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First-order estimate of the Canary Islands plate-scale stress field:**Implications for volcanic hazard assessment**

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Abstract:

In volcanic areas, the existing stress field is a key parameter controlling magma generation, location and geometry of the magmatic plumbing systems and the distribution of the resulting volcanism at surface. Therefore, knowing the stress configuration in the lithosphere at any scale (i.e. local, regional and plate-scale) is fundamental to understand the distribution of volcanism and, subsequently, to interpret volcanic unrest and potential tectonic controls of future eruptions. The objective of the present work is to provide a first-order estimate of the plate-scale tectonic stresses acting on the Canary Islands, one of the largest active intraplate volcanic regions of the World. In order to obtain the orientation of the minimum and maximum horizontal compressive stresses, we perform a series of 2D finite element models of plate scale kinematics assuming plane stress approximation. Results obtained are used to develop a regional model, which takes into account recognized archipelago-scale structural discontinuities. Maximum horizontal compressive stress directions obtained are compared with available stress, geological and geodynamic data. The methodology used may be easily applied to other active volcanic regions, where a first order approach of their plate/regional stresses can be essential information to be used as input data for volcanic hazard assessment models.

Keywords

Canary Islands, plate-scale tectonic stress field, volcanic activity, numerical modelling, volcanic hazard assessment

1. Introduction

The evaluation of the present-day stress field at different scales has been the focus of several recently published research works (e.g. Dyksterhuis et al., 2005a; Dyksterhuis and Müller, 2004; Gölke and Coblenz, 1996; Jarosiński et al., 2006; Jimenez-Munt and Negredo, 2003). The stress on a specific location can be subdivided into plate-, mountain- and fault-scale (Zang and Stephansson, 2010). In this sense, plate-scale tectonic stresses tend to be uniform over large areas of continents, whereas the other two can vary significantly over short distances. The complex tectonic plate movements and their interactions originate a particular regional and local stress field in each tectonic setting and volcanically active area, which may be eventually modified due to more specific and smaller-in-scale structural elements.

Magmatism and tectonism in volcanically active areas are strongly related to the regional and local stress fields, affecting the orientation of faults and fractures and the location of volcanic vents, two fundamental aspects when interpreting volcanic unrest and forecasting volcanic eruptions. The Canary Islands is one of the largest active intraplate volcanic regions of the World. Located at the Nubia plate, their plate-scale stress field, and partly also the regional one, is presumably controlled by the Eurasia-Nubia kinematics, the Middle Atlantic Ridge (MAR), and other more regional structures such as the Terceira Ridge (TR), the Gloria Fault (GF), the Transmoroccan (Transalboran) Fault System (TFS), the Gibraltar Arc (GA) and probably, to a lesser extent, the Gorringe Thrust (GT) (Jimenez-Munt et al., 2001; Jimenez-Munt and Negredo, 2003; Mantovani et al., 2000) (Fig. 1a). Additionally to these tectonic features, some authors have also indicated the presence of a mantle plume beneath this region that may importantly influence the stress field at a regional or even plate-scale level (Fullea et al., 2015; Hoernle and Schmincke, 1993).

In the last decades, several studies have investigated the neotectonics of the Africa-Eurasia plate boundary from the Middle Atlantic Ridge to the Iberian Peninsula and Tell Atlas mountains including the Terceira Ridge, the Gibraltar Arc and the Ibero-Maghrebian region (southern part of the Iberian Peninsula and northwestern Africa) (Jimenez-Munt et al., 2001; Jimenez-Munt and Negredo, 2003; Mantovani et al., 2000). Nevertheless, none of these models extends south of the 30°N parallel, leaving the Canary Islands always out of the computational domain.

The objective of this work is to provide a first-order estimate of the plate-scale tectonic stresses acting on the Canary Islands, modelling numerically the distribution of the minimum and maximum horizontal compressive stresses (S_{hmin} and S_{Hmax} , respectively) and the tectonic regime in the area. For this, we have performed a series of 2D finite element models of plate scale kinematics assuming plane stress approximation as previously adopted by other authors (e.g. Hu et al., 1996; Mantovani et al., 2000). Results obtained are used to design a regional scale stress field model for the Canary Islands aimed to evaluate the effect of archipelago-scale structures on the distribution of the maximum horizontal compressive stress and related stress regime. Calculated S_{Hmax} orientations are consistent with stress, geological and geodynamic data available for the area of study. We consider that results obtained here are useful: 1) as input data for more detailed regional models that may be capable of considering the influence of other processes affecting the state of stress in the area; 2) to define potential tectonic controls of future volcanism; and 3) to cover volcanic hazard assessment necessities, specially the development of volcanic susceptibility maps used to identify those areas with greatest likelihood of hosting new vents. The methodology used here may be easily applied to other active volcanic regions in order to obtain a first order approach of their plate/regional stresses.

2. Geological setting

The Canarian archipelago, a roughly linear 500 km long chain formed by seven islands, is the result of a long volcanic and tectonic activity that started ~60 Ma ago (Marinoni and Gudmundsson, 2000; Marinoni and Pasquarè, 1994; Robertson and Stillman, 1979). During the last years, it has been repeatedly proven that regional and local tectonics is of high relevance when trying to understand the origin and evolution of the Canary Islands (e.g. Anguita and Hernan, 1975; Anguita and Hernan, 2000; Hernández-Pacheco and Ibarrola, 1973).

In order to describe the regional tectonic setting of the archipelago, one must take into account the structures at the African continent and those in the open sea. On the one hand, the Atlas chain, constructed through the tectonic inversion of a Triassic and Jurassic intracratonic rift associated with the opening of the North Atlantic (Jacobshagen et al., 1988), is characterized by thrusts (Binot et al., 1986; Mattauer et al., 1977; Proust et al., 1977) and strike-slip faults (mostly sinistral) (Herbig, 1988; Jacobshagen, 1992). Most faults strike NNE (in the High Atlas), NE (in the Middle Atlas), or NW (dispersed though less marked), although abundant N-S structures were also detected in a morphometric survey (Deffontaines et al., 1992).

