Dear Executive Editor SE,

we are deeply grateful for the critical comments that helped us to improve the clarity and quality of the manuscript. In this new version we have revised the English writing, shortened and reorganised the text in order to avoid repetitions and too generic statements. We accepted all the corrections listed in your comment.

In particular, we defined the magmatic pressure as either excess pressure (ΔP_e, magmatic minus lithostatic pressure but below the tensile strength of wall rocks) or over pressure (or driving pressure ΔP_o, which is the magmatic pressure exceeding tensile strength of wall rocks) according to Gudmundsson (2012). The first pertains to the FEMs using isolated magma chambers (single or double), while the second is used for models with connected magma chambers (with conduit/feeding system).

Please find attached here the manuscript with the tracked changes, along with a clean version. We hope this presentation can fulfil your requests.

With our best regards,

On the behalf of Authors

Silvia Massaro

Analysing stress field conditions of the Colima Volcanic Complex (Mexico) by integrating FEM simulations and geological data

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Abstract

In the last decades Finite Element Modelling have become very popular tools in volcanological studies, increasing the relevant parameters considered in their calculations, and raising complex geometry with introduction of multiple reservoirs, topography, and heterogeneous distribution of host rock mechanical properties. In spite of this, the influence of geological information on the numerical simulations is still poorly considered. In this work a 2D Finite Element Modelling of Colima Volcanic Complex (Mexico) is provided by using the LInear Static Analysis (LISA) software, in order to investigate the stress field conditions at increasing detail of geological data. By integrating the published geophysical, volcanological and petrological data, we modelled the stress field considering either one or two magma chambers connected to the surface via dykes or isolated (not connected) in the elastic host rocks (considered homogeneous and not homogeneous). We also introduced tectonic disturbance, considering the effects of direct faults bordering the Colima Rift and imposing an extensional far field stress of 5 MPa. We run the model using gravity in the calculations. Our results suggest that an appropriate set of geological data is of pivotal importance for obtaining reliable numerical outputs, which can be considered as proxy for natural systems. Beside and beyond the importance of geological data in FEM simulations, the model runs using the complex feeding system geometry and tectonics show how the present-day Colima volcanic system can be considered in equilibrium by stress state point of view, in agreement with the long lasting open conduit dynamics that lasts since 1913.

1 Introduction

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Magmatism and tectonism are strongly related to the regional and local stress fields, affecting both the orientation of faults and the location of volcanic vents (Geyer et al., 2016). The stress field around a magmatic source originates from three main contributions: (1) the background stress, composed of a vertical gravitational load, a lateral horizontal load (lithostatic confinement), and tectonic regime; (2) the stress field caused by the loading of the volcano edifice; and, (3) the stress field generated by the magmatic pressure (e.g. Martí and Geyer, 2009; Currenti and Williams et al., 2014). In recent years, a large number of semi-analytical and numerical methods have been proposed for the solution of stress field state of natural systems (e.g. Cayol and Cornet, 1998; Simms and Garven, 2004; Manconi et al., 2007; Long and Grosfils, 2009; Currenti et al., 2010; Currenti and Williams et al., 2014; Zehner et al., 2015), taking into account the static elastic deformation in a multi-layered half-space (e.g. Dieterich and Decker, 1975; Bonafede et al., 2002; Wang et al., 2003; Gudmundsson and Brenner, 2004; Zhao et al., 2004; Pritchard and Simons, 2004; Gottsmann et al., 2006; Geyer and Gottsmann, 2010; Zhong et al., 2019). Following the successful application in mechanical engineering, fluid dynamics and thermodynamics (e.g., Gutiérrez and Parada, 2010; Gelman et al., 2013), the use of Finite Element Method (FEM) has been extensively introduced in volcanology, in order to investigate the effects of topography, lithologic heterogeneities, tectonic stresses and the gravity field on stress state of volcanic systems (e.g. Fujita et al., 2013; Carcho and Gàlan del Sastre, 2014; Bunney, 2014; Ronchin et al., 2015; Hickey et al., 2015; Cabaniss et al., 2019; Rivalta et al., 2019).

The use of FEM for volcanic systems has several examples, which span from the influence of layered materials on the surface deformation process during volcanic inflation (e.g. Darwin volcano, Galapagos Islands; Manconi et al., 2007; Albino et al., 2010) to processes affecting chamber rupture (e.g. Grosfils, 2007; Long and Grosfils, 2009).

The local stress around a volcanic feeding system depends on the geometry of the magma plumbing system, including chamber(s) and dykes forming it, and on the mechanical properties of the host rock around it (e.g. Martì and Geyer, 2009), and especially on changes in Young Modulus (e.g. Gudmundsson et al., 2011; Jeanne et al., 2017; Heap et al., 2020). For instance, limestones, lava flows, welded pyroclastic deposits and subvolcanic rocks can be very stiff (high Young Modulus; ca.

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1.7-27 GPa for limestones, Touloukian, 1981; ca. 5.4 GPa for volcanic rocks, Heap et al., 2020), but young and non-welded pyroclastic units may be very soft (low Young Modulus; ca. 1.7 – 3.1 GPa, Margottini et al., 2013). Therefore, the local stress may abruptly change from one layer to another (e.g., Gudmundsson, 2006). Irrespective of the scope of the numerical investigation, the importance of applying accurate physical constraints to FEM modelling was already discussed in many studies (e.g., Folch et al., 2000; Newman et al., 2001; Fernandez et al., 2001; Currenti et al., 2010; Geshi et al., 2012). However, in the last decade few investigations have been carried out to assess the influence of the amount and quality of geological data into FEM computations (Kinvig et al., 2009; Norini et al., 2010, 2019; Cianetti et al., 2012; Ronchin et al., 2013; Chaput et al., 2014). To bridge this gap, in this work we use the Linear Static Analysis (LISA) software (version 8.0; www.lisafea.com) to study the subsurface stress field state at Colima Volcanic Complex (CVC, Mexico) at increasing geological detail.

The CVC area is a good candidate for testing the response of FEM software against different geological conditions, being constituted by a large volcanic complex (Lungarini et al., 2005) within a tectonic graben filled with volcaniclastic material (Fig. 1a; Norini et al., 2010, 2019). The FEM was run starting from simple homogeneous vs. stratified lithology of subsurface, and successively detailed by the addition of single and double magma chamber, feeder dykes, faults, and extensional far field tectonic stress (Fig. 1b).

2 The Colima Volcanic Complex (Mexico)

2.1 Geological framework

The Pleistocene-Holocene CVC is one of the most prominent volcanic edifices within the Trans-Mexican Volcanic Belt (TMVB) (Macías et al., 2006; Capra et al., 2016; Norini et al., 2019; Fig. 1a). In this area, the Rivera microplate and the Cocos plate subduct beneath the North America plate along the Middle American Trench, (Stock and Lee, 1994), forming a triple junction that delimits the tectonic units known as the Jalisco Block (JB) and the Michoacán Block (MB) (Luhr et al., 1985;

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Allan, 1986; Rosas-Elguera et al., 1996; Rosas-Elguera et al., 1997; Ferrari and Rosas- Elguera, 1999; Rosas-Elguera et al., 2003; Frey et al., 2007). The three rifts of this system are the Tepic-Zacoalco (TZR), the Chapala-Tula (CTR), and the Colima Rift (CR). The still active NS trending CR was formed during a rifting phase occurred after the Late Cretaceous–Paleogene compressive and transpressive phase (Allan, 1986; Serpa et al., 1992; Bandy et al., 1995; Cortés et al., 2010). While opening, CR was gradually filled with Pliocene–Quaternary lacustrine sediments, alluvium and colluvium (e.g. Allan, 1986; Allan et al., 1991; Norini et al., 2010). The geometry, kinematics and dynamics of the CR have been studied on the basis of field, seismic, and geodetic data, mainly collected in its northern and central sectors (see Fig. 1 in Norini et al., 2010).

The magnitude of vertical displacement of the northern and central sectors is ca. 2.5 km by adding the topographic relief of the bounding fault scarps (1.5–1.6 km) to the calculated sediment depth (Allan, 1985; Serpa et al., 1992). Field data and focal mechanism solutions are consistent with a direction of opening of the northern and central sectors oriented from E-W to NW-SE, with a mainly normal and minor right-lateral displacements of the bounding faults (Barrier et al., 1990; Suárez et al., 1994; Rosas-Elguera et al., 1996; Garduño-Monroy et al., 1998; Norini et al., 2010, 2019). In contrast to field and seismic evidence of long-term slightly dextral oblique extension, recent GPS geodetic measurements suggest a possible left oblique extension of the CR (Selvans et al., 2011). In both cases, the stress regime is extensional with an E-W orientation of the minimum horizontal stress in the CVC basement (Barrier et al., 1990; Suárez et al., 1994; Rosas-Elguera et al., 1996; Selvans et al., 2011; Norini et al., 2010, 2019).

The CVC stands within the central sector of the CR, on top of the Cretaceous limestones, Late Miocene-Pleistocene volcanic rocks, and Pliocene-Holocene lacustrine sediments, alluvium, and colluvium (Allan, 1985, 1986, 1991; Cortès, 2005; Norini et al., 2010; Escudero and Bandy, 2017). It is formed by three andesitic stratovolcanoes: Cantaro (2900 m a.s.l.), Nevado de Colima (4255 m a.s.l.) and, in the southern part, the youngest and active Volcàn de Colima (3763 m a.s.l.) (Norini et al., 2019 and reference therein; Fig. 1a).

