbf{e}}_p^{n+1}$  and  $\Delta \bar{\epsilon}_p^{n+1} = \Delta t \dot{\bar{\epsilon}}_p^{n+1}$  are the deviatoric and volumetric plastic strain increments, respec-  
1020 tively and

$$\begin{cases} \mathbf{s}_e := \mathbf{s}^n + 2G \Delta t \dot{\mathbf{e}}, \\ p_e := p^n + K \Delta t \dot{\bar{\epsilon}}, \end{cases} \quad (\text{A.8})$$

1021 are known at the beginning of the time-step and correspond to the elastic prediction of the stress field.

1022  
1023 If the predicted stress  $\boldsymbol{\sigma}_e = \mathbf{s}_e + p_e \mathbf{I}$  lies within  $\Omega$ , then the solution at  $t^{n+1}$  is obtained :  $\boldsymbol{\sigma}^{n+1} = \boldsymbol{\sigma}_e$ ,  $\dot{\boldsymbol{\epsilon}}_p^{n+1} = \mathbf{0}$ .  
1024 Otherwise the prediction is not plastically admissible and  $\boldsymbol{\sigma}_e$  must be projected onto the surface of  $\Omega$ . To uniquely  
1025 define this projection, one possible strategy is to first split the exterior of  $\Omega$  into the following three complementary  
1026 domains that may contain  $\boldsymbol{\sigma}_e$  (see Figure A.1):

$$\Omega_t = \{ \boldsymbol{\sigma} \in \mathbb{R}^6 \mid f_t(\boldsymbol{\sigma}) > 0, h_t(\boldsymbol{\sigma}) := J(\mathbf{s}) - J^* \leq 0 \}, \quad (\text{A.9})$$

1027 where  $J^* = \alpha(p_0 - p_t)$  is the radius of the terminal section of the truncated cone  $\Omega$ ,

$$\Omega_s = \{ \boldsymbol{\sigma} \in \mathbb{R}^6 \mid f_s(\boldsymbol{\sigma}) > 0, h_s(\boldsymbol{\sigma}) := p_t - p + \beta h_t(\boldsymbol{\sigma}) > 0 \}, \quad (\text{A.10})$$

1028 and

$$\Omega' = \{ \boldsymbol{\sigma} \in \mathbb{R}^6 \mid h_s(\boldsymbol{\sigma}) \leq 0, h_t(\boldsymbol{\sigma}) > 0 \}. \quad (\text{A.11})$$

1029 Then, depending on the domain in which  $\boldsymbol{\sigma}_e$  is located, the plastic correction is defined as follows:

1030 1) if  $\boldsymbol{\sigma}_e \in \Omega_t$ : the projection is done along the direction of the gradient of  $g_t$ . The plastic strain rate is therefore  
1031 given by (A.3) with  $\dot{\lambda}_s = 0$  and  $\dot{\lambda}_t \geq 0$ . Using equations (A.4) (which gives  $\dot{\bar{\epsilon}}_p = \dot{\lambda}_t$ ) and (A.7), the expression  
1032 of  $\dot{\lambda}_t$  follows from the consistency condition  $f_t(\boldsymbol{\sigma}^{n+1}) = 0$ :

$$\dot{\lambda}_t \Delta t = \frac{f_t(\boldsymbol{\sigma}_e)}{K}. \quad (\text{A.12})$$

1033 Hence, the plastic strain increment and the updated stress in this case are simply

$$\begin{aligned} \bullet \Delta \mathbf{e}_p^{n+1} &= \mathbf{0} & \bullet \Delta \bar{\epsilon}_p &= \dot{\lambda}_t \Delta t \\ \bullet \mathbf{s}^{n+1} &= \mathbf{s}_e & \bullet p^{n+1} &= p_t \end{aligned} \quad (\text{A.13})$$

1034 2) if  $\boldsymbol{\sigma}_e \in \Omega_s$ : the projection is made along the direction of the gradient of  $g_s$ . The plastic strain rate is then  
 1035 given by (A.3) with  $\dot{\lambda}_t = 0$  and  $\dot{\lambda}_s \geq 0$  follows from the consistency condition  $f_s(\boldsymbol{\sigma}^{n+1}) = 0$ . Using (A.4)  
 1036 (which gives  $\dot{\boldsymbol{e}}_p = \dot{\lambda}_s \frac{3\boldsymbol{s}}{2J}$  and  $\dot{\boldsymbol{\varepsilon}}_p = \dot{\lambda}_s \boldsymbol{\beta}$ ) and (A.7) and noting that  $J(\boldsymbol{s}^{n+1}) = J(\boldsymbol{s}_e) - 3G\dot{\lambda}_s\Delta t$ , in absence of  
 1037 hardening, this condition gives :

$$\dot{\lambda}_s \Delta t = \frac{f_s(\boldsymbol{\sigma}_e)}{3G + K\alpha\beta}. \quad (\text{A.14})$$

1038 Hence, the plastic strain increment and the updated stress in this case are

$$\begin{aligned} \bullet \Delta \boldsymbol{e}_p^{n+1} &= \frac{3\dot{\lambda}_s \Delta t}{2J(\boldsymbol{s}_e)} \boldsymbol{s}_e & \bullet \Delta \bar{\boldsymbol{\varepsilon}}_p^{n+1} &= \beta \dot{\lambda}_s \Delta t \\ \bullet \boldsymbol{s}^{n+1} &= \left(1 - \frac{3G\dot{\lambda}_s \Delta t}{J(\boldsymbol{s}_e)}\right) \boldsymbol{s}_e & \bullet p^{n+1} &= p_e - K\beta \dot{\lambda}_s \Delta t \end{aligned} \quad (\text{A.15})$$

1039 It is worth noting that when hardening is allowed the consistency condition is a non-linear function of  $\dot{\lambda}_s$  and  
 1040 it is generally no longer possible to have a closed-form such as (A.14) for  $\dot{\lambda}_s$ . In this case (A.14) can however  
 1041 be used as an initial guess of  $\dot{\lambda}_s$  in an iterative procedure (the standard Newton method is used in Adeli).

1042 3) if  $\boldsymbol{\sigma}_e \in \Omega'$ : the correction is achieved by projecting  $\boldsymbol{\sigma}_e$  on the closest point of the terminal cone contour zone  
 1043 (see Figure A.1). Then  $p^{n+1} = p_t$  and  $\boldsymbol{s}^{n+1} = (J^*/J(\boldsymbol{s}_e)) \boldsymbol{s}_e$ . The plastic strain increment is obtained by  
 1044 injecting these values into (A.7). Hence,

$$\begin{aligned} \bullet \Delta \boldsymbol{e}_p^{n+1} &= \frac{1 - J^*/J(\boldsymbol{s}_e)}{2G} \boldsymbol{s}_e & \bullet \Delta \bar{\boldsymbol{\varepsilon}}_p^{n+1} &= \frac{p_e - p_t}{K} \\ \bullet \boldsymbol{s}^{n+1} &= \frac{J^*}{J(\boldsymbol{s}_e)} \boldsymbol{s}_e & \bullet p^{n+1} &= p_t \end{aligned} \quad (\text{A.16})$$

1045 **General remark:** These four cases can be rewritten into the single form:

$$\begin{aligned} \bullet \Delta \boldsymbol{e}_p &= \zeta^{dev} \boldsymbol{s}_e / 2G & \bullet \Delta \bar{\boldsymbol{\varepsilon}}_p &= \zeta^{vol} p_e / K \\ \bullet \boldsymbol{s}^{n+1} &= (1 - \zeta^{dev}) \boldsymbol{s}_e & \bullet p^{n+1} &= (1 - \zeta^{vol}) p_e \end{aligned} \quad (\text{A.17})$$