In the open sea, geophysical data has highlighted an array of tectonic structures including antiforms, synforms and unconformities (Carbó et al., 2003; Dañobeitia and Collette, 1989; Dillon, 1974; Uchupi et al., 1976). Most of the identified submarine fractures are transcurrent (Le Bas et al., 1986) or normal (Banda et al., 1992; Bosshard and MacFarlane, 1970; MacFarlane and Ridley, 1968) faults. Another relevant tectonic feature is a 50 km long submarine fault, similar to the sinistral transcurrent faults associated with folds located at the border of the Atlas (Piqué et al., 1998), with transcurrent (left-lateral) and reverse components located between Tenerife and Gran Canaria (Mezcua et al., 1992).

Different tectonic studies carried out at the Canary Islands have shown specific trends in fault and volcanic alignments coherent with main oceanic and continental structures (e.g. Lanzarote, Marinoni and Pasquarè, 1994; Fuerteventura, Rodríguez-Pascua et al., 2015 Gran Canaria, Anguita et al., 1991). Main fractures in the islands and ocean floor may be classified in two types or families

(Hernandez-Pacheco and Ibarrola, 1973): Atlantic “oceanic” (strikes: N160-N180E, N120-N135E) and African “continental” (strikes: N20E, N45E, N75E), depending on their relation with the opening of the Atlantic or the tectonics of the Atlas range in the African continent (Anguita and Hernan, 1975; Carracedo, 1984; Danobeitia, 1988; Emery and Uchupi, 1984; Fuster, 1975).

3. Methodology

3.1. Model set-up

As previously adopted by other authors (e.g. Mantovani et al., 2000), the numerical procedure applied here is based on the finite element technique, with 2-D linear elastic isotropic (i.e. mechanical properties are the same regardless of the direction of measurement) and orthotropic elements (i.e. mechanical properties vary along the axisymmetric axes of the material) in a plane stress approximation (see Jaeger et al., 2007; Turcotte and Schubert, 2002 for further details on linear elastic plane stress formulation). Even if this kind of studies does not allow considering stress effects due to topography, buoyancy, etc. and thermomechanical deformation within the lithosphere, 2D plane stress models have been successfully applied to obtain first-order estimates of the maximum horizontal compressive stress S_{Hmax} regimes in various areas (e.g. Dyksterhuis et al., 2005a; Dyksterhuis and Muller, 2004; Dyksterhuis et al., 2005b; Hu et al., 1996).

Regarding sign convention, calculated compressive and tensional stresses are taken as positive and negative, respectively. The assumption of elastic rheology, which precludes any true time dependency, is justifiable for the modelling of such large scale, low order tectonic stresses (Dyksterhuis et al., 2005a). Finite-element modelling has been carried out using the commercial software package COMSOL Multiphysics (<http://www.comsol.com/>) version 4.4. An example of the performed models (COMSOL Multiphysics commercial software version 4.4 or higher is required), as well as further details and clarifications concerning the model set up are available from

the corresponding author upon request.

The considered computational domain is comprised between the 18°N and 44°N parallels and the 50°W and 2°E meridians (Fig. 1a). This ensures the model boundaries to be located far enough from the area under study (Canary Islands) in order to avoid boundary conditions affecting the results obtained.

Following the procedure described by Mantovani et al. (2000), we have modelled the computational domain as a mosaic of poorly deformable zones (hereafter referred to as “blocks”) (Fig. 2a, labels I-VII), separated by highly deformable narrow “decoupling zones”, where most deformation is accommodated (Fig. 2a colour areas). The nature (compressional, extensional or transcurrent) and geometry of the “decoupling zones” have been extracted from previous studies describing the kinematics and neotectonics of the area (Bufo and Udías, 2010; Bufo et al., 1988; Jimenez-Munt and Negredo, 2003; Mantovani et al., 2007). Regarding terminology, note that the use of the word “weak” refers to deformability within the elastic regime (as governed by Young’s modulus and Poisson’s ratio) (Mantovani et al., 2000).

Available in different geographic coordinate systems, input data for the models has been transformed into a Cartesian x-y coordinate system, with meters as measurement units, to allow its implementation into COMSOL Multiphysics. For this, we have converted required data to a Lambert Conformal Conic projection (LCC) with horizontal datum WGS84, standard parallels 18°N and 44°N and middle meridian at 24°W. The LCC is a conic map projection often used for aeronautical charts and is considered the best projection for regions predominantly east–west in extent and located in middle North or South latitudes.

The selected area (Fig. 1a), once projected to LCC, is imported into COMSOL Multiphysics and meshed with ~112,000 linear triangular elements (Fig. 2b). The size of the elements has been chosen on the basis of the geometrical complexity of the different blocks and decoupling zones. Between the 25°N and 32°N parallel and the 24°W and 7°W meridian, the mesh has been thoroughly

refined to improve resolution within the area of interest (i.e. the Canary Islands and surroundings) (Fig. 2b).

3.2 Material properties

3.2.1 Mechanical properties of the “blocks”

Within each block (Fig. 2a, labels I-VII) material properties are assumed to be homogeneous and defined by the Poisson's ratio ($\nu = 0.25$ for all blocks), Young's modulus (E) (constant within each block) and elastic thickness of the mechanical lithosphere (h) (Table 1). In our approximation, the latter is the part of the plate that sustains the stresses induced by tectonic forces. Following the approach by Mantovani et al. (2000), the stiffness of each unit is expressed by the parameter $M = E \cdot h$ (Calladine, 1983). Within the blocks, M is assumed to be between 10^{15} and 10^{16} N/m (Supplementary Material, Fig. S1), mainly controlled by the variations of the Young's modulus E (25-100 GPa) (Table 1) and the lateral changes of the mechanical lithosphere thickness h (18-260 km) (Supplementary Material, Fig. S2). Input data for the lithospheric thickness correspond to the Conrad and Lithgow-Bertelloni (2006) model (<http://www.soest.hawaii.edu/GG/FACULTY/conrad/liththick/liththick.html>). The values of the elastic parameters of the blocks have been chosen based on previous published works on plate scale stress modelling (Dyksterhuis et al., 2005a; Hu et al., 1996; Mantovani et al., 2000). We have run several simulations varying M (changing E but keeping h constant) in order to explore the sensitivity of our results to this parameter (Model set 7, Table 2).