2.2 Eruptive activity

The eruptive history of the CVC started in the northeast area with the formation of Cantaro volcano

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at ca. 1-1.5 Ma followed by Nevado de Colima at ca. 0.53 Ma, which is composed of voluminous andesitic lava domes and deposits associated with caldera forming eruptions and partial sector collapses (Robin et al., 1987; Roverato et al., 2011; Roverato and Capra, 2013; Cortès et al., 2019). The youngest Volcàn de Colima comprises the Paleofuego edifice, which suffered several sector collapses that formed a horseshoe-shaped depression where the new active (also known as Volcàn de Fuego) cone grew up. Its activity was characterised by dome growths and collapses, extrusion of lava flows, Vulcanian and occasionally sub-Plinian explosive eruptions (Saucedo et al., 2010; Massaro et al., 2018, 2019).

2.3 The CVC plumbing system

Seismic tomography (Spica et al. 2017) highlights a 15 km-deep low velocity body (LVB), which was interpreted as the deep magma reservoir. It is confined within the CR, suggesting a structural control of the normal fault system on it (Spica et al., 2014). The LVB has an extent of ca. 55 km× 30 km in the N-S and E-W directions respectively, showing an averaged thickness < 8 km. Escudero and Bandy (2017) obtained a higher resolution tomographic image of the CVC subsurface area, showing that the most active magma generation zone is now under the Fuego de Colima edifice. The ambient seismic noise tomographic study of Spica et al. (2014) indicates a shallow magma chamber above ca. 7 km depth, in agreement with petrological studies (Medina-Martinez et al., 1996; Luhr, 2002; Zobin et al., 2002; López-Loera et al., 2011; Reubi et al., 2013, 2019; Macìas et al., 2017). Cabrera-Gutiérrez and Espíndola (2010) suggested the shallow active magma storage has a volume of ca. 30 km^3. It is connected to the surface by conduits, whose path is facilitated by the presence of the CR fault zone, which provide a natural pathway for fluids (e.g., Allan, 1986; Norini et al., 2010, 2019). The arrangement of dykes and the alignment of volcanic centres of CVC suggest that the dykes swarm draining the magma chambers developed along the NNE-SSW-trending, steep, eastward dipping normal fault exposed on the northern CVC flank (Norini et al., 2010, 2019).

Massaro et al. (2018) provided a first-order geometrical reconstruction of the Fuego de Colima feeding system during the 1913 sub-Plinian eruption, by using volcanological data (Saucedo et al.,

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2010, 2011; Bonasia et al., 2011) as input and constraints for numerical simulations. Results showed good matches for a hybrid configuration of the shallow conduit-feeding system composed of a ca. 5500 m long, 200-2000 m wide, and 40 m width dyke passing into a shallower (500 m long, 40 m diameter) cylindrical conduit. The shallow magma chamber top was set at 6 km of depth, and dyke-cylinder transition at 500 m below the summit as inferred from geophysical data (Salzer et al., 2014; Aràmbula et al., 2018).

3 Methods

In this study, we used the commercial 8.0 version of LISA (www.lisafea.com), a general-purpose Finite Element Analysis (FEA) software developed in the ‘90s and based on the formulations proposed by Rao (1989), and successively integrated from other sources (Bathe, 1990; Michaeli, 1991; Schwarz, 1991; Babuska et al., 1995). Despite LISA was originally used for structural analysis (Rao, 1989; 2013), it successfully predicts the stress-strain behaviour of rock masses in elastic models, in particular the deformation mechanisms even in layered rock masses (Gabrieli et al., 2015).

3.1 Modelling approach

The stress field of the CVC plumbing system is simulated considering an E-W cross-section, parallel to the extension associated to the active CR (Norini et al., 2010; 2019) as shown in Figure 1a-b (a-a’). Since the extent of the CVC magma chambers in the NNE-SSW direction is typically much longer than the dimensions of the E-W cross section (Spica et al., 2017), 2D solutions of either numerical or analytical models describing E-W elongated magma chambers in the crust can be reasonably adopted (Jaeger et al., 2009; Costa et al., 2011). A topographic profile and 2D plane along the chosen E-W cross-section of the CVC area was obtained in ESRI ArcGIS from a Digital Elevation Model (DEM, resolution 50 m (Instituto Nacional de Estadística y Geografía - INEGI https://en.www.inegi.org.mx/)

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and imported into Autodesk Auto-Cad R13 using a third-degree spline approximation. The IGES file was then imported into LISA for the mesh discretization.

The investigated domain extends 60 x 30 km in a *x-z* Cartesian Coordinate System with a three and four-node finite element discretization (Table 1). Zero normal displacements are assigned at the bottom and the lateral boundaries, while the upper boundary represents the free-stress ground surface (Fig. 1c). The FEM is carried out by using a plane strain approximation, implying that the deformation in the third direction is assumed to be negligible.

As reported in Zehner et al. (2015), FEM of geological structures requires accurate discretization of the computational domain. It follows that the unstructured tetrahedral meshes has to fulfil the following requirements: i) sufficient mesh quality: the tetrahedrons should not be too acute-angled, since numerical instabilities can occur, ii) incorporation of geometry for defining boundary conditions and constraints, iii) local adaption, which is a refinement of the mesh in the vicinity of physical sources in order to avoid numerical errors during the simulation. In this work we adopted a mesh composed of 4660 plane continuum elements, which have been refined in the regions of higher gradients (i.e. near the contours of the magmatic feeding system).

In our simulations, the extent of the rock layers (Table 2) is referred to Norini et al. (2010, 2019). The configuration of the CVC feeding system (i.e. depth, shape and dimensions of the magma chambers and feeder dykes) derives from the literature (Spica et al., 2014, 2017; Massaro et al., 2018, 2019) and it is simplified in Figure 1d. In particular, magma chambers and dykes are considered as pressurized finite-size bodies in an elastic crustal segment, acting as fluid-filled holes. The boundary condition (pressurization) is provided by applying internal forces that act on the walls. This approach has been extensively used in several analytical and numerical models that treat magma reservoirs as internally pressurized ellipsoidal cavities within an elastic half space, in order to gain insight into the behaviour of magma plumbing systems (Pinel and Jaupart, 2004; Gudmundsson, 2006; Grosfils, 2007; Andrew and Gudmundsson, 2008; Hautmann et al., 2013; Currenti and Williams, 2014; Zhong et al., 2019).

Previously published studies indicate that differences between, and problems with, elastic models derive principally from the key role played by gravity (e.g. Albino et al., 2018; Gerbault, 2012; Lister and Kerr, 1991; Watanabe et al., 2002). Some authors argued on whether it is appropriate or not to

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Eliminato: such that geological units are represented correctly. Zehner et al. (2015) reported that

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Spostato in su [2]: Zehner et al. (2015)

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Eliminato: The geometrical configuration set for the CVC feeding system (i.e. the shape and dimensions of the magmatic chambers) derives from the literature (Spica et al., 2014, 2017; Massaro et al., 2018, 2019) and it is simplified in Figure 1d. The overpressure in magma chambers may be produced by a variety of processes, including fractional crystallization, volatile exsolution and magma recharge, leading to deviatoric stresses in the country rock that may be tens of MPa in magnitude (Jellinek and DePaolo, 2003; Karlstrom et al., 2010).

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Spostato in giù [1]: The overpressure in magma chambers may be produced by a variety of processes, including fractional crystallization, volatile exsolution and magma recharge, leading to deviatoric stresses in the country rock that may be tens of MPa in magnitude (Jellinek and DePaolo, 2003; Karlstrom et al., 2010).

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Eliminato:) that. Gravity plays a first order role on bedrock failure conditions (… ... [35]

account for the gravity body force in models of volcanic systems (e.g. Currenti and Williams, 2014; Grosfils et al., 2015). When the gravitational loading is not included in the model, the volcanic deformation results from a change with respect to a stage previously at equilibrium (e.g. Gerbault et al. 2018). In this work, we carried out simulations considering the effect of the gravitational loading in the host rock, implemented via body forces. The model initial condition has a pre-assigned lithostatic stress, whose computation, in presence of topography and material heterogeneities, is not trivial because it requires applying the gravity load preserving the original not deformed geometry of the mesh (Cianetti et al., 2012). Since the presence of a lithostatic stress field, the load applied at the reservoir boundaries represents a superposition of the magmatic pressure and lithostatic component. We define here the magmatic pressure as either excess pressure (ΔP_e, magmatic minus lithostatic pressure but below the tensile strength of wall rocks) or over pressure (or driving pressure ΔP_o, which is the magmatic pressure exceeding tensile strength of wall rocks; Gudmundsson, 2012). The first pertains to the FEMs using isolated magma chambers (single or double), while the second is used for models with connected magma chambers (with conduit/feeding system).