1046 with  $\zeta^{dev}$  and  $\zeta^{vol}$  two dimensionless numbers defined as follows:

$$\begin{aligned} 0) \text{ if } \boldsymbol{\sigma}_e \in \Omega_e : \quad & \zeta^{dev} = 0, & \zeta^{vol} &= 0, \\ 1) \text{ if } \boldsymbol{\sigma}_e \in \Omega_s : \quad & \zeta^{dev} = 3G\dot{\lambda}_s \Delta t / J(\boldsymbol{s}_e), & \zeta^{vol} &= K\beta \dot{\lambda}_s \Delta t / p_e, \\ 2) \text{ if } \boldsymbol{\sigma}_e \in \Omega_t : \quad & \zeta^{dev} = 0, & \zeta^{vol} &= 1 - p_t / p_e \\ 3) \text{ if } \boldsymbol{\sigma}_e \in \Omega' : \quad & \zeta^{dev} = 1 - J^* / J(\boldsymbol{s}_e), & \zeta^{vol} &= 1 - p_t / p_e. \end{aligned} \quad (\text{A.18})$$

1047 In perfect plasticity,  $\dot{\lambda}_s \Delta t = f_s(\boldsymbol{\sigma}_e) / (3G + K\alpha\beta)$  otherwise is determined numerically as the root of  $f_s(\boldsymbol{\sigma}^{n+1}(\dot{\lambda}_s \Delta t)) = 0$ .

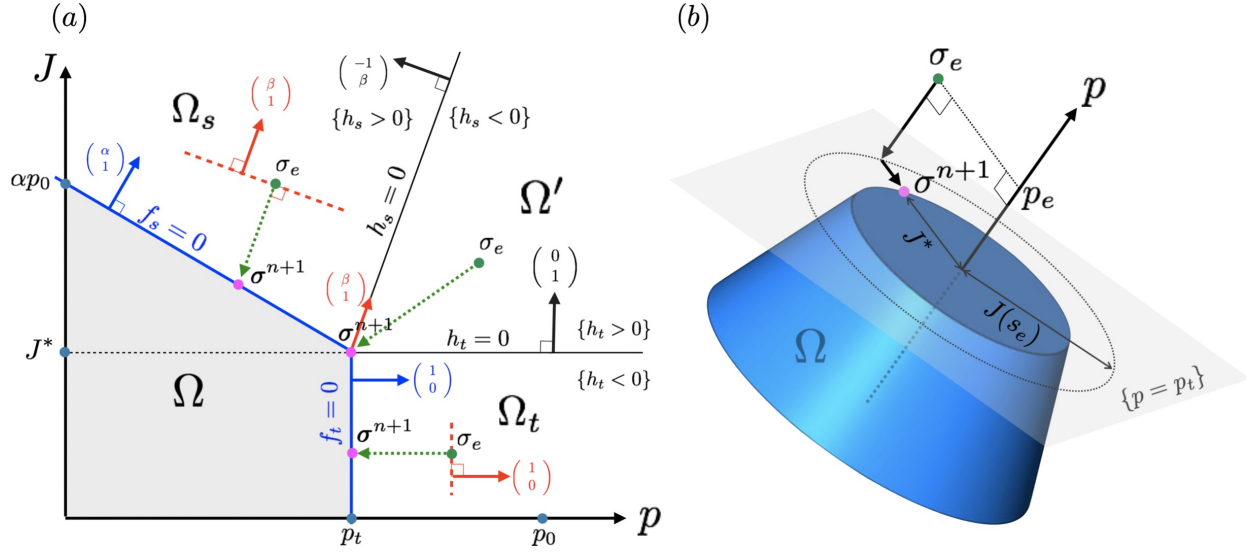


Figure A.1: Combined Drucker-Prager criterion and tensile failure criterion. (a) View in the  $p$ - $J$  plane of the plastically admissible domain ( $\Omega$ ) and plastic corrections and their corresponding projections (green arrows) when the elastic prediction  $\sigma_e$  lies in  $\Omega_s$ ,  $\Omega_t$  or  $\Omega'$ . Gradients of the yield and potential functions are represented by blue and red arrows, respectively.  $h_s$  and  $h_t$  are defined in (A.10) and (A.9). (b) View in the principal stresses space and correction for  $\sigma_e \in \Omega'$ .

Table A.3: Definition of main models parameters.

Symbol	meaning	values
$E$	Young modulus	10 GPa
$T$	Tensile strength	3-5 MPa
$C$	Cohesion	3-10 MPa
$\phi$	Friction angle	-
$\varphi$	Effective Friction angle	0-20°
$\psi$	Dilatation angle	0°
$f_s, f_t$	Yield functions for shear and tensile failure	
$\lambda_s, \lambda_t$	Plastic strain potentials multipliers	
$g_s, g_t$	Plastic potentials	
$DP$	Imposed pressure at source walls	
$\sigma$	Stress tensor	
$\varepsilon$	Total strain tensor	
$p$	Mean stress (1st invariant of the stress tensor)	
$\mathbf{s}$	Deviatoric Stress tensor	
$J_2(\sigma)$	2nd Invariant of the deviatoric Shear Stress	
$J_2(\varepsilon)$	2nd Invariant of the deviatoric strain tensor	
$I_1(\varepsilon)$	1st Invariant of the deviatoric strain tensor	
$\varepsilon_p$	Effective plastic strain (2nd invariant of the plastic strain tensor)	

1048 **Appendix B. Benchmarks for the combined shear and tensile yield criteria**

1049 *Appendix B.1. Uniaxial traction test*

The purpose is to validate the implementation of the numerical stress update on an elementary test. The sample is a cube of side length  $L$  whose faces perpendicular to axis  $Ox$  are subjected to a constant normal velocity  $v_n = v_0/2$  ( $v_0 > 0$ ). All other faces are set free. The strain rate is then uniform and within the small strain assumption ( $v_0 t \ll L$ ) the only non-zero strain and stress components in the elastic regime are

$$\varepsilon_{xx} = \frac{v_0 t}{L}, \quad \varepsilon_{yy} = \varepsilon_{zz} = -\nu \varepsilon_{xx}, \quad \sigma_{xx} = \sigma(t) = E \varepsilon_{xx}$$

where  $\nu$  is Poisson's coefficient and  $E$  is Young's modulus. The duration of the experiment is  $T$  ( $T \ll L/v_0$ ). The first and second invariants of  $\boldsymbol{\sigma}(t)$  are simply given by:

$$p(t) = \frac{1}{3} \sigma(t), \quad J(t) = \sigma(t).$$

1050 *Onset of plastification*

Plasticity onset occurs at the time  $t_p = \min\{t \geq 0 \mid f_s(\boldsymbol{\sigma}(t)) \times f_t(\boldsymbol{\sigma}(t)) = 0\}$  which is readily found to be

$$t_p = \frac{\sigma_p}{E} \cdot \frac{L}{v_0} \quad \text{with} \quad \sigma_p = \sigma(t_p) = \begin{cases} 3p_t & \text{if } p_t < p_t^*, \\ 3p_t^* & \text{if } p_t^* \leq p_t \leq p_0. \end{cases}$$

where

$$p_t^* = \frac{2 \cos \varphi}{3 + \sin \varphi} c.$$

1051 In other words, failure will occur in shear mode if the tensile strength is greater than  $p_t^*$ , in tensile mode if it is  
1052 smaller than  $p_t^*$ , and in mixed tensile and shear mode if it is equal to  $p_t^*$ .