3.2.2 Mechanical properties of the “decoupling zones”

Decoupling zones are subdivided in two main groups (Albareello et al., 1997; Mantovani et al., 2007). The first one, characterized by “weak” isotropic elements, tries to reproduce shortening

(Fig. 2a, labels W_S1-S3) or extensional processes (Fig. 2a, labels W_R1-R2). In the case of convergent boundaries, the vaster shortening allowed by the “weakened” border should reproduce the consumption of lithosphere, crustal thickening or/and other possible kinds of thrusting processes (Mantovani et al., 2000). In these zones, the value of the Poisson's ratio is 0.25 and M is between 10^{12} and 10^{13} N/m (Supplementary Material, Fig. S1), representing the diverse levels of resistance that the processes taking place are presumed to encounter at the simulated trenches (Mantovani et al., 2000). Along divergent boundaries, extremely weak decoupling zones ($M = 10^{10} - 10^{12}$ N/m) replicate the crustal stretching and thinning occurring in extensional belts. The influence of the mechanical properties of the different weak zones (extensional or compressional) on the results obtained has been also tested (Model sets 6 and 8, Table 2).

The transcurrent decoupling zones (Fig.2a, labels W_T1-T4) are simulated by orthotropic elements (Mantovani et al., 2000). In these elements, weakness relates to the direction of the presumed fault strike, while in the other directions, the values of the elastic parameters are one order of magnitude higher. In the model, the unidirectional weakness in shear zones has been assumed to be between 10^{10} and 10^{13} N/m. In order to avoid unrealistic deformations due to the behaviour of orthotropic elements, the Poisson's ratio along the strike of the shear zone is considered close to zero, i.e. 0.01 (cf. Mantovani et al., 2000). In the other directions, the Poisson's ratio is 0.25 (Table 1).

Additionally to the decoupling zones identified before (Fig. 2a, labels W_R1-R2, W_S1-S3 and W_T1-T4), the work by Mantovani et al. (2007) also indicates possible existence of two additional weak areas, namely the Atlantic Fracture Zone (AFZ) and a transcurrent fault (TF) running from the eastern end of the Gloria Fault (GF) to the southeast (Fig. 2a). We evaluate their effect on the stress field by alternatively “activating” the TF considering orthotropic elements with a Young's modulus of 0.1 GPa along the strike of the shear zone (Model set 10), and the AFZ assuming an isotropic linear elastic material of $E=0.1$ GPa or 0.01GPa (Model set 11, Table 2).

3.3. Boundary conditions

Boundary conditions (BCs) are given in terms of velocities reproducing the motion of the Nubia and America plates with respect to a fixed Eurasia plate (Fig. 2c). Thus, kinematic boundary conditions have been imposed in the form of finite displacements proportionally to the velocities of Nubia and America as given by the UNAVCO plate motion calculator (<http://www.unavco.org>) based on the MORVEL 2010 model assuming a fix Eurasia plate (DeMets et al., 2010; DeMets et al., 2011). For this, we have estimated the velocity vector (norm and direction) along the boundaries of the model corresponding to the America and Nubia plates and calculated the displacement in one-year time step. We have tested that fixing the displacement according to various time intervals does not substantially affect the results obtained.

Concerning the boundaries along the Eurasia plate (blue boundaries in Fig. 2c), we have considered different scenarios (Model set 1-5, Supplementary Material, Fig. S3): a) fixing to zero displacement the whole plate boundary (Model set 1); b) fixing the whole plate (Model set 2); c) assigning a roller condition to the whole boundary (displacement is allowed only in the direction parallel to the boundary) (Model set 3); d) assigning a roller condition only to the northern boundary leaving the eastern one free (i.e. traction free) (Model set 4), and e) fixing the displacement to zero (in x and y direction) along the northern boundary leaving the eastern one free (i.e. traction free) (Model set 5).

3.4. *Defining stress regimes*

By definition, the resultant state of stress obtained with a plane stress approximation has two principal horizontal stresses being the third zero (or orders of magnitude smaller relative to the in-plane stresses so that it can be ignored and approached to zero) and out-of-plane (Jarosiński et al., 2006). An intuitive method of identifying the direction of the maximum horizontal compressive stress S_{Hmax} is to simply assume that it is parallel to the maximum horizontal principal stress, unless

this is vertical, in which case S_{Hmax} is parallel to the axis of the intermediate principal stress.

The corresponding stress regime, i.e. compressional, extensional or strike-slip, is determined considering that if S_{Hmax} and S_{hmin} are both extensional (i.e. $S_{Hmax} < 0$ and $S_{hmin} < 0$), or the absolute value of extension higher than compression (i.e. $|S_{hmin}| > |S_{Hmax}|$), normal faulting is enhanced (Jarosiński et al., 2006). Extensional stress regime is also likely to occur when the tectonic stress contribution is small, even if compressive. Thrust faulting is only favoured when both tectonic stress components are highly compressive (i.e. $S_{Hmax} \gg 0$ and $S_{hmin} \gg 0$). Finally, when S_{Hmax} is highly compressive and $|S_{hmin}| < |S_{Hmax}|$, strike-slip faulting is the most plausible regime. Thus, even if plane stress models cannot distinguish between stress regimes, these rules allow making a good estimate of the most likely one (Jarosiński et al., 2006).