We also took into account the effect of the existing faults of the CR system even if LISA cannot include a frictional law to represent the fault movement (i.e. Chaput et al., 2014). As reported in Jeanne et al. (2017 and reference therein) the damage induced by faults increases from the host rocks to the fault core, implying the reduction in the effective elastic moduli. In this light, we represented the faults bordering the CR as two damage zones (ca. 70° of inclination, ca. 1 km thick, and down to 10 km of depth) showing reduced elastic properties with respect to the surrounding host rocks. To take into account the effect of far field extensional regime, we applied a uniform stress of 5 MPa to the lateral boundaries of the domain (as reported in Martì and Geyer, 2009).

Considering the E-W cross-section (a-a'; Fig. 1a), we provided six domain configurations: i) "*homogeneous lithology model*" in which the volcanic domain is only composed of andesite rocks; ii) "*not homogeneous lithology model*" where different geological units are considered; iii) "*single magma chamber model*" composed of a not homogeneous lithology and a 15 km-deep magma

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chamber; iv) "*dual magma chamber model*" composed of a not homogeneous and 6 km- and 15 km-deep magma chambers; v) "*conduit feeding system model*" composed of not homogeneous lithology, 6 km- and 15 km-deep magma chambers connected through a deep dyke evolving into a shallow conduit near the surface; vi) "*extensional model*", with a 5 MPa horizontal extensional stress (far field) and, vii) "*faulted model*", in which are also added two damaged zones mimicking the CR faults (local stress) (Fig. 1b).

The number of nodes in the only substratum and single magma chamber models is set at 4426, for the dual magma chamber model is set at 4161, and at 3737 for the conduit feeding system and faulted models.

It is important to note that simulations outputs are shown using different colour scales. Although such a choice may result into a difficult visual comparison of the different runs, it preserves the necessary details of stress distribution, which would have been lost using a common colour scale.

Finally, in the following we refer to σ_1 as the greatest compressive stress and σ_3 is the least compressive stress.

4 Geological data

4.1 Stratigraphy and rock mechanics

Four units forming the CVC system are defined from the available geological data (Table 2): i) Basement (Unit B): cretaceous limestones and intrusive rocks forming the bed-rock underlying the CVC; ii) Graben fill deposits (Unit GF): Quaternary alluvial, colluvial, and lacustrine deposits filling the graben; iii) Fuego de Colima deposits (Unit FC): andesitic lavas and pyroclastic deposits forming the Paleofuego-Fuego de Colima edifices; and iv) Volcaniclastic deposits (Unit VD): volcaniclastic deposits covering the southern flank of the CVC (e.g. Cortés et al. 2010; Norini et al., 2010, 2019).

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Eliminato: In this work, we used geological information available in literature as input data, in order to estimate the stress variations around the CVC magmatic plumbing system. Here we briefly describe the main geological features taken into account in LISA simulations.

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Eliminato: Being the area interested by FEM extended down to 30 km, it is evident how Unit B is dominant with respect to the others, which occupy only few km in the upper part of the simulated domain.

We assumed constant mechanical characteristics within each Unit using the typical rock mass properties, density (ρ), Young Modulus (E) and Poisson Ratio (ν) (Table 2). The rock masses are considered dry, in order (eventual) pore pressure to be neglected. Only for Unit GF a higher value for the Poisson Ratio was used close to the surface in order to mimic high water content in the graben sediments. The maximum thickness of the graben fill (about 1 km) is assumed from the literature (Allan, 1985; Serpa et al., 1992; Norini et al., 2010, 2019). For Units B and GF rock mass proprieties are derived from Hoek and Brown (1997) and Marinos and Hoek (2000), while for volcanic materials (units FC and VD; Table 2) are estimated according to the approach proposed by Del Potro and Hürlimann (2008). In order to describe the effects of the CR faults on stress field distribution, the mechanical properties are locally degraded in proximity of the faults themselves.

4.2 The geometry of the plumbing system

In our 2D model, we assume the CVC composed of a two magma chambers connected by dykes and to the surface by a conduit (Fig. 1d). The shape of the magma chambers and dykes are represented by elliptical cross-sections with the major (2*a*) and minor (2*b*) axes.

Generally, the magma chambers have a sill-like shape that is often imaged in seismic studies of volcanoes and rift zones (Macdonald, 1982; Sinton and Detrick, 1992; Mutter et al., 1995; MacLeod and Yaouancq, 2000; Singh et al., 2006; Canales et al., 2009). Most of them are not totally molten but rather a mixture of melt and crystal mush (i.e. Parfitt and Wilson, 2008). Various estimates have been made to infer the actual amount of melt in a magmatic body, showing that it is only ca. 10% of the total chamber volume (Gudmundsson et al., 2012 and reference therein).

After Spica et al. (2017), the 15 km-deep LVB is ca. 7000 km^3, therefore, if we assume the melt as 10%, the deep magma chamber volume would be ca. 700 km^3. Simplifying this volume in an elliptical sill-like geometry, the magma chamber dimensions (i.e. *2a, 2b, 2c* axes) have to be scaled according to the LVB (55 × 30 × 8 km; Spica et al., 2017) using $2a$ = 14 km, $2b$ = 3.6 km, $2c$ = 26 km, being $2c$ elongated in NW-SE direction. For the shallow part of the feeder system, we have no detailed geophysical constraints. However, Massaro et al. (2019) reproduced through numerical modelling the nonlinear cyclic eruptive activity at Fuego de Colima in the last 20 years, using a

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Spostato in giù [3]: We assumed constant mechanical characteristics within each Unit (Table 2).

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Eliminato: Deformation within the brittle upper crust is described by elastic material's behaviour.

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Eliminato: (Table 2). For each Unit we fixed

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Eliminato: was …s assumed from th ... [45]

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Eliminato: This information allowed Norini et al. (2019) to derive the equivalent Mohr-Coulomb properties for the stress ranges expected in the different sectors of the CVC.

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Eliminato: The geometry of the E-W cross-section of the CVC plumbing system was modelled taking into account the previous subsurface information described in Section 4.1.

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shallow magma chamber volume in the range of 20-50 km^3, according to the estimation of Cabrera-Gutiérrez and Espindola (2010). Here we assume a volume of 30 km^3, using $2a$ = 3.5 km, $2b$ =2 km, $2c$ = 8 km as dimensions of the shallow magma chamber.

Numerous theoretical and field studies have established that host rock stresses dictate the magma pathways (e.g. Maccaferri et al., 2011; Gudmundsson, 2011). During ascent to the surface, the dykes align themselves with the most energy-efficient orientation, which is roughly perpendicular to the least compressive stress (e.g. Gonnermann and Taisne, 2015; Rivalta et al., 2019), providing the magma driving pressure remains small compared to the deviatoric stress (Pinel et al., 2017; Maccaferri et al., 2019). This behaviour, however, can be modulated in the presence of significant variations in fracture toughness of the surrounding rock due to stratification (Maccaferri et al., 2010) or to old and inactive fracture systems (Norini et al., 2019).

Although for oblate magma chambers the propagation of dykes is most probable from the tip areas, in our simulations the orientation of dykes is assumed vertical, because of the preferential pathways represented by the CR fault planes (Spica et al., 2017).

We set the dimensions of feeder dykes in agreement with Massaro et al. (2018): deep dyke $2a_d$ = 2 km; shallow dyke $2a$ varies from 1 km at bottom to 500 m in the upper part of the volcano; width of both deep and shallow dyke $2b_d$ = $2b$ = 100 m (Fig. 1d).

It is worth noting that it is outside the scope of this work providing the conditions for the magma chamber rupture, being LISA accounting only for the elastic regime. For these reasons, we fixed ΔP_e and ΔP_o (for isolated and connected magma chamber models, respectively) in the range of 10 - 20 MPa for the 15 km-deep chamber, and 5 MPa for the 6 km-deep one. For the dykes and conduit, ΔP_o is set to 10 MPa in the deeper dyke and 5 MPa in the shallower one, while in the upper 500 m of conduit is 0.4 MPa.

5 Results

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Eliminato: Although, for decades, magma conduits were modelled as cylinders, because of easiness of their mathematical treatment, geophysical data and field observations highlight the importance and peculiarities of dykes in magma transport and hence the need to adopt more realistic geometries (Costa et al., 2009; Hautmann et al., 2013; Tibaldi, 2015). It is important to stress that

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Eliminato: Aalthough all cavities/inclusions in a medium modify the local stress field and concentrate stresses, the induced perturbation depends mainly on the geometry of the cavity/inclusion (Savin, 1961; Boresi et al., 1985; Tan, 1994; Saada, 2009). Geophysical data and field observations highlighted the importance and peculiarities of dykes in magma transport and hence the need to adopt more realistic geometries for magma pathways (Costa et al., 2009; Hautmann et al., 2013; Tibaldi, 2015). We Here w

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Eliminato: the selected magma overpressures (ΔP) acting on the magma reservoirs chambers and dykes have to be less than the tensile strength of the rocks. We therefore fixed

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In this section we reported the sensitivity analysis carried out to quantify the approximation of the Young Modulus variation on FEM outputs, and the description of the model outputs when adding complexity to the input geological/geophysical data.