1053 *Numerical Results*

The tests are carried out with the following fixed parameters:  $L = 1$  m,  $v_0 = 1$  m/s,  $E = 10^{11}$  Pa,  $\nu = 0.25$ ,  $c = 10^7$  Pa,  $\psi = 0^\circ$  and  $\varphi = 30^\circ$ . Then  $p_0 = \sqrt{3}c$  and  $p_t^* = \frac{2}{7} p_0$ . Four values of the tensile strength  $p_t$  are considered:

$$p_t \in \{ p_0, 2 \times p_t^*, 1 \times p_t^*, 0.5 \times p_t^* \}.$$

For the first three tests ( $p_t \geq p_t^*$ ) we must obtain

$$t_p = t_{p,1} := \frac{3p_t^*}{E} = \frac{6\sqrt{3}}{7} \times 10^{-4} \text{ s}$$

while for the last test ( $p_t = p_t^*/2$ ) we must obtain

$$t_p = t_{p,2} := \frac{3p_t}{E} = \frac{t_{p,1}}{2}.$$

1054 The total duration of the numerical experiment is set to  $T = 2t_{p,1}$ . Although the mesh size does not matter (strain  
1055 is uniform) we nevertheless conducted tests with two meshes: a coarse one with 8 nodes and 6 tetrahedrons and a  
1056 fine one with ca. 1700 nodes and ca. 8000 tetrahedrons. Both give the expected values of  $t_p$  and  $\sigma_p$ . Figure (B.1)  
1057 displays the resulting stress-strain curves and the loading paths in the  $(p, J)$  plane.

1058

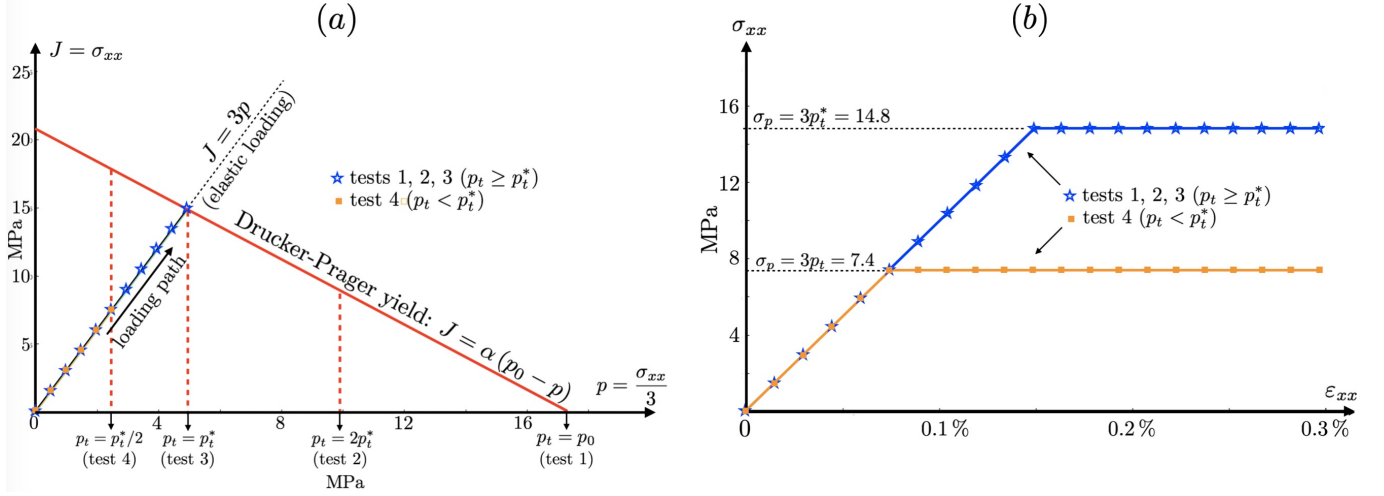


Figure B.1: Test 1 – Uniaxial traction. The loading path (similar color dots) reaches the plastic yielding analytical solutions (plain lines). (a) In the  $p$ - $J$  plane and (b) in the  $(\sigma_{xx}, \epsilon_{xx})$  space, for the four different test cases  $p_t \in \{p_0, 2 \times p_t^*, p_t^*, 0.5 \times p_t^*\}$ .

### 1059 Appendix B.2. Compression of a plate with a circular hole

1060 This test is well known in metal engineering, and details can be found in several books (eg. Nádai (1963)).  
 1061 A rectangular plate with a notch is compressed or extended in one direction. With increasing shortening, tensile  
 1062 cracking can occur in the direction parallel to compression while inclined plastic shear bands develop, ultimately  
 1063 breaking the sample in two. Analytical expressions of the elastic stresses are function of the imposed stress  $\sigma_\infty$ , the  
 1064 hole's radius  $a$ , coordinate  $r$  and angle  $\theta$  that originates parallel to the loading direction (eg. Jaeger and Cook, 1979):

$$\begin{aligned}
 \sigma_{rr} &= \frac{\sigma_\infty}{2} \left(1 - \frac{a^2}{r^2}\right) + \frac{\sigma_\infty}{2} \left(1 - \frac{3a^4}{r^4} - \frac{4a^2}{r^2}\right) \cos(2\theta) \\
 \sigma_{\theta\theta} &= \frac{\sigma_\infty}{2} \left(1 + \frac{a^2}{r^2}\right) - \frac{\sigma_\infty}{2} \left(1 - \frac{3a^4}{r^4}\right) \cos(2\theta) \\
 \sigma_{r\theta} &= -\frac{\sigma_\infty}{2} \left(1 - \frac{3a^4}{r^4} + \frac{2a^2}{r^2}\right) \sin(2\theta),
 \end{aligned} \tag{B.1}$$

1065 Fig.B.2b represents isocontours of the shear stress in case of an applied horizontal traction. Despite a switch in  
 1066 signs these isocontours geometries are similar when exerting a vertical compression. Along the hole's edge in  $\theta = 0$   
 1067 (parallel to the  $z$  axis), the radial stress  $\sigma_{rr}$  is null while the tangential stress  $\sigma_{\theta\theta}$  becomes equal to  $-\sigma_\infty$ . In turn in  
 1068  $\theta = \pi/2$  (along the horizontal axis), the radial stress remains null while  $\sigma_{\theta\theta}$  reaches  $3\sigma_\infty$ . Hence, tangential extension  
 1069 occurs at the hole's apex and a crack may appear if the tensile yield is reached there. In turn maximum shear stress  
 1070 develops along the horizontal direction where shear failure will then tend to initiate instead.

1071 We consider here a rectangular plate of size  $2\ell_x \times 2\ell_z = 20 \text{ mm} \times 36 \text{ mm}$  with an inner circular hole of radius  
 1072  $a = 5 \text{ mm}$ , that is compressed at a constant velocity of  $v_z = -0.1 \text{ mm/s}$  during 0.3 s. Since the problem is  
 1073 symmetrical, only a quarter of the model domain is considered (cf. Figure B.3a). The material properties are the  
 1074 following :  $E = 10^{11} \text{ Pa}$ ,  $\nu = 0.25$ ,  $\varphi = 30^\circ$ ,  $\psi = 0^\circ$ ,  $c = 10 \text{ MPa}$  and  $p_t = c/10$ . As a result, a tensile stress  $\sigma_{xx}$   
 1075 develops at the hole's apex. With increasing shortening, tensile yield is reached at this location, while a plastic shear  
 1076 band develops at an angle of ca.  $60^\circ$  to the  $x$ -direction (Fig. B.3).