4. Results

4.1 Evaluating the quality of the results

To evaluate the numerical results obtained, we have compared the computed S_{Hmax} directions with data contained in the most recent World Stress Map (WSM) open-access database compilation (Heidbach et al., 2008; Reinecker et al., 2005) (Fig. 3a). Data collected as part of the World Stress Map project (Zoback, 1992) provide important constraints on present orientation and magnitude of S_{Hmax} regimes of continents. The content of this database (or older versions of it) has been repeatedly used in the literature to constrain and evaluate the accuracy of numerically modelled S_{Hmax} orientations (e.g. Dyksterhuis et al., 2005a; Jimenez-Munt and Negredo, 2003).

The WSM has standardized the quality-ranking scheme for the individual stress indicators making them comparable on a global scale. This internationally accepted ranking scheme is mainly based on the number, accuracy, and depth of the measurements and guarantees reliability and global comparability of the stress data (Sperner et al., 2003). Each stress data record is assigned a quality between *A* and *E*, being the *A* highest and *E* the lowest quality, respectively. In more detail, *A*-, *B*-,

C- and *D*-quality means that the orientation of the maximum horizontal compressional stress S_{Hmax} is accurate to within $\pm 15^\circ$, $\pm 20^\circ$, $\pm 25^\circ$ and $\pm 40^\circ$, respectively. *E*-quality data records do not provide sufficient information or have standard deviations greater than 40° . For this work, we have selected from the WSM database only *A*-, *B*- and *C*-quality stress indicators since these are the most reliable for their use in stress pattern analysis and the interpretation of geodynamic processes (Fig. 3a).

At those locations where WSM data is available (hereafter referred to as “WSM control points”) (Fig. 3b), we have evaluated the deviation between the S_{Hmax} azimuth provided by the WSM and the one predicted by the numerical models (Fig. 3c). Then, we have estimated the mean misfit (i.e. mean azimuth deviation) (Supplementary Material, Table S1) and the percentage of WSM control points with an azimuth deviation falling within specific quality ranges (Supplementary Material, Table S2).

We have considered two WSM control points datasets. One takes into account all WSM control points within the area of study with stress data of *A*- to *C*- quality (hereafter referred to as “Complete set” containing 228 control points) (Fig. 3b). The second, the “Selected set”, has 120 control points and discards all data in the Pyrenees and inland the Iberian Peninsula (Fig. 3d). The rationale behind this latter selection is that: a) some control points may be too close to the north-eastern corner of the computational domain being the numerical solution highly affected by the boundary conditions and ii) abundant regional/local structures, not considered in the present models, may play an important role and distort the results. Since the definition of the “Selected set” may result quite arbitrary, for one of the models, we have also checked the accuracy of the numerical results using a third set, “Selected set 2”, with 140 control points (Fig. 3e). The latter is aimed to highlight any possible differences in the misfit estimate due to the selection of the control points.

In addition to the WSM control points, we have evaluated the S_{Hmax} azimuth in specific locations at each of the islands comprising the Canarian archipelago (Fig. 1b) (Supplementary

Material, Table S3). This helps assessing how the selected boundary conditions and material properties may affect the numerical results in this area. Since no WSM data is available in the Canary Islands (Fig. 3a), we have also compared our numerical results with the information concerning the orientation of the P-axis (pressure axis) for four moderate earthquakes occurred in the Canary Islands between 1989 and 2013 (Fig. 1b). Information concerning the location and focal mechanism of the different earthquakes has been obtained from the Spanish National Geographic Institute (<http://www.ign.es>) and the Global Centroid Moment Tensor Project (<http://www.globalcmt.org>) (Dziewonski et al., 1981; Ekström et al., 2012).

4.2 Influence of the selected boundary conditions and material properties on the calculated stress field

Forward modelling with a trial-and-error procedure was used in order to best fit the computed S_{Hmax} directions to stress data provided by the WSM data (Fig. 3a). Thus, to examine the influence of factors such as boundary conditions or material properties, 11 models sets (30 model runs in total) with variable complexity were designed (Table 2). Once estimated which mechanical properties and boundary conditions best fit the numerical results obtained and the available WSM stress data, we have constructed the hereafter called Final Model.

From all BCs combinations considered (Model set 1-5, Table 1) (Supplementary Material, S3), the ones offering a better fit are those assuming the northern limit of the model (belonging to the Eurasia plate) to be fixed or with a roller, and the eastern margin free (Model set 4 and 5) (Supplementary Material, Tables S1 and S2 and Fig. S4). The latter boundary conditions are similar to the ones applied in previous research works (Jimenez-Munt et al., 2001; Jimenez-Munt and Negredo, 2003).

The calculated S_{Hmax} orientations are especially sensible to the mechanical properties selected for the North Atlantic Ridge (Fig. 2a, label W_R1)(Model set 6, Table 2), particularly in

the Canarian archipelago (Supplementary Material, Table S3 and Fig. S5a). Results obtained indicate that assigning a weaker material to this decoupling zone tends to adjust slightly better the numerical results to the WSM data (Supplementary Material, Table S1). Similarly, better fits are obtained when assuming $E = 0.1\text{GPa}$ for the decoupling zone simulating the Gibraltar Arc (Fig. 2a, label W_S2) and weaker E values for the shortening areas located to the west (Model 8C and 8D, Table 2). The latter correspond partially to the Gorringe Thrust (Fig. 2a, label W_S1). The mechanical properties of the weak areas located along the Atlas (Fig. 2a, label W_S3) do not seem to have further influence on the stress distribution in the Canarian archipelago (compare results of Model 8C and 8D, Supplementary Material, Table S3).

We have observed that changes in the mechanical properties of the blocks (Model set 7, Table 2) imply significant variations of S_{Hmax} orientations in the Canarian archipelago (Supplementary Material, Fig. S5b). Better fits are obtained when considering a Young's Modulus of 70GPa for the oceanic lithosphere and 50GPa or 25GPa for the continental one (Model 7C and 7D, Table 2)(Supplementary Material, Table S2).