5.1 Sensitivity analysis of Young Modulus

Using the single magma chamber model as reference case, we quantified the influence of the Young Modulus variation in each geological Units. Taking into account the mechanical properties of rocks (Table 2) as reference values, we compared the stress state of the computational domain at changing Young Modulus by (±) an order of magnitude. This sensitivity analysis, although incomplete, may lead to raise awareness on the selection of input data when running a FEM. The sensitivity analysis was carried out on a reduced simulation domain (the *x*-axis was set to 35 km) in order to diminish the influence of binding effects along the domain borders.

We applied the Euclidean norm (L2) method for illustrating the results. The L2 norm applied on a vector space *x* (having components $i = 1,...n$) is strongly related with the Euclidean distance from its origin, and is equal to:

$$||x||_2 = \sqrt{\sum_i^n x_i^2} \quad (1)$$

In our case, the vector space *x* is composed of all nodes of the computational domain (Table 1). We defined x_{ref} the vector containing the results for the maximum and minimum principal stress when using the selected values of material properties (Table 1) and $x(-)$, $x(+)$ the vectors at varying the Young Modulus of one order of magnitude in each Unit.

In Figure 2 are reported the global relative variations in L2 of σ_1 and σ_3 caused by the variation of Young Modulus in each Unit, for each model configuration (i.e. not homogeneous lithology, single magma chamber, dual magma chamber, and dual magma chamber with conduits models) as follow:

$$L2(-) = \frac{||x_{ref} - x(-)||_2}{||x_{ref}||_2} \quad (2)$$

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Eliminato: Considering the E-W cross-section (a-a'; Fig. 1a), we provided six domain configurations with increasing geological complexity: i) "*homogeneous lithology model*" in which the volcanic domain is only composed of andesite rocks; ii) "*not homogeneous lithology model*" where different geological units are considered; iii) "*single magma chamber model*" composed of a not homogeneous lithology and a 15 km-deep magma chamber; iv) "*dual magma chamber model*" composed of a not homogeneous and 6 km- and 15 km-deep magma chambers; v) "*conduit feeding system model*" composed of not homogeneous lithology, 6 km- and 15 km-deep magma chambers connected through a deep -dyke evolving into, and a shallow conduit connecting tonear the surface; vi) "*extensional model*", with a in which we added a 5 MPa horizontal extensionaextensivel stress (far field) and, vii) "*faulted model*", in ... [58]

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$$L_2(+) = \frac{||x_{ref} - x(+)||_2}{||x_{ref}||_2} \quad (3)$$

All the models show variability less than 15%, with few exceptions within Unit B that have variability over 30% (Fig. 2). In this light, the spatial distribution of the major variations seems to not significantly affect the final stress distributions, because: i) they are located near the mesh borders (Fig. 3a, b); and, ii) when not at the mesh borders, the variations are limited to few % (Fig. 3c, d). It means that the one order of magnitude variation in Young Modulus produces variation in FEM outputs distributed over a large domain, and the change affecting the single nodes is limited to few %.

5.2 Homogeneous and not homogeneous lithology

In Figure 4 we reported σ_1 and σ_3 stresses for gravity loaded models with homogeneous lithology composed by only andesitic lavas (Fig. 4a) and not-homogeneous lithology composed of carbonates (Unit B), alluvional, volcaniclastic and pyroclastic deposits (Units GF and VD; Fig. 4b). It is important to stress that the *x*-*z* zero displacement assigned at the bottom and at the lateral boundaries of the domain created substantial artefacts in the results (i.e. curved patterns of stress), especially considering σ_3 (Fig. 4, panels i-ii) where the boundary effect on *x*-axis is amplified by the presence of the upper free surface. It follows that the only unperturbed area extends ca. 30 km horizontally and ca. 15 km vertically (within the blue contour in Fig. 4). It is worth noting that the homogeneous and not-homogeneous models show quite similar results in stress patterns (Fig. 4).

5.3 Gravitational modelling using the inferred feeding system geometry

In Figures 5 and 6 we show three cross-section profiles describing the feeding system starting from a single to two magma chambers, then adding the conduits, and, finally, considering the full complexity by adding the effects of far-field stress and CR faults. Figure 5a describes σ_3 (panel i) and σ_1 (panel ii) stress distribution for the single magma chamber model and ΔP_e = 10 MPa. No significant differences in magnitude and pattern of stresses are visible using ΔP_e = 20 MPa (Appendix 1a).

The addition of the shallow magma chamber significantly changes the values and pattern of both σ_3

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and σ_1 (Fig. 5b). In particular, σ_3 and σ_1 stresses describe a typical inflation pattern produced by excess pressure in magma chamber(s) (Anderson, 1936; Gudmundsson, 2006; 2012), producing well-defined stress arches of σ_3 (red dotted lines in Figs. 5bi) and divergent strong gradients of σ_1 around the deep magma chamber (Fig. 5bii). Very slight differences in magnitude and pattern of stresses appear when using ΔP_o = 10 MPa (Fig. 5b) or 20 MPa (Appendix 1b).

Looking at Figure 6 it is evident how the insertion of the conduits in the CVC feeding system dramatically changes the stress distribution, with the disappearance of the stress arch and a nearly constant stress in the computational domain except around the deep magma chamber tips.

5.4 Application of an extensional stress field

In order to explore the influence of the extensional far field stress on stress patterns (Fig. 1a), we run simulations applying 5 MPa stress (typical low value for rift zones; Turcotte and Schubert, 2002; Moeck et al., 2009; Maccaferri et al., 2014; Sulpizio and Massaro, 2017) along the lateral boundaries of the computational domain (Fig. 7).

In the case of a single magma chamber (ΔP_e = 10 MPa; Fig. 7, panels i-ii), the addition of the far field stress reduces the confinement effect due to the no displacement condition imposed along the *x-z* directions (plane strain approximation). When considering the double magma chamber configuration (ΔP_o = 10 MPa in the deep chamber and ΔP_o = 5 MPa in the shallower one), the presence of the far field stress produces slight changes in stress magnitude and pattern for both σ_3 and σ_1 (Fig. 7, panels iii-iv) with respect to Figure 5b. Very similar effects appears on the complete feeding system configuration model (Fig. 7, panels v-vi). Also in this case using ΔP_o = 20 MPa in the deep magma chamber does not significantly affect the model outputs (Appendix 2).

5.5 Faults bordering the Colima Rift

The effect of faults bordering the CR on the final feeding system configuration is simulated through two damage zones by degrading their elastic properties. Adding these elements does not significantly alter the stress distribution observed in Figures 7v and 7vi, but only provide a slight reduction in both

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σ_1 and σ_3 intensities around their edges (Figs. 7vii and 7viii). The different distance of the two damage zones from the feeding system produces a small asymmetry in both σ_1 and σ_3 patterns with respect to simulations without damage zones, especially near the deep magma chamber (Figs. 7v-viii).

6 Discussions

6.1 FEM analysis at increasing geological details

This study highlights some important features of crustal stress distribution at changing geological and geophysical constraints as input conditions (Spica et al., 2014, 2017; Massaro et al., 2018). Although the results have to be considered as a first order approximation, the changes in stress distribution are appreciable and useful for a better understanding of the FEM limitations and advantages.

Under the assumptions of plane strain and gravitational loading, the use of homogeneous or not homogeneous lithology provides negligible effects in stress intensity and pattern (Fig. 4). This is likely due to the limited thickness of the shallow Units (Units FC, VD, GF; Table 2) in the simulated domain, which results dominated by Unit B (Table 2). However, this does not mean that the influence of the upper Units may be still negligible using smaller scales of the simulated domain.

Analysing the single magma chamber model outputs, it emerges how the ΔP_e limited the effects of gravitational loading. On the contrary, the dual magma chamber geometry better describes the inflation induced by the ΔP_e within magma chambers, with the formation of the stress arch in the σ_3 plot. It is worth noting that for both single and dual magma chamber models, the ΔP_e change from 10 to 20 MPa slightly affects the magnitude of the stress but not its general pattern (Appendix 1-2).

The presence of dykes in the magma feeding system dramatically change the σ_3 and σ_1 patterns (Fig. 6), which become quite homogeneous throughout the computational domain, with the only exception of sidewall effects induced by the zero displacement conditions.

The addition of extensional field stress of 5 MPa reduces the sidewall effects and produces an almost homogeneous stress distribution in the upper part of the computational domain, above the top of the deep magma chamber. This, along with the additional inclusion of the damage zones introduced to

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mimic the effects of CR faults, describes a close to equilibrium volcanic system, in which pressure within the volcano feeding system almost equilibrate the lithostatic stress (Sulpizio et al., 2016).

6.2 Some implication of the stress state of the CVC inferred from FEM

The results from the most complete FEM runs highlight an almost homogeneous stress distribution in the CVC area. This means the dual magma chamber model and the application of the far field stress provide a stable geometry, which limits the stress changes to few MPa. The majority of stress variations are located at the tips of the magma chambers, as expected for pressurized or under-pressurized cavities in the lithosphere (Martì and Geyer, 2009), implying that the whole feeding system is in a quasi-equilibrium state. Even if we consider the scenario of complete emptying the upper conduit and part of the shallow magma chamber, as occasionally occurred during the past sub-Plinian and Plinian eruptions (Luhr et al., 2002; Saucedo et al., 2010; Massaro et al., 2018), this would result in the restoration of the stress arch, which is still a stable stress configuration. Even the complete emptying of the shallow magma chamber probably would be ineffective for triggering a large collapse (caldera forming) of the feeding system.