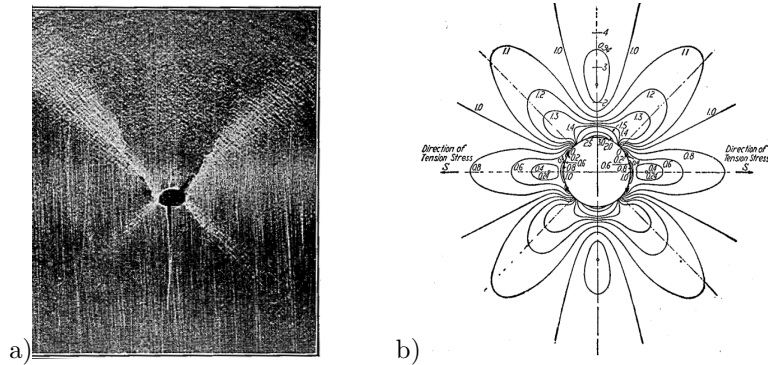


Figure B.2: a) Compression test with a paraffin plate containing a cylindrical hole, and formation of two distinct slip layers departing from the hole . b) Shear stress isocontour lines from equations B.1, for a horizontally stretched elastic plate (opposite stress input). Note the factor 3 concentration at the hole's bottom and apex ( $\theta = \pm\pi/2$ ). After Nádai (1963) (p.286-289).

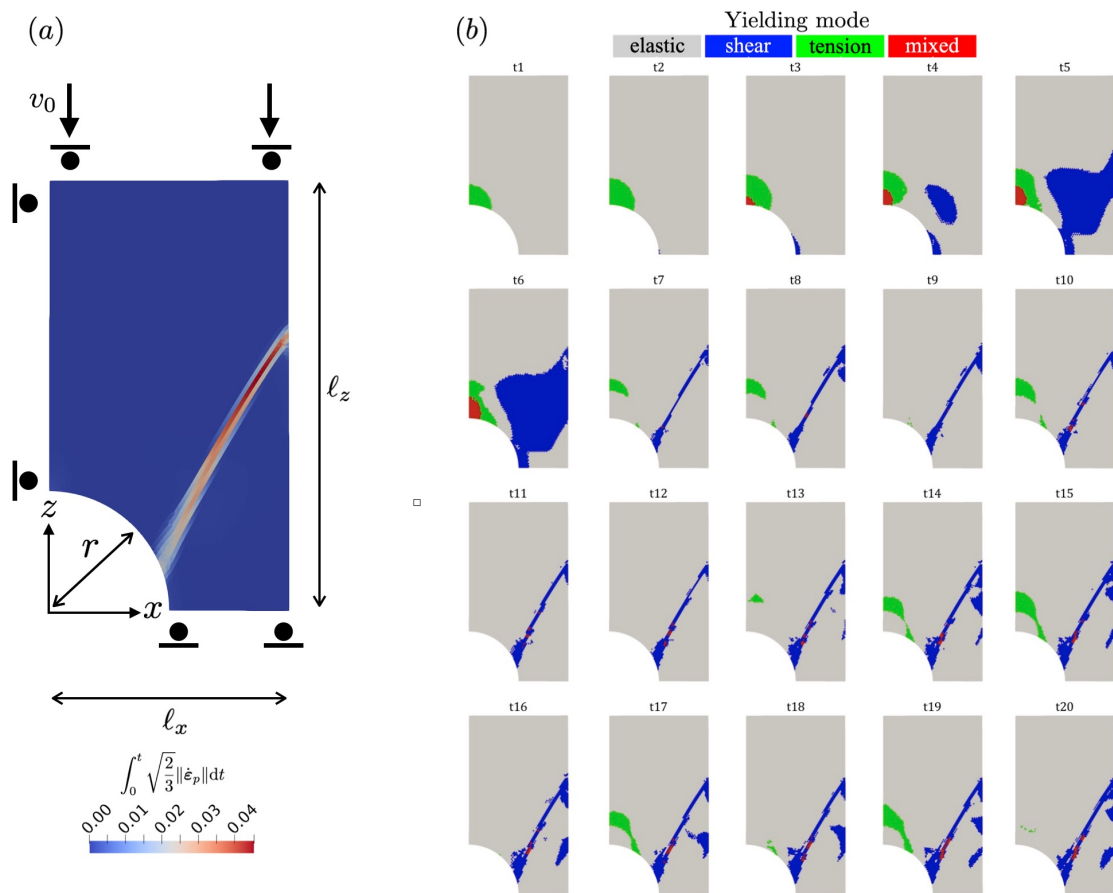


Figure B.3: Test 2 – Compression of a pierced plate. a) set up and accumulated plastic deformation after a nominal shortening of 0.16%. b) 20 snap-shots during loading illustrate the development of the four deformation modes: elastic, plastic shear mode, plastic tensile mode, and mixed tensile and shear mode.



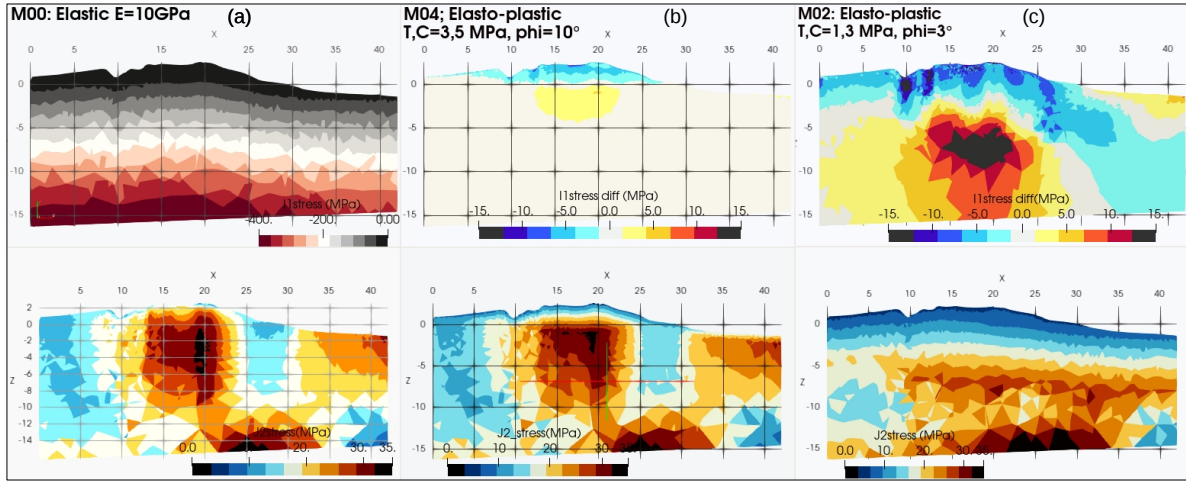


Figure C.1: Stress field with gravity and no magma inflation, in a vertical section along axis  $Y = 25.8$  km in models M00 (a), M04 (b) and M02 (c). Top row displays the mean stress ( $I_1$ ), full values plotted for the elastic case M00 (a), and the differential with respect to this elastic state for M02 (b,  $\varphi = 10^\circ$ ) and M04 (c,  $\varphi = 3^\circ$ ). Plots indicate changes of  $\pm 5$  MPa and  $\pm 15$  MPa for M04 and M02, respectively, due to plastic yielding above a certain depth. Bottom row displays the deviatoric stress  $J_2$ : the first 2 km in M04 (b) and 5 km in M02 (c) are "cut off" by plastic behavior.