The different mechanical properties selected for the transcurrent decoupling zones (Model 9, Table 2) influence considerably the stress field distribution in the Canarian archipelago (Supplementary Material, Table S3 and Fig. S6). Best solutions are obtained when considering the same mechanical properties for the Gloria Fault (GF) and the transcurrent area along the Gorringe Thrust zone (Fig. 2, label W_T3). The properties given to the Transmorrocan Fault System (Fig. 2, label W_T4) appear to be less relevant at a plate-scale but quite influencing in the Canarian Archipelago area (Supplementary Material, Table S3).

Finally, regarding the potential influence of the TF and AFZ weak zones (Fig. 2a)(Model sets 10 and 11, respectively), the activation of TF does not significantly vary the S_{Hmax} distribution in the Canary Islands. However, the latter is clearly affected when considering AFZ as a weak transcurrent zone (Supplementary Material, Table S3 and Fig. S7).

4.3 Final Model

Based on the results of previous section, for the Final Model we have selected the following BCs and material properties (Fig. 4):

- * Fixed zero displacement along the northern limit of the Eurasia plate leaving the eastern margin free (Model set 5). This is consistent with previous works (Jimenez-Munt et al., 2001; Jimenez-Munt and Negredo, 2003).

- * A Young's Modulus of 70GPa for the oceanic lithosphere and 25GPa for the continental one (Model 7D).

- * At the extensional weak zones: $E=0.001\text{GPa}$ at the North Atlantic Ridge (Fig. 2a, label W_R1) and $E=0.01\text{ GPa}$ at the Terceira rift (Fig. 2a, label W_R2) considered as hyper-slow spreading axis (Vogt and Jung, 2004).

- * At the compressional weak zones: $E=0.01\text{GPa}$ for the shortening areas at the oceanic crust along the Eurasia continental one (Fig.2a, label W_S1), and $E=0.1\text{ GPa}$ along the Gibraltar Arc region (Fig. 2a, label W_S2) and the shortening areas at the African continent (Fig.2a, label W_S3).

- *All transcurrent decoupling zones have equal mechanical properties ($E = 0.1\text{GPa}$) along the strike of the shear zone (Model 9A)(Supplementary Material, Tables S4 and S5).

Based on the evaluation at a plate-scale, the Final Model does not consider AFZ as active. If activated, the best fit is obtained for the AFZ having $E = 1\text{GPa}$ (as in Model 11A) (Supplementary Material, Tables S4 and S5) and imposing a Young's Modulus of 0.01GPa along the strike of the

shear zone to all transcurrent decoupling zones except to those located in the African continent (Model 9C)(Supplementary Material, Tables S5 and S6). The observed influence of the AFZ in the results obtained highlights the necessity of regional stress field models in the Canary Islands to consider the possibility of integrating further regional/local structures or weak zones. In order to evaluate this last point, we have run a set of additional simulations assuming the Final Model configuration and incorporating four local structural discontinuities previously identified in the Canarian archipelago (Fig. 5) (Becerril et al., 2015).

5. Discussion

Regarding the stress field at a plate scale, results observed are partly consistent with those obtained by Jimenez and Negredo (2003). The Final Model is able to replicate the rotation of the Nubian plate towards the Eurasian plates (Supplementary Material, Fig. S8), and provides consistent S_{Hmax} orientations along the North Atlantic Ridge and the Terceira Ridge (i.e. S_{Hmax} runs roughly parallel to the expansion axis) (Figs. 6a and b, respectively), and the Nubian-Eurasia plate boundary and the Gibraltar Arc (i.e. S_{Hmax} runs roughly parallel to the compression axis) (Fig. 6c). Also consistent are, for example, the inferred stress regimes along the Terceira Ridge (extensive regime, i.e. $S_{Hmax} < 0$ and $S_{hmin} < 0$) (Fig. 6d), or the Ibero-Maghrebian and the Atlas regions, where thrusting (i.e. $S_{Hmax} > 0$ and $S_{hmin} > 0$) and strike-slip (i.e. $S_{Hmax} \gg 0$ and $|S_{hmin}| < |S_{Hmax}|$) regimes alternate (Fig. 6e). Additionally, the model reproduces the NW-SE trend of S_{Hmax} in the Iberian Peninsula deduced from geologic and seismotectonic studies and already predicted by previous works of plate stress modelling (Jimenez-Munt and Negredo, 2003 and references therein) (Fig. 6c).

On the contrary, the model fails to reproduce the NE-SW direction of the compressive axis in the eastern Pyrenees as indicated by Jimenez and Negredo (2003), being this disagreement easily explained by the fact that this area is too close to the limits of our model and may be strongly

affected by boundary effects. Besides, even if the estimated directions of S_{Hmax} in the Middle Atlantic Ridge are roughly parallel to the spreading axis, and a regime of normal faulting is predicted, our model is not able to fit all WSM data, leading to azimuth deviations over 60° (Supplementary Material, Fig. S9). These punctual discrepancies between model and data may be related to the process of defining the geometry and determining the nature (extensive or transcurrent) of the decoupling zones representing the ridge. Thus, when translating the Middle Atlantic Ridge into a set of decoupling zones of simplified geometry, we may have skipped some strike-slip areas or modelled them as extensional weak zones (i.e. the model uses isotropic elements instead of orthotropic ones that induce strike slip behaviour). When analysing the WSM data in detail (Fig. 3a), we can see that there are also some inconsistencies in the real data, being quite contradictory that along the ridge, S_{Hmax} is orientated almost perpendicular to the spreading axes and not parallel as theoretically expected (and as obtained by the numerical models).