Beside and beyond the limitations due to the first order approximation of the FEM analysis, other sources of uncertainties in the discussion about present and future stress state of the CVC come from not considering gravity-driven processes, such as volcano spreading due to plastic deformation of the GF Unit (Norini et al., 2010, 2019) and detailed regional tectonics (Norini et al., 2010, 2019). The effect of the two fault systems bordering the CR are here simulated by degrading the mechanic properties of rocks in an area of about 1 km width up to a depth of 10 km. Although the effects are negligible at the scale of the computational domain, it cannot be excluded some local significant effects that cannot be resolved using the described approach.

7 Summary and conclusion

The presented study highlighted the importance to use complete and detailed geological and geophysical data when dealing with FEM of volcanic areas. The different geological detail used in

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the model runs showed how the stress pattern critically depends on geometry of the volcano feeding system, with huge differences in having a single or double magma chamber system and, in particular, if the magma chamber(s) are connected or not to the surface by feeder dykes and conduit. The geometry of the feeding system is prevalent on model outputs with respect to varying rock properties (i.e. Young Modulus) of one order of magnitude. In the case of CVC the use of subsurface homogeneous or stratified lithology not influence much the FEM outputs, being the subsurface geology of the computational domain dominated by carbonates (Unit B).

Beside and beyond the results obtained by analysing the influence of detailed geological and geophysical data, the presented modelling confirms the close to equilibrium state of the volcano, which is the expected stress distribution induced by a feeding system directly connected to the surface.

The complete emptying the upper conduit and part of the shallow magma chamber, as occasionally occurred in the past, originating sub-Plinian and Plinian eruptions, would result in the restoration of the stress arch, which is still a stable stress configuration. Descends that large magnitude, caldera forming eruptions are possible only if the bigger deep magma chamber is also involved and significantly emptied during an eruption.

Appendices

Appendix 1

E-W gravitational modelling of the CVC domain (stratified lithology) for all configurations investigated. The magnitude and pattern of the principal stress account for a) single magma chamber model (number of nodes: 4426); b) dual magma chamber model (number of nodes: 4161); c) dual magma chamber with conduits model (number of nodes: 3737). The dimension of the deep magma chamber: $2a$ = 14 km and $2b$ = 3.6 km at 15 km of depth; shallow magma chamber: $2a$ = 3.5 km and $2b$ = 2 km at 6 km. ΔP_e and ΔP_o are equal to 20 MPa for the deep chamber, and 5 MPa for the shallower. Black dotted lines highlight the passage from different stress values. Note that the scales of stress values are different for each panel in order to maximise the simulation details.

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Appendix 2

E-W gravitational modelling of the CVC domain (stratified lithology) considering an extensional far-field of 5 MPa for all configurations investigated. The magnitude and pattern of the principal stress account for a) single magma chamber model (number of nodes: 4426); b) dual magma chamber model (number of nodes: 4161); c) dual magma chamber with conduits model (number of elements: 3737). The dimension of the deep magma chamber: *2a* = 14 km and *2b* = 3.6 km at 15 km of depth; shallow magma chamber: *2a* = 3.5 km and *2b* = 2 km at 6 km. ΔP_e and ΔP_o are equal to 20 MPa for the deep chamber, and 5 MPa for the shallower. Black dotted lines highlight the passage from different stress values. The red arrows indicate the direction of the applied far field stress. Note that the scales of stress values are different for each panel in order to maximise the simulation details.

Code/Data Avaiability

The LISA code is available at https://lisafea.com/.

Author's contribution

SM, RS, AC, GN and GG conceived the study. SM and RS wrote the bulk of the manuscript with the input of all the co-authors. SM and GL compiled the numerical simulations and formulated the adopted methodology. MP and SM carried out the sensitivity analysis. All the authors worked on the interpretation of the results.

Competing interests: The authors declare that they have no conflict of interest.

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Table 1 - Element types used in LISA analysis considering the final conduit feeding system configuration – Fig.1d, panel vi)

E-W cross-section (a-a')	Element Type	Elements	Nodes

FC	Fuego de Colima	quad4-tri3	372	384
VD	Volcanic Deposits	quad4-tri3	245	273
GF	Graben Fill	quad4-tri3	456	338
B	Basament	quad4-tri3	3088	2907
CG	Colima graben	quad4-tri3	48	71

Total Elements: 4209

Table 2 - Rock mass and mechanical properties of the geological Units used in the finite-element model (from Norini et al., 2010, 2019).

Acronym	Model Unit	Rock Type	Density (kg/m^3)	Young's Modulus (MPa)	Poisson's ratio *v*
FC	Fuego de Colima	Andesitic lavas and pyroclastic deposits forming the Paleofuego-Fuego de Colima volcano	2242	1.4×10^3	0.30
VD	Volcaniclastic deposits	Pyroclastic and epiclastic deposits covering the southern flank of the CVC	1539	1.7×10^3	0.32
GF	Graben Fill	Quaternary alluvial, colluvial, lacustrine deposits filling the graben	1834	1.5×10^3	0.35
B	Basement	Cretaceous limestones and intrusive rocks forming the bed-rock underlying the CVC	2650	3.6×10^4	0.30

Figures Captions

Fig. 1 (a) Morphotectonic map of the Colima Volcanic Complex (NC=Nevado de Colima volcano; FC=Fuego de Colima volcano) and Colima Rift with the main tectonic and volcano-tectonic structures (NCG =Northen Colima Graben; CCG= Central Colima Graben, from Norini et al., 2019). In the inset, the location of the Colima Volcanic Complex (CVC) within the Trans-Mexican Volcanic Belt (TMVB) is shown in the frame of the subduction-type geodynamic setting of Central America (from Davìla et al., 2019); (b) general sketch of the geometrical configurations used in LISA; (c) example of mesh of the investigated area for the dual magma chamber model with conduits (case v in panel (b), considering zero-displacement along the bottom and left and right sides. Note that for case

(vi) in panel (b) the zero-displacement is removed from the lateral sides; (d) sketch of the Fuego de Colima feeding system composed of a 15 km-deep magma chamber connected to surface via a 6 km-deep magma chamber and dykes. ΔP_{chs} and ΔP_{chd} indicate either excess or over pressure (depending on the model used) in the shallow and deep chambers, respectively (modified from Massaro et al., 2019).

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Fig. 2 Results of the sensitivity analysis carried out on the Young Modulus variations within each rock layer of the domain considering different configurations (stratified substratum model – nodes: 4426; single magma chamber model – nodes: 4426; dual magma chamber model – nodes: 4161; dual magma chamber with conduits model – nodes: 3737). For each geological Unit (B, FC, GF, VD), the relative global variation in L_2 (%) is provided for σ_1 and σ_3. The x(-) and x(+) vectors indicate the Young's Modulus variation by an order of magnitude with respect to x_{ref} vector, containing the stress values calculated by using the values of material's properties indicated in Table 2.

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Fig. 3 Spatial variation (%) of the L_2 norm's components at varying Young Modulus for selected cases of Units B and VD: (a) Unit B in the stratified substratum model (nodes: 4426); (b) Unit B in the single magma chamber model (nodes: 4426); (c) Unit B in the dual magma chamber model (nodes: 4161); (d) Unit VD in the dual magma chamber with conduits model (nodes: 3737). Symbols x(-) and x(+) have the same meaning of Figure 2.

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Fig. 4 E-W gravitational modelling of the CVC domain. The scale of the mesh is expressed in Unit of Design (1 UD = 1 km). The domain extends 60 km along the x-axis, and 30 km along the z-axis. The number of nodes used in the mesh is set to 4426. The magnitude and pattern of the principal stresses (dotted black lines) are reported for (a) the homogeneous stratigraphy (Unit FC =andesitic lavas and pyroclastic deposits) and for (b) the not homogeneous stratigraphy (Unit FC; Unit B= Cretaceous limestones and intrusive rocks forming the bed-rock underlying the CVC; Unit GF= Quaternary alluvial, colluvial, and lacustrine deposits filling the graben; Unit VD= volcaniclastic deposits covering the southern flank of the CVC). The blue line contours the unperturbed part of the domain, which extends ca. 30 km horizontally and ca. 25 km vertically. Note that the scale of stress values is the same for the all simulations.

Fig. 5 E-W gravitational modelling of the CVC domain with a not homogeneous stratigraphy. The magnitude and pattern of the principal stresses are reported for (a) the single magma chamber model represented by a magma chamber ($2a$ = 14 km and $2b$ = 3.6 km) at 15 km of depth, and (b) the dual magma chamber model composed of a 15 km-deep magma chamber ($2a$ = 14 km and $2b$ = 3.6 km) and a shallow 6 km-deep one ($2a$ = 3.5 km and $2b$ = 2 km). The magma chambers are not connected. ΔP_0 is set to 10 and 5 MPa for the 15 km-deep and 6 km-deep magma chambers, respectively. The number of nodes is set to 4426 and 4161 for the single and dual magma chamber models, respectively. Black dotted lines highlight the passage from different stress values. The red dotted line in panel (b-i) indicates the formation of the stress arch. Note that the scale of stress values are different for each panel in order to maximise the simulation details.