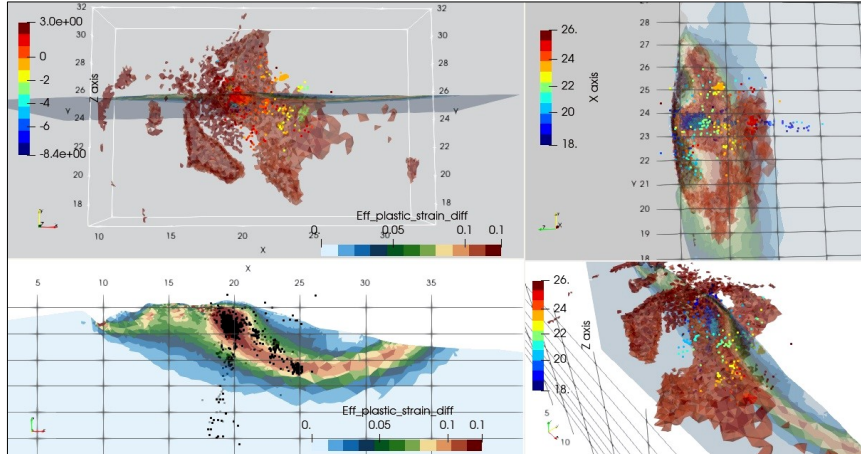


Figure C.2: Comparison of the listric shear zone formed in model M01 with the observed cup-shape seismicity.

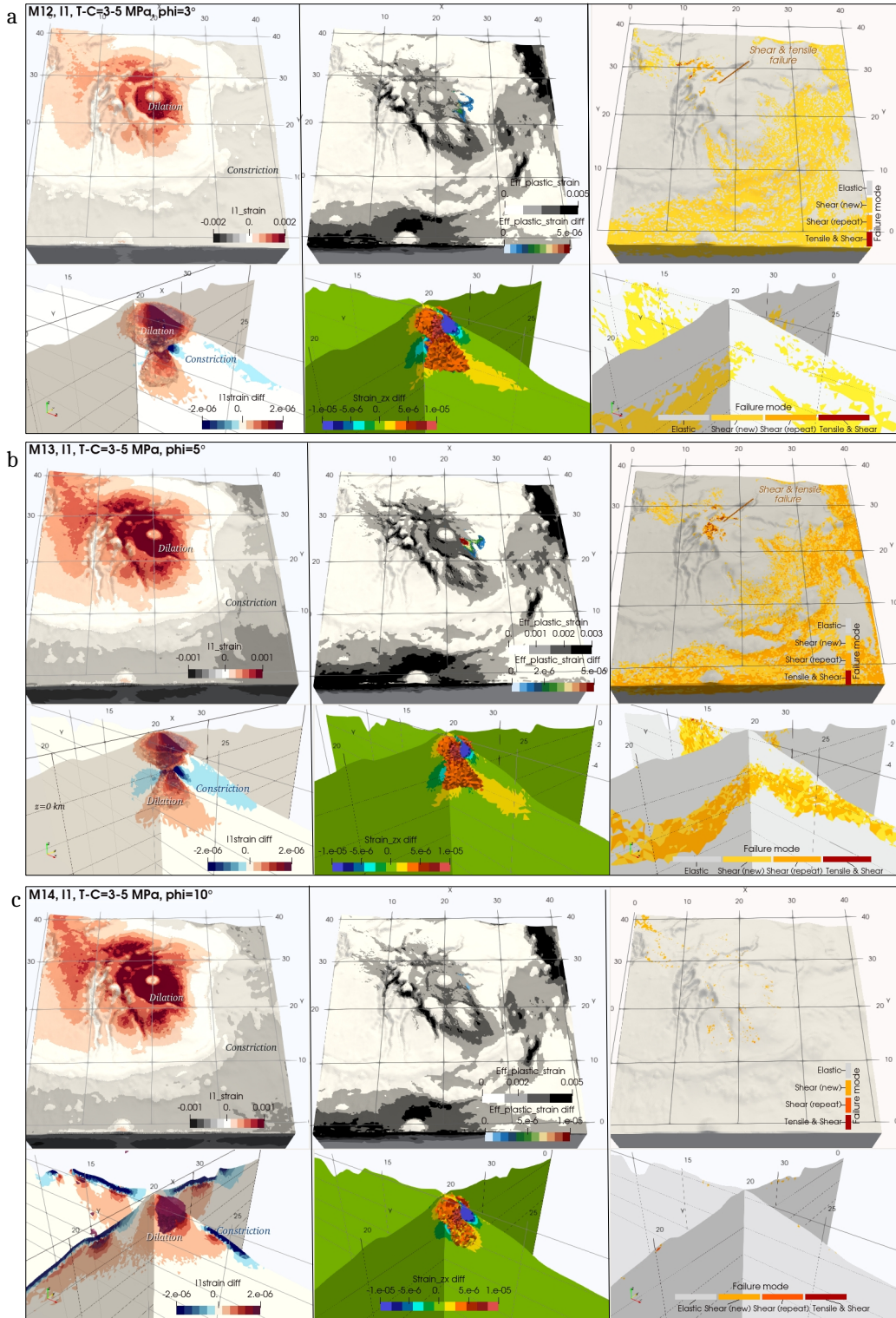


Figure C.3: Complementary figures for models of a dike-like injection (I1): a) M12, b) M13, c) M14, with 3D top views and 2D vertical sections along  $Y=25.8$  km and  $X=20$  km. Left : the trace of the strain tensor (dilatation in red, constriction in black or blue), with total values (top) and differential values (bottom). Middle-top : both the total (grey color palette) and the plastic shear strains. Middle-bottom: the differential  $zx$  shear strain component, with 3D threshold at  $\geq 2.10^{-6}$ . Right: shear and tensile failure modes, indicating tensile failure only to the west of the Enclos Fouqué when  $\varphi \leq 5^\circ$ .