From the results obtained in the Canary Islands, we can observe how S_{Hmax} is oriented NNW-SSE at the easternmost islands (Fuerteventura and Lanzarote) and NW-SE at the westernmost ones (La Palma and El Hierro). This stress distribution varies considerably when modelling the AFZ as a weak and highly deformable material (Figs. 7b and c). Along the section of the computational domain assumed to be the AFZ (blue area in Figs. 7b and c), S_{Hmax} orientations change dramatically rotating in some cases up to 90° . This effect attenuates outside the AFZ area. The inferred stress regimes may also vary when assuming AFZ as active and strongly depend on the mechanical properties assigned to this decoupling zone. Thus, instead of a compressive regime trough the whole archipelago, areas of extension and strike-slip are also observed (Figs. 7b and c).

No definite answers are obtained when comparing the numerical results with the P-axis orientation calculated for the four earthquakes with defined focal mechanism occurred in the Canary Islands between 1989 and 2003 (Fig. 1b). The activation of the AFZ, regardless the selected mechanical properties, tends to give better fits for all earthquakes except the one occurred in El Hierro in 2011 (misfit close to 90°). On the contrary, the stress field obtained without considering

AFZ, leads to a better fit with the P-axis of the above mentioned earthquake (error is reduced to 4°), but to worse fits for the earthquake occurred between Tenerife and Gran Canaria in 1989 (error over 46°) and the one in El Hierro in 2013 (error over 114°). Analysing in parallel the modelled stress regimes and the mechanisms inferred for the earthquakes, we observe that whereas the latter are mainly strike-slip, thrust or a combination of these two, calculated stress regimes in these locations correspond to extension if AFZ is activated. Contrarily, thrust or strike-slip faulting is enhanced when AFZ is not active, being this result in agreement with the four earthquakes mechanisms. In short, the calculated S_{Hmax} orientations are quite consistent with the P-axes trend estimated for the four earthquakes. However, we have seen that the existence, or not, of a “weak” zone that may correspond to the eastern extension of the Atlantic Fracture Zone plays a fundamental role in determining the orientation of S_{Hmax} and the stress regimes in the area, specially close to the AFZ.

From the archipelago-scale models, we observe that local structural discontinuities affect S_{Hmax} orientations and the calculated stress regime but their effect is restricted to an area of few kilometres distance from the active structure (Figs. 5b-e). The existence of such kind of discontinuities may explain, for example, the important difference between the P-axes trend estimated for both earthquakes occurred at El Hierro Island. Comparing the results obtained with the Final Model (Fig. 5a) and the one considering the structure at El Hierro island as active (Fig. 5c), we observe how S_{Hmax} rotates at both tips of the discontinuity.

Results obtained here indicate that second-order stress field models in the Canary Islands, i.e. archipelago-scale models, have to take into account other regional structures that may influence the imprint of the plate-scale stress field. Additionally, since the plate-scale stress field is assumed to be the same during all recent eruptive events, it is evident that changes in the stress field may be linked to variations related to more regional structures and to local changes induced, for example, by the island’s growth or destruction episodes, e.g. landslides, flank collapses, etc., or even the presence of a regional/local accumulation of magma.

Going into further detail in the interpretation and application of the results obtained, the

S_{Hmax} orientation calculated with the Final Model (Fig. 7a) is in quite good agreement with the observations during the 2011-2012 El Hierro submarine eruption (e.g. del Fresno et al., 2015; González et al., 2013; López et al., 2012; Martí et al., 2013). The latter is the first eruption in the Canary Islands tracked in real time starting October 10, 2011 after an unrest episode initiated on July 17, 2011. Monitoring data (e.g. Seismicity, surface deformation, and petrological data) indicated that a batch of basanitic magma coming from a reservoir located at a depth of about 25km below the El Hierro Island was emplaced at shallower depth creating a new reservoir about 10–12km above, where magma evolved until the initiation of the eruption. After this first intrusion episode, part of the magma started to migrate laterally toward the SE for nearly 20 km, always keeping the same depth and following a path apparently controlled by stress barriers created by tectonic and rheological contrasts in the upper lithosphere (Fig. 8). During the first 3 days of eruption, the eruptive focus migrated along the eruptive fissure to the north for about 3 km until reaching a depth of 300m below sea level, at about 1800m from the coast. At this point, its advance was halted by an intersecting NE-SW regional normal fault (Martí et al., 2013). This favoured the formation of a central eruptive conduit at the intersection between the two fracture planes and the construction of a volcanic edifice by the accumulation of pyroclastic material at the vent. One of these new seismic events with a magnitude of 4.6 corresponds to earthquake I of Figure 1b. This lateral migration of magma ended with a submarine eruption at about 5 km offshore from the southern corner of El Hierro. In their work, Martí et al. (2013) indicated that the fact that magma migration occurred through a NE fracture zone suggests that the regional/local tectonics also played an important role, and mentioned that the path followed by the El Hierro magma, as well as the orientation of the eruption fissure, defines a stress configuration in which the maximum compressional stress is oriented approximately N-S, and the minimum compressional stress is E-W. A NS tectonic stress would have prevented the opening of magma fractures oriented E-W (i.e., the western rift zone, see Figure 8) but would have facilitated the opening of structures oriented N-S as it was the eruption fissure. Also, the tectonic effect should be added to the flexural one. For the

effect of the tectonic stress field, dyke opening should occur in the direction of smallest compressive stress, such that an ascent along the southern rift is clearly consistent with a NNW-SSE compression.

The El Hierro eruption is just one example of the applicability of the kind of models presented here and illustrates, at the same time, the necessity of volcanic hazards assessment models to incorporate the plate/regional stress field into the analysis. Thus, in those active areas with a necessity of evaluating the spatial probability of a forthcoming eruption, i.e. to develop volcanic susceptibility maps to identify areas with greatest likelihood of hosting new vents, we strongly recommend to include the plate/regional stress field as input data.