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Fig. 6 E-W gravitational modelling of the CVC domain with a not homogeneous stratigraphy accounted for a dual magma chamber system connected by dykes via surface (deep magma chamber, $2a$ = 14 km and $2b$ = 3.6 km at 15 km of depth; shallow magma chamber, $2a$ = 3.5 km and $2b$ = 2 km at 6 km od depth). The magnitude and pattern of the principal stresses are shown. The number of nodes used is set to 3737. ΔP_0 is set to 10 and 5 MPa for the 15 km-deep and 6 km-deep magma chambers, respectively. The black dotted lines in panel (ii) highlight the passage from different stress values. Note that the scale of stress values are different for each panel in order to maximise the simulation details.

Silvia 20/9/20 11:14
Eliminato: The magmatic overpressures are
Silvia 25/9/20 14:36
Formattato: Tipo di carattere:9 pt

Fig. 7 E-W gravitational modelling of the CVC domain with a not homogeneous stratigraphy considering the extensional field stress. The magnitude and pattern of the principal stresses are shown for the single magma chamber model (panels i-ii), the dual magma chamber model (panels iii-iv), the dual magma chamber with conduits model (panels v-vi-vii-viii). Note that in panel vii-viii the faults bordering the CG are shown. For all configurations an extensive far-field stress of 5 MPa is applied at the lateral boundaries of the domain. In panels vii-viii the additional effect of the local extensive field is simulated using a reduced values of material's properties (Table 2). ΔP_0 is set to 10 and 5 MPa for the 15 km-deep and 6 km-deep magma chambers, respectively. Black dotted lines highlight the passage from different stress values. The red arrows indicate the direction of the applied far field stress. Note that the scale of stress values are different for each panel in order to maximise the simulation details.

Silvia 20/9/20 11:15
Eliminato: Colima graben
Silvia 25/9/20 14:36
Formattato: Tipo di carattere:10 pt
Silvia 20/9/20 11:15
Eliminato: The magmatic overpressures are

Figures

Figure 1

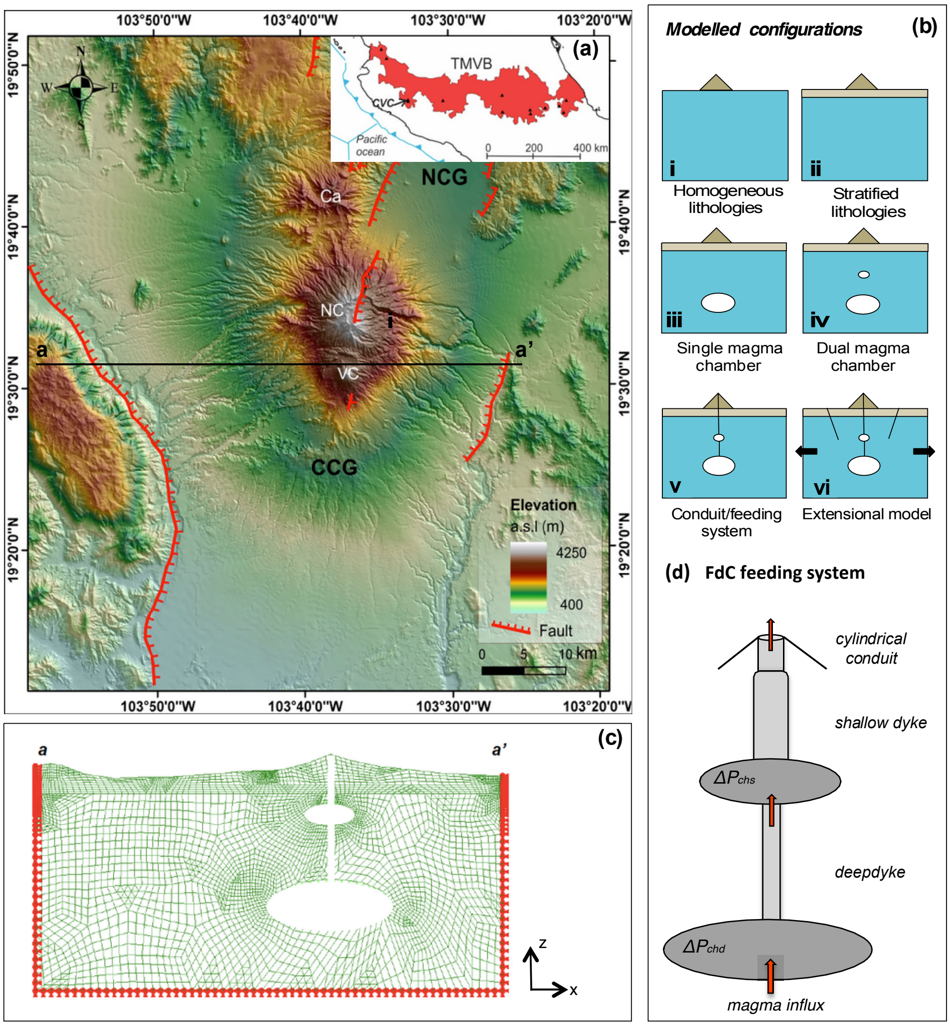

103°50'0"W
103°40'0"W
103°30'0"W
103°20'0"W
19°50'0"N
19°40'0"N
19°30'0"N
19°20'0"N
(a)
TMVB
CVC
Pacific ocean
0
200
400 km
NCG
Ca
NC
VC
CCG
a
a'
Elevation
a.s.l (m)
4250
400
Fault
0
5
10 km
Modelled configurations
(b)
i
Homogeneous lithologies
ii
Stratified lithologies
iii
Single magma chamber
iv
Dual magma chamber
v
Conduit/feeding system
vi
Extensional model
(d) FdC feeding system
cylindrical conduit
shallow dyke
ΔPchs
deepdyke
ΔPchd
magma influx
(c)
a
a'
z
x

Figure 2

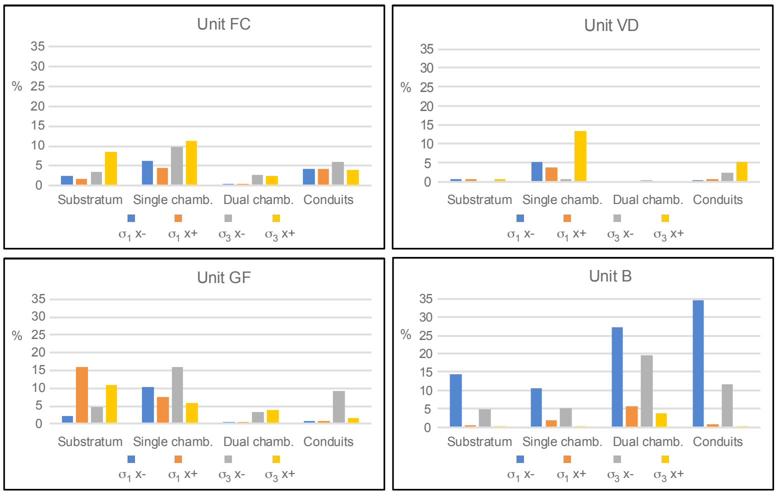
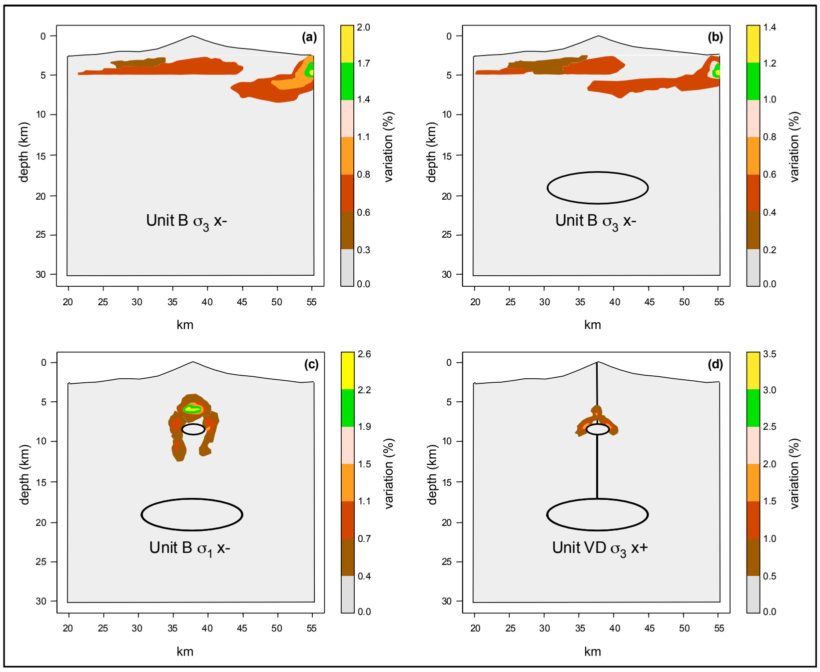
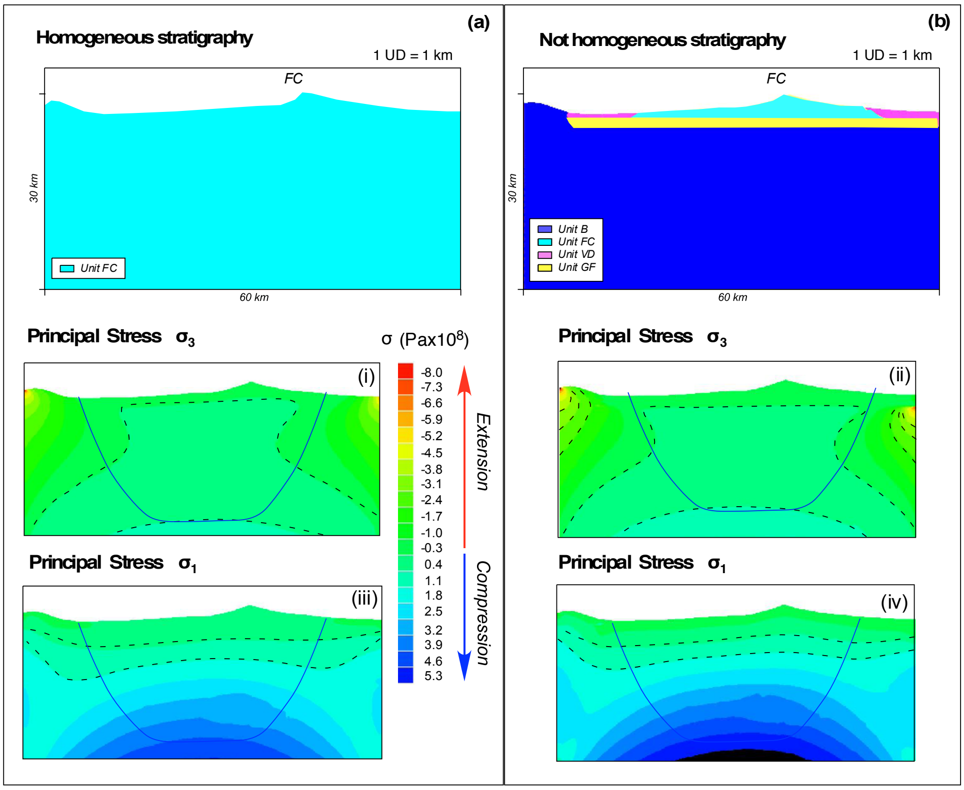