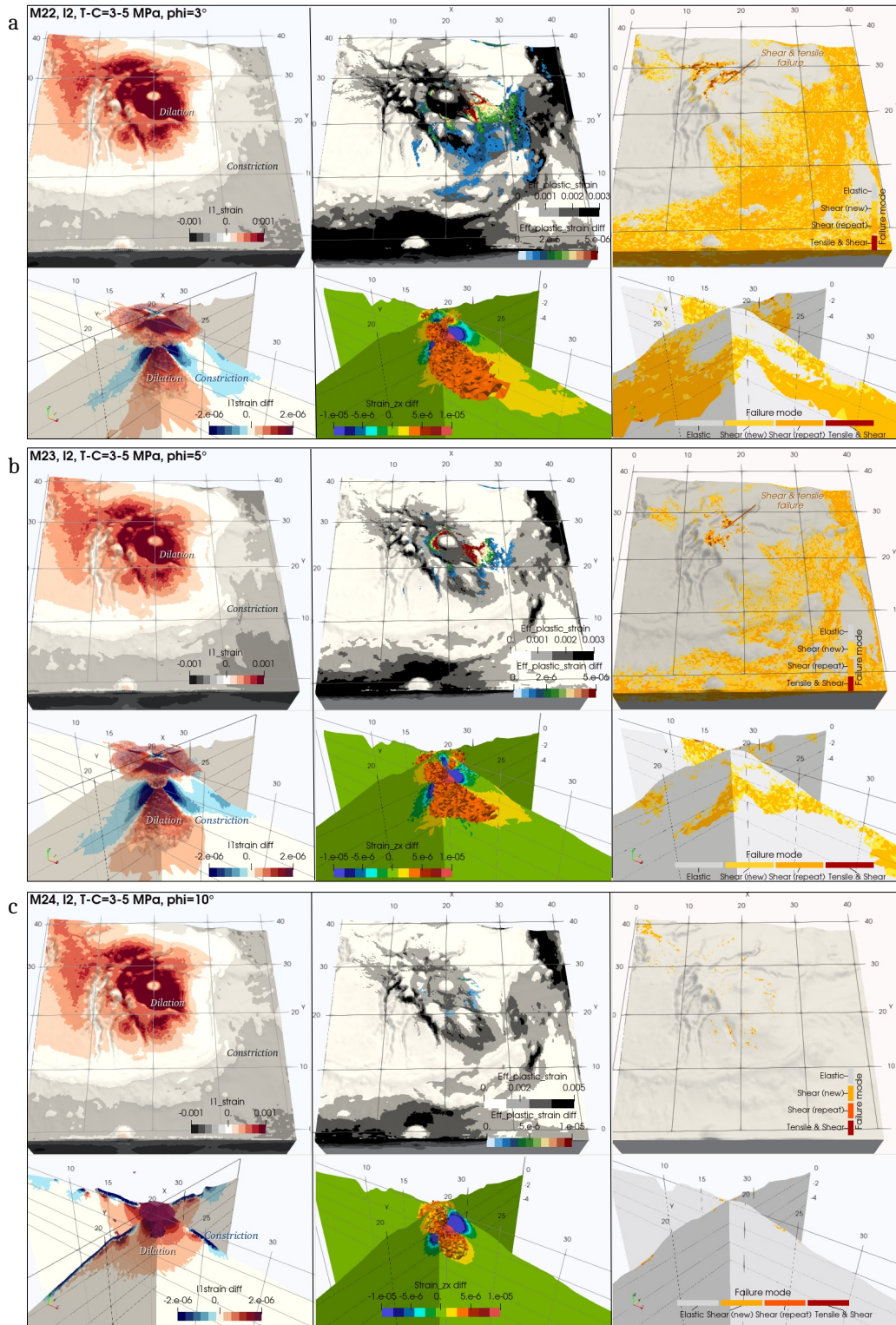


Figure C.4: Complementary figures for models of magmatic reservoir inflation (I2): a) M22, b) M23, c) M24, with 3D top views and 2D vertical sections along  $Y=25.8$  km and  $X=19.5$  km. Left : the trace of the strain tensor (dilatation in red, constriction in black or blue), with total values (top) and differential values (bottom). Middle-top : both the total (grey color palette) and the plastic shear strains. Middle-bottom: the differential  $zx$  shear strain component, with 3D threshold at  $\geq 3.10^{-6}$ . Right: shear and tensile failure modes, indicating tensile failure only to the west of the Enclos Fouqué when  $\phi \leq 5^\circ$ .

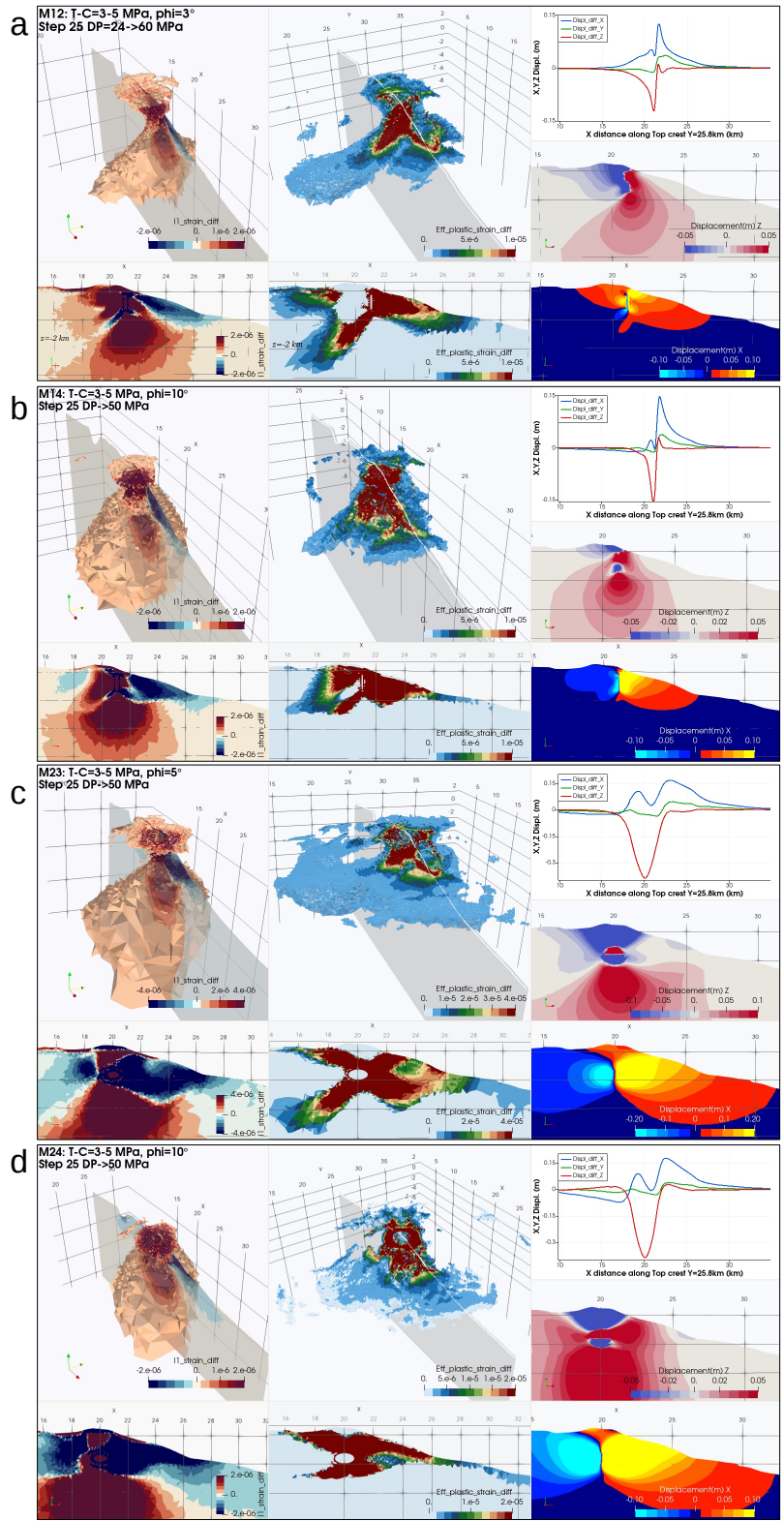


Figure C.5: Models with an overpressure  $DP = 50$  MPa at the walls of a distal dike (I1, a-b) and of the magma reservoir (I2, c-d). Left: differential mean strain (dilatation in red). Middle: differential plastic shear strain. Right: displacements. Surface displacements reach 10-20 cm, the strain structures developed at  $DP = 10$  MPa remain and no catastrophic flank slide occurs.