The methodology used here is easily applicable to other active volcanic regions in order to obtain a first order approach of their plate/regional stresses. However, it has to be pointed out that, as any other numerical approximation to nature, the methodology presented here has some restrictions that should be taken into consideration when interpreting the results obtained. On the one hand, we have already mentioned that the 2D plane stress approximation does not consider stress effects due to topography, buoyancy, etc. and thermomechanical deformation within the lithosphere. The advantages of 2D plane stress models towards full 3D models that could take into account the above mentioned aspects (e.g. Petricca et al., 2013) are mainly numerical. In general, 2D models required much less computational capacity and time than 3D ones. This is an important aspect when the information regarding the plate-stress field is missing, but necessary, to carry out a volcanic hazard assessment that has to be performed in a short time. Besides, full 3D models may also require further details on input data and boundary conditions that may not be available or well known for the area of interest. A good, and commonly used, alternative to the 2D plane stress approximation is the thin shell modelling method (e.g. Jimenez-Munt and Negredo, 2003). As mentioned in the previous sections, at least for first-order estimates of the plate-scale stress, both methodologies give similar results.

Another aspect worth mentioning are the consequences of assigning isotropic (i.e.

mechanical properties are the same regardless of the direction of measurement) or orthotropic elements (i.e. mechanical properties vary along the axisymmetric axes of the material) to the different decoupling zones depending on the nature of the processes they are supposed to reproduce (i.e. extension, strike-slip, etc.). Since choosing one or the other element type determines the way a specific section of the model deforms, the decision strongly influences the results obtained in terms of stress field distribution. Therefore, it is highly recommended to perform some tests to evaluate the sensibility of the estimated stress field to the selected material properties and type of element. In the case of the Canary Islands, although the scarcity of real data available, the performed models provide S_{Hmax} orientations are consistent with existent stress, geological and geodynamic information. Nonetheless, new coming data will help refining the model in the future.

6. Summary and conclusions

In the present work, we provide a first order estimate of the current plate-scale stress field in the Canary Islands, paying special attention in the distribution of the maximum horizontal compressive stress and stress regime. The uncertainty of the numerical results is estimated comparing the S_{Hmax} directions obtained with real stress data provided by the last version of World Stress Map project. The results demonstrate that the model is able to reproduce the expected S_{Hmax} directions with a mean azimuth deviation of $\sim 30^\circ$. Future coming data should help refining and improving the present results.

The best-fitted model succeeds in reproducing the S_{Hmax} directions and stress regimes in significant control areas such as the North Atlantic Ridge and the Terceira Ridge. The fact that all discontinuities in the model have ended up being in quite agreement with observed features, encourages to think that the boundary conditions and structural-tectonic setting adopted in the model are compatible with the real dynamic and structural context at a first order level. In the Canary Islands, comparison between the numerical models and the P-axes orientation and

mechanism estimated for different earthquakes in the area allow us to assess the uncertainty of our numerical results in a more regional/ local scale. Results obtained indicate that the best-fitted model succeeds in reproducing most of the S_{Hmax} directions and stress regimes. The effect in the results of the AFZ reinforces the idea that to go into regional detail, regional tectonic structures have to be included since they may importantly affect the stress field in the area depending if they are active or not in certain moments of time.

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8. References

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Table caption

Table 1: Mechanical properties and element type for the different blocks and decoupling zones

Table 2: List of Young's modulus values (in GPa) assigned to the “blocks” and “decoupling” zones depending on the model set. White and grey colours indicate when the block or decoupling zone is modelled with isotropic or orthotropic properties elements, respectively. In the latter case, the Young's modulus is given in a vector format (E_{strike} , $E_{\text{strike}} \cdot 10$, $E_{\text{strike}} \cdot 10$), where E_{strike} is the Young's modulus along the strike.

Figure caption:

Figure 1: a) Digital Elevation Model (DEM) of the modelled area obtained from ETOPO 1 Global Relief Model (<http://www.ngdc.noaa.gov/mgg/global/global.html>), with WGS84 as geographic horizontal datum (Amante and Eakins, 2009). Main tectonic features are also indicated based on the work by Mantovani et al. (2007). Dashed white and pink lines indicate presumed tectonic features and broad plate limit, respectively. b) Focal mechanism of the four moderate earthquakes occurred in the Canary Islands between 1989 and 2013 obtained from the Spanish National Geographic Institute (<http://www.ign.es>) (Earthquake I) and the Global Centroid Moment Tensor Project (<http://www.globalcmt.org>) (Dziewonski et al., 1981; Ekström et al., 2012) (Earthquakes II-IV). Yellow stars indicate the location of the points used for evaluating the results obtained in the area of study. For each earthquake, information concerning nodal plane, magnitude, percentage of faulting mechanism and P-axis orientation is also indicated. A: azimuth; d: dip, Mw: Moment Magnitude; NF: normal; p: plunge; r: rake; s: strike, SS: strike-slip; TF: thrust.

Figure 2: a) Sketch of the computational domain subdivided in the different "blocks", i.e. poorly deformable zones (I-VII), "weak borders", i.e. highly deformable homogeneous zones, simulating consuming (W_S1-W_S3) and extensional (W_R1-W_R2) plate boundaries, and shear zones (W_T1-W_T4). The rectangle indicates the zone of interest. b) Mesh of the COMSOL Multiphysics finite element model used in the analysis. The model contains 112,241 triangular plane stress elements from 5 to 100 km in size depending on the area. c) Sketch of the boundary conditions assigned to the Model set 1. Black crosses indicate fixed zero displacement and red arrows prescribed displacement based on the MORVEL 2010 model (DeMets et al., 2010; DeMets et al., 2011) assuming that Eurasia plate is fixed.

Figure 3: a) Section of the World Stress Map (WSM) open-access database compilation (Heidbach

et al., 2008; Reinecker et al., 2005) used in the present work. Illustrated in the map are the directions of the maximum horizontal compressive stress S_{Hmax} . Data included in the map are of A- to C- quality, i.e. the error is under NF: Normal Faulting; SS: Strike-Slip; TF: Thrust Faulting, U: Unknown. Complete set (b), Selected set (d) and Selected set 2 (e) of WSM control points where the misfit between the calculated azimuths of S_{Hmax} and those provided by the WSM have been evaluated. (c) Sketch of how to estimate the S_{Hmax} azimuth deviation between the numerical results and the WSM data.