Unit FC
Unit VD
Unit GF
Unit B
%
0
5
10
15
20
25
30
35
Substratum
Single chamb.
Dual chamb.
Conduits
σ1 x-
σ1 x+
σ3 x-
σ3 x+

Figure 3



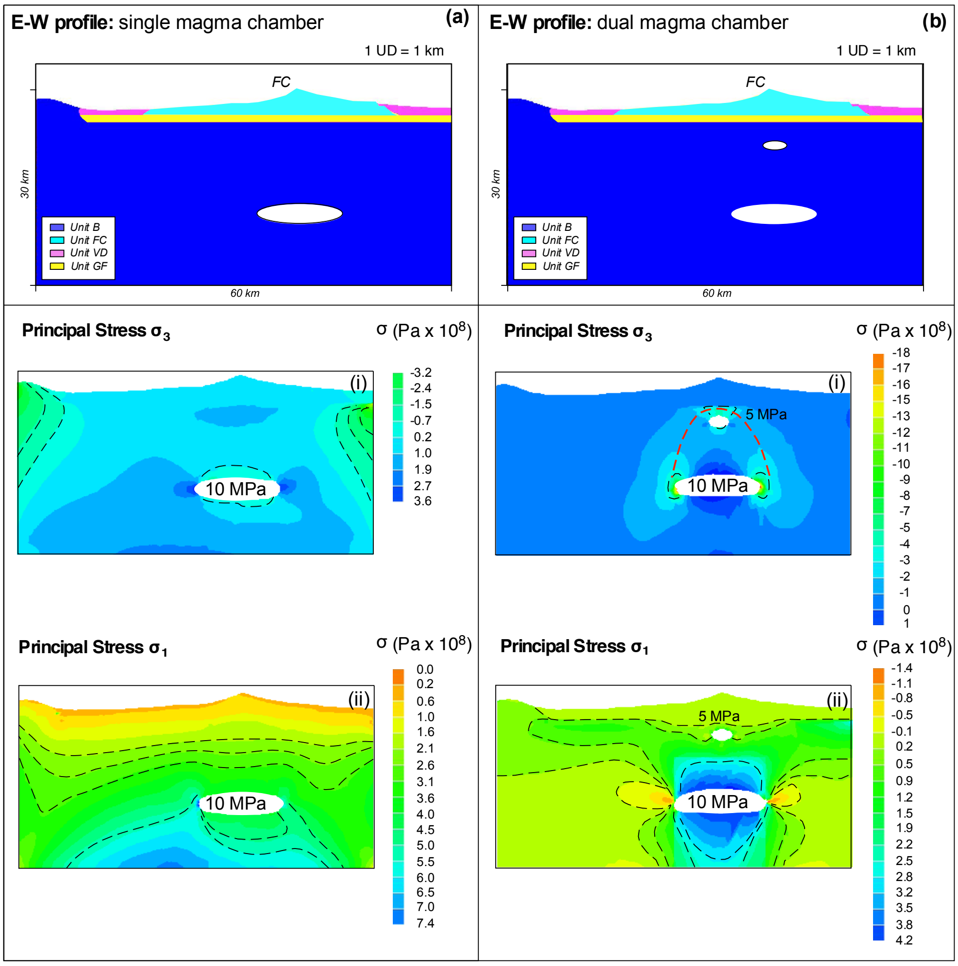
(a)
Unit B σ3 x-
(b)
Unit B σ3 x-
(c)
Unit B σ1 x-
(d)
Unit VD σ3 x+
depth (km)
km
variation (%)

Figure 4



(a)
Homogeneous stratigraphy
1 UD = 1 km
FC
30 km
60 km
Unit FC
(b)
Not homogeneous stratigraphy
1 UD = 1 km
FC
30 km
60 km
Unit B
Unit FC
Unit VD
Unit GF
Principal Stress σ3
σ (Pax10^8)
(i)
(ii)
-8.0
-7.3
-6.6
-5.9
-5.2
-4.5
-3.8
-3.1
-2.4
-1.7
-1.0
-0.3
0.4
1.1
1.8
2.5
3.2
3.9
4.6
5.3
Extension
Compression
Principal Stress σ1
(iii)
(iv)

Figure 5



E-W profile: single magma chamber
(a)
1 UD = 1 km
FC
30 km
60 km
Unit B
Unit FC
Unit VD
Unit GF
E-W profile: dual magma chamber
(b)
1 UD = 1 km
FC
30 km
60 km
Unit B
Unit FC
Unit VD
Unit GF
Principal Stress σ3
σ (Pa x 10^8)
(i)
10 MPa
-3.2
-2.4
-1.5
-0.7
0.2
1.0
1.9
2.7
3.6
Principal Stress σ3
σ (Pa x 10^8)
(i)
5 MPa
10 MPa
-18
-17
-16
-15
-13
-12
-11
-10
-9
-8
-7
-5
-4
-3
-2
-1
0
1
Principal Stress σ1
σ (Pa x 10^8)
(ii)
10 MPa
0.0
0.2
0.6
1.0
1.6
2.1
2.6
3.1
3.6
4.0
4.5
5.0
5.5
6.0
6.5
7.0
7.4
Principal Stress σ1
σ (Pa x 10^8)
(ii)
5 MPa
10 MPa
-1.4
-1.1
-0.8
-0.5
-0.1
0.2
0.5
0.9
1.2
1.5
1.9
2.2
2.5
2.8
3.2
3.5
3.8
4.2