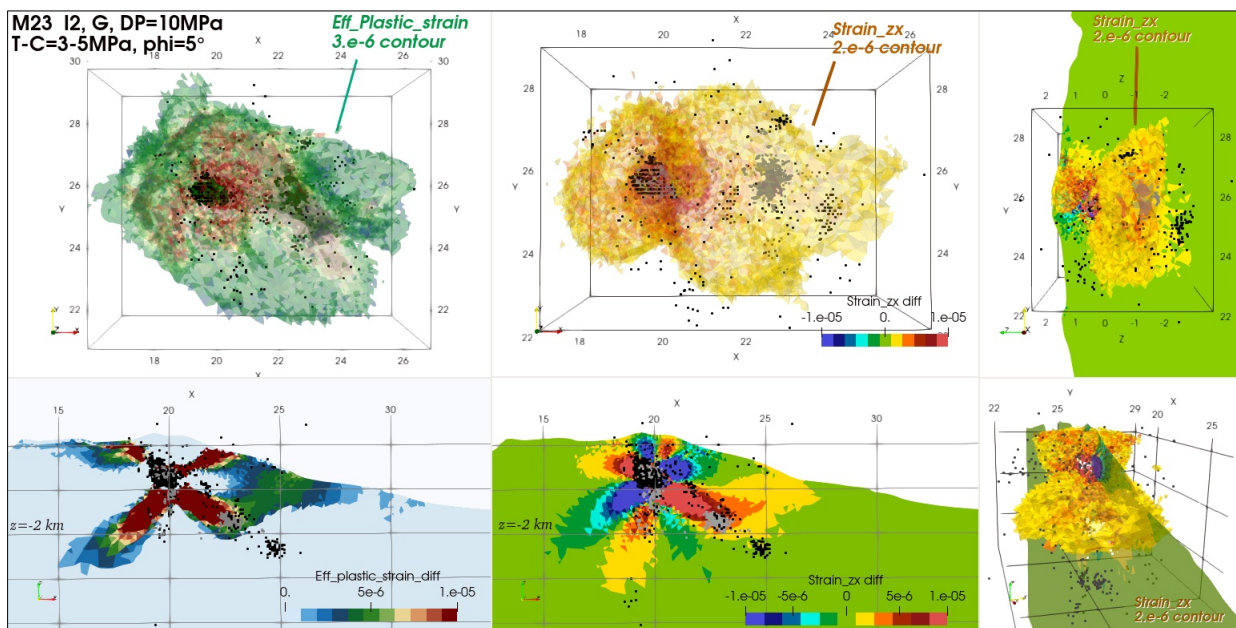
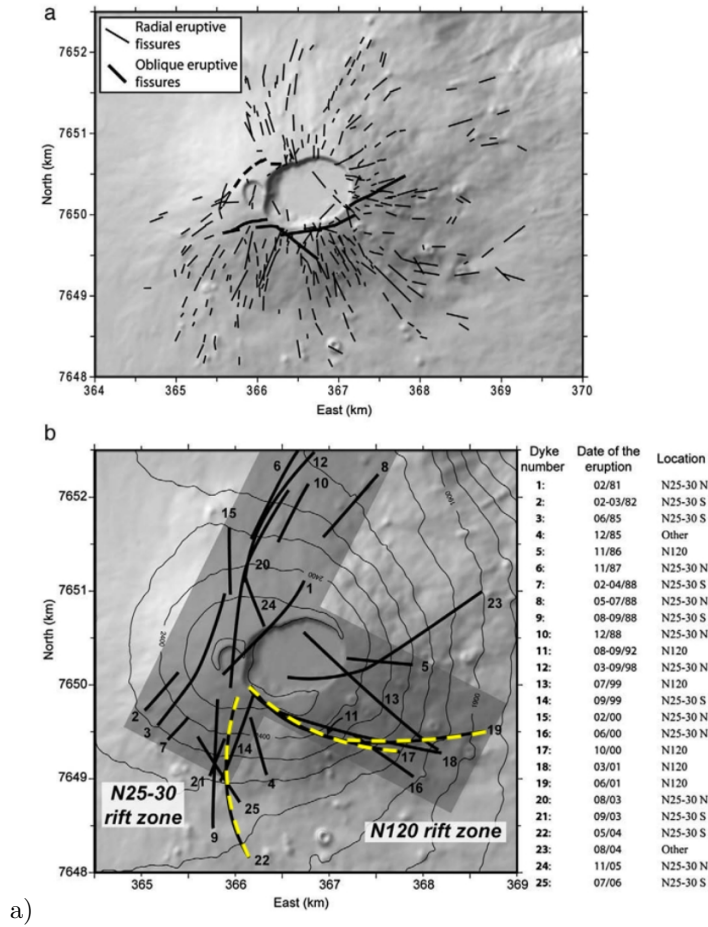


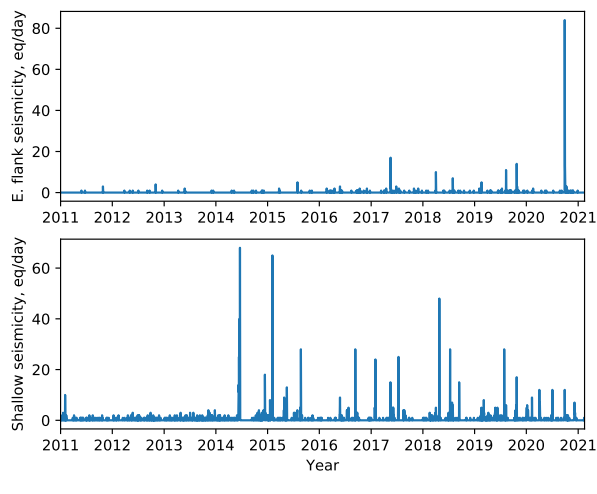
Figure C.6: Comparison of the observed cup-shape seismicity with the shear strain obtained in Model M23 with friction  $\varphi = 5^\circ$ . The shear zone remains above the seismicity pattern, indicating that this area is still too strong in the models to reproduce observations.

1078 Appendix D. Other Piton de la Fournaise related data



a)

Figure D.1: Mapped structures at Piton de la Fournaise, after Michon et al. (2009): a) Eruptive fissures, b) Dike locations associated to proximal eruptions since 1981 (UTM WGS84 coords.). Note shapes of n°17, 19, 22, comparable to the models.



b)

Figure D.2: Seismic activity recorded since 2011 under the Eastern flank and above sea level (source: OVPF).