Figure 6

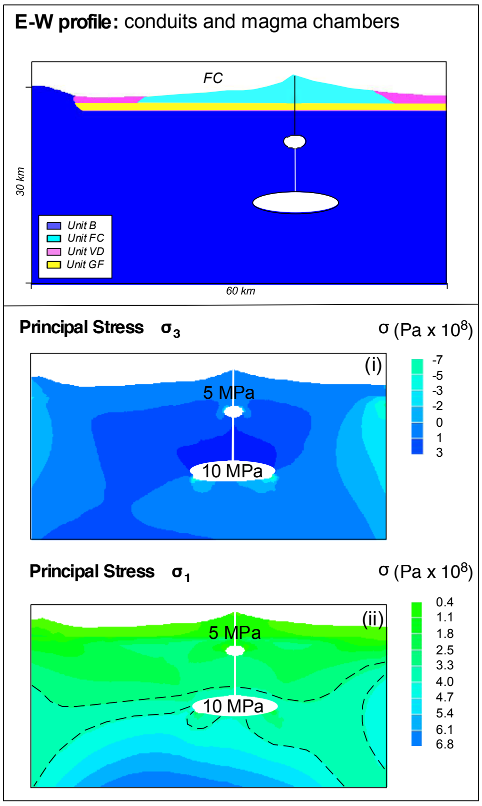
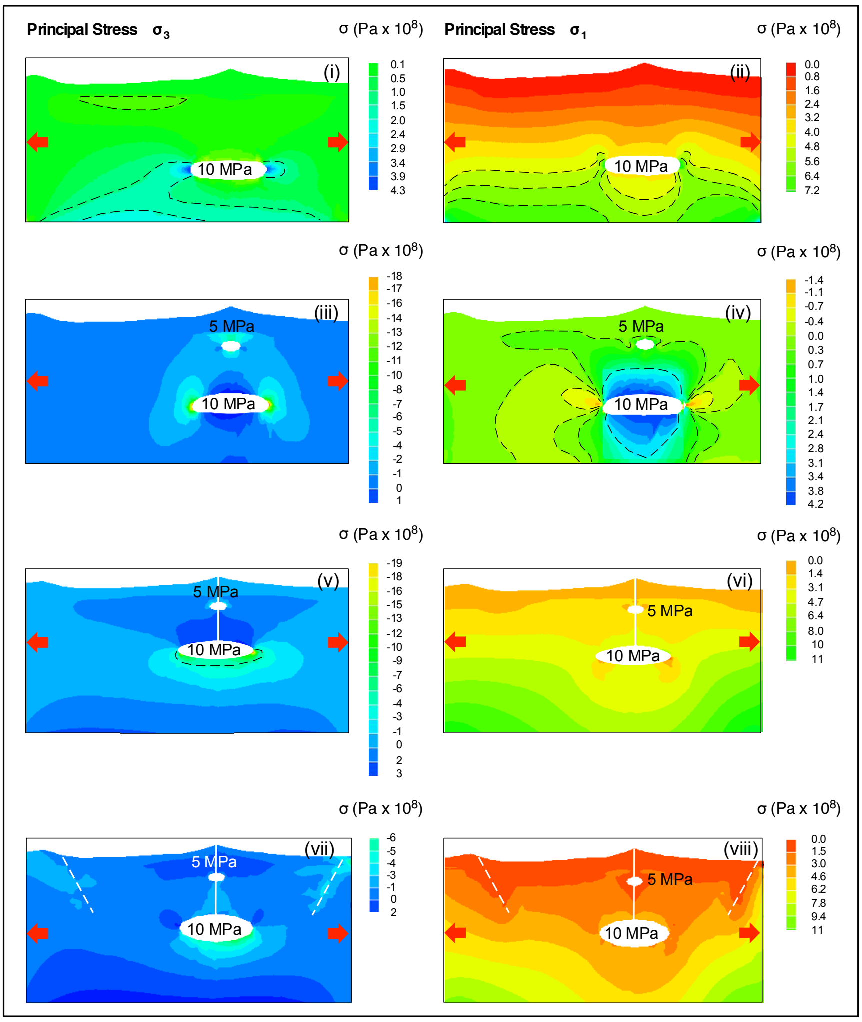

E-W profile: conduits and magma chambers
FC
30 km
60 km
Unit B
Unit FC
Unit VD
Unit GF
Principal Stress σ3
σ (Pa x 10^8)
(i)
5 MPa
10 MPa
-7
-5
-3
-2
0
1
3
Principal Stress σ1
σ (Pa x 10^8)
(ii)
5 MPa
10 MPa
0.4
1.1
1.8
2.5
3.3
4.0
4.7
5.4
6.1
6.8

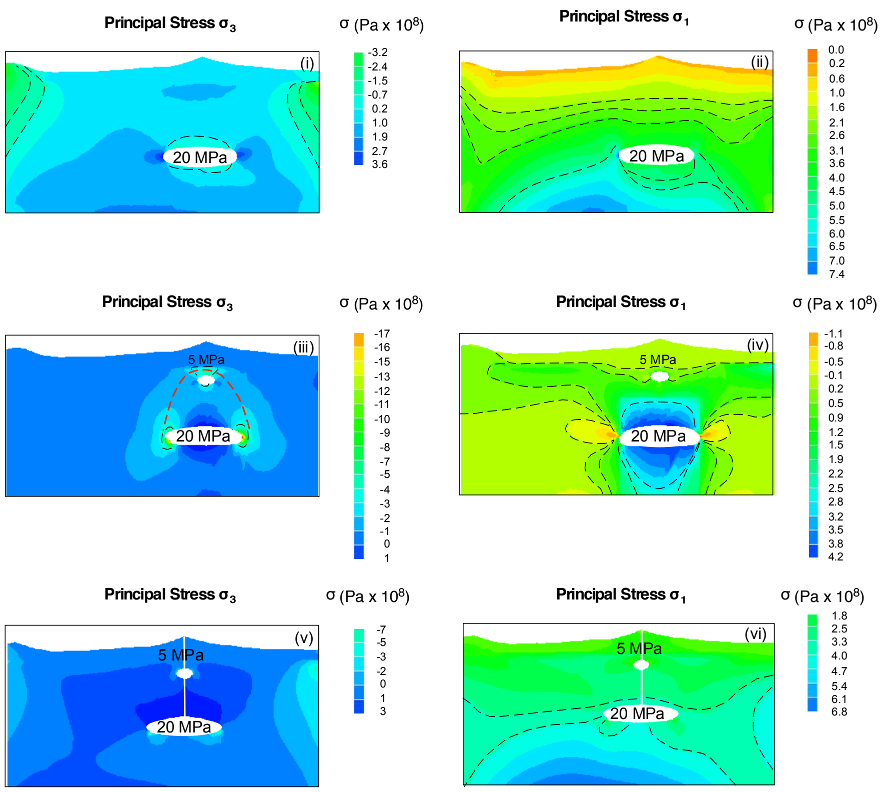
Figure 7



Principal Stress σ3
σ (Pa x 10^8)
Principal Stress σ1
σ (Pa x 10^8)
(i)
10 MPa
(ii)
10 MPa
(iii)
5 MPa
10 MPa
(iv)
5 MPa
10 MPa
(v)
5 MPa
10 MPa
(vi)
5 MPa
10 MPa
(vii)
5 MPa
10 MPa
(viii)
5 MPa
10 MPa

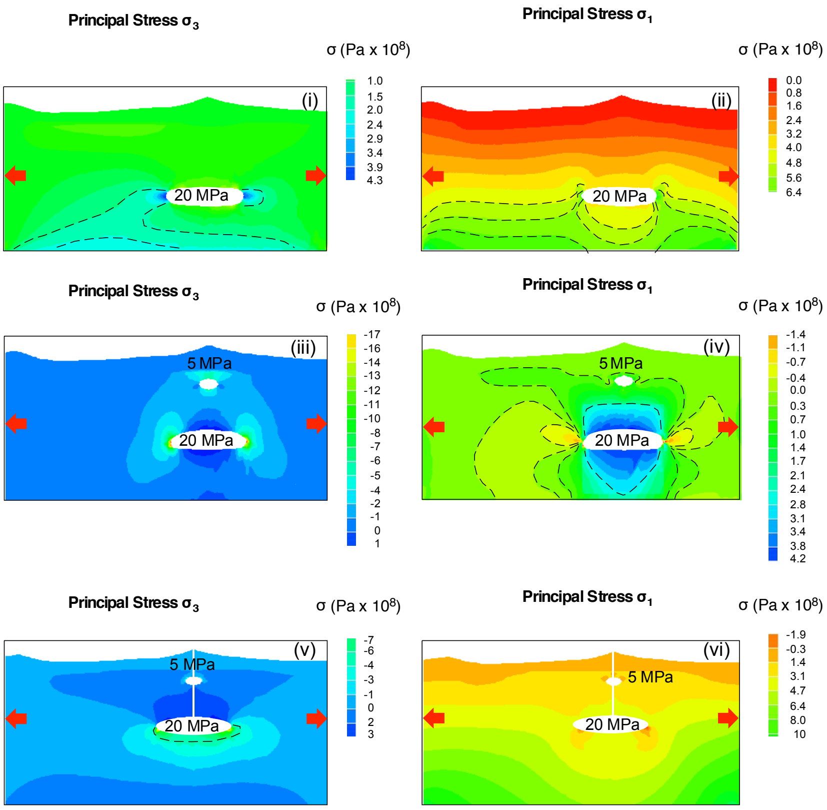
Appendix 1

Appendix 1



Appendix 2

Appendix 2



Principal Stress σ3
σ (Pa x 10^8)
1.0
1.5
2.0
2.4
2.9
3.4
3.9
4.3
(i)
20 MPa
Principal Stress σ1
σ (Pa x 10^8)
0.0
0.8
1.6
2.4
3.2
4.0
4.8
5.6
6.4
(ii)
20 MPa
Principal Stress σ3
σ (Pa x 10^8)
-17
-16
-14
-13
-12
-11
-10
-8
-7
-6
-5
-4
-2
-1
0
1
(iii)
5 MPa
20 MPa
Principal Stress σ1
σ (Pa x 10^8)
-1.4
-1.1
-0.7
-0.4
0.0
0.3
0.7
1.0
1.4
1.7
2.1
2.4
2.8
3.1
3.4
3.8
4.2
(iv)
5 MPa
20 MPa
Principal Stress σ3
σ (Pa x 10^8)
-7
-6
-4
-3
-1
0
2
3
(v)
5 MPa
20 MPa
Principal Stress σ1
σ (Pa x 10^8)
-1.9
-0.3
1.4
3.1
4.7
6.4
8.0
10
(vi)
5 MPa
20 MPa