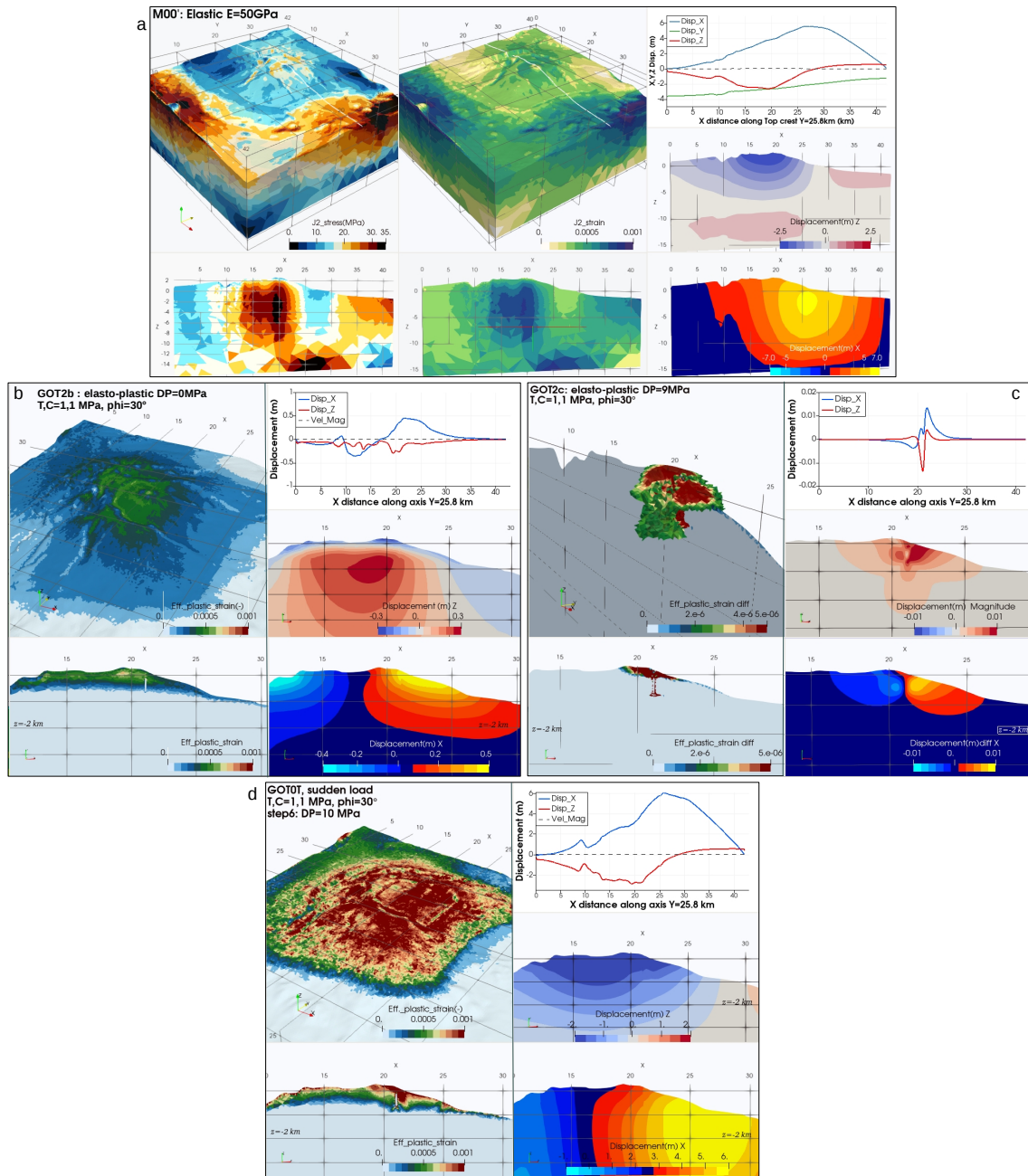


Figure E.1: Inflation of a dike (I1) with parameters similar to those of Got et al. (2013):  $E = 50\text{ GPa}$ ,  $T = C = 1\text{ MPa}$ ,  $\varphi = 30^\circ$ , in 3 stages: **a**) the elastic pre-inflation stage (legend as Fig. 5), shows  $\sim 6\text{ m}$  of displacements. **b**) The elasto-plastic pre-inflation stage produces additional displacements  $\sim 50\text{ cm}$ . Left: plastic strain, and right: displacement patterns. **c**) Dike inflation up to  $DP = 10\text{ MPa}$ , produces displacements  $\sim 1\text{ cm}$ . **d**) Alternative model in which dike inflation is applied directly (no pre-inflation stage): note the similar surface displacements to case a).

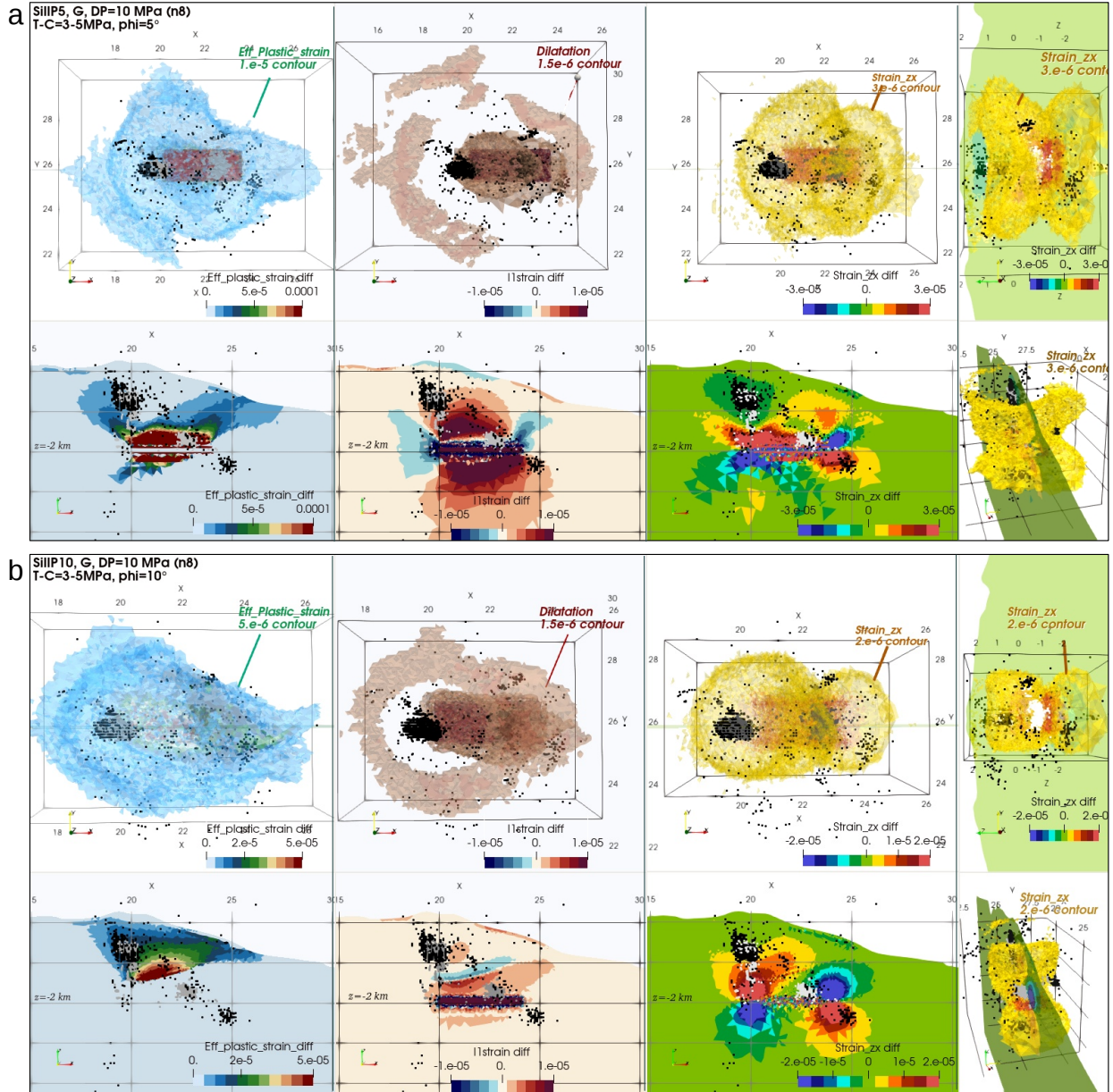


Figure E.2: Inflation of a sill, located at  $z = -2$  km depth, departing from below the summit ( $X = 20$  km and extending for 4 km eastward). Results are for a friction angle  $\varphi = 5^\circ$  (a) and  $\varphi = 10^\circ$  (b). From left to right, the plastic shear strain, the mean strain, and the  $xz$  strain component, respectively (differentials from the pre-inflation stage). Upper row displays 3D view from above, lower row displays a vertical section along  $Y = 25.8$  km. Superposition of the seismicity cross-cuts the different patterns, and does not provide a clear relationship in either case.