Figure 4: Sketch of the geometry of the computational domain used for the Final Model. Boundary conditions and material properties for the different blocks and weak zones are also indicated.

Figure 5: S_{Hmax} and S_{hmax} distribution in the Canarian archipelago obtained with the Final Model (a) and incorporating also weak deformable areas representing one local structural discontinuity in El Hierro (b), Tenerife (c), Gran Canaria (d), Fuerteventura (e) or in all four locations (f). L: Lanzarote; F: Fuerteventura; GC: Gran Canaria; T: Tenerife; H: El Hierro; LP: La Palma.

Figure 6: Results obtained with the Final Model. S_{Hmax} distribution at the different areas of interest such as the North Atlantic Ridge (a), the Terceira Ridge (b) and the Gibraltar Arc (c). S_{Hmax} and S_{hmax} distribution at the Terceira Ridge (d) and the Transmorrocan Fault System (e) with indication of compression and extension.

Figure 7: S_{Hmax} and S_{hmax} distribution in the Canarian archipelago obtained with the Final Model (a) and with the next two best-fitted numerical solutions (b and c). Focal mechanism for the four moderate earthquakes occurred in the Canary Islands between 1989 and 2013 obtained from the Spanish National Geographic Institute (<http://www.ign.es>) (Earthquake I) and the Global Centroid Moment Tensor Project (<http://www.globalcmt.org>) (Earthquakes II-IV) are also included.

Figure 8: Simplified geologic map of El Hierro island (from Ancochea, 2004) showing the main morphological and structural features, and the epicentral migration of seismicity with time (black arrows) (modified from Martí et al., 2013). Location and focal mechanism of the earthquake preceding the onset of the eruption (corresponding to earthquake I in Fig. 1b)(del Fresno et al., 2015), and location of the vent are also shown.

Figure 1:

a) Digital Elevation Model (DEM) of the modelled area obtained from ETOPO 1 Global Relief Model (<http://www.ngdc.noaa.gov/mgg/global/global.html>), with WGS84 as geographic horizontal datum (Amante and Eakins, 2009). Main tectonic features are also indicated based on the work by Mantovani et al. (2007). Dashed white and pink lines indicate presumed tectonic features and broad plate limit, respectively. b) Focal mechanism of the four moderate earthquakes occurred in the Canary Islands between 1989 and 2013 obtained from the Spanish National Geographic Institute (<http://www.ign.es>) (Earthquake I) and the Global Centroid Moment Tensor Project (<http://www.globalcmt.org>) (Dziewonski et al., 1981; Ekström et al., 2012) (Earthquakes II-IV). Yellow stars indicate the location of the points used for evaluating the results obtained in the area of study. For each earthquake, information concerning nodal plane, magnitude, percentage of faulting mechanism and P-axis orientation is also indicated. A: azimuth; d: dip, Mw: Moment Magnitude; NF: normal; p: plunge; r: rake; s: strike, SS: strike-slip; TF: thrust.

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Figure 5: S_{Hmax} and S_{hmin} distribution in the Canarian archipelago obtained with the Final Model (a) and incorporating also weak deformable areas representing one local structural discontinuity in El Hierro (b), Tenerife (c), Gran Canaria (d), Fuerteventura (e) or in all four locations (f). L: Lanzarote; F: Fuerteventura; GC: Gran Canaria; T: Tenerife; H: El Hierro; LP: La Palma.

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(a) Final Model

(b) Final Model 11B + 9C

(c) Final Model 11C + 9C

Figure 7: S_{Hmax} and S_{Hmin} distribution in the Canarian archipelago obtained with the Final Model (a) and with the next two best-fitted numerical solutions (b and c). Focal mechanism for the four moderate earthquakes occurred in the Canary Islands between 1989 and 2013 obtained from the Spanish National Geographic Institute (<http://www.ign.es>) (Earthquake I) and the Global Centroid Moment Tensor Project (<http://www.globalcmt.org>) (Earthquakes II-IV) are also included.

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TABLE 1

	E (GPa)	ν	M (N/m)	type of element
Blocks				
I-VII	25-100	0.25	10^{15} - 10^{16}	isotropic
Decoupling zones				
W_S1-S3	0.01-0.1	0.25	10^{12} - 10^{13}	isotropic
W_R1-R2s	0.001-0.1	0.25	10^{10} - 10^{12}	isotropic
W_T1-T4	0.001-1	0.01 [*] , 0.25	10^{12} - 10^{13}	orthotropic

^{*} Along strike of the shear zone

TABLE 2

	I	II	III	IV	V	VI	VII	W_R1	W_R2	W_T1	W_T2	W_T3	W_T4	W_S1	W_S2	W_S3
Model set 1-5	70	70	70	70	50	50	100	0.01	0.1	(0.01, 0.1, 0.1)	(0.1, 1, 1)	(0.1, 1, 1)	(0.1, 1, 1)	0.1	0.1	0.1
Model set 6	70	70	70	70	50	50	100	0.001 (A) 0.01 (B) 0.1 (C)	0.1	(0.001, 0.01, 0.01) (A) (0.01, 0.1, 0.1) (B) (0.1, 1, 1) (C)	(0.1, 1, 1)	(0.1, 1, 1)	(0.1, 1, 1)	0.1	0.1	0.1
Model set 7	70 (A) 70 (B) 70 (C) 70 (D) 50 (E)	70 (A) 70 (B) 70 (C) 70 (D) 50 (E)	70 (A) 70 (B) 70 (C) 70 (D) 50 (E)	70 (A) 70 (B) 70 (C) 70 (D) 50 (E)	50 (A) 50 (B) 25 (C) 25 (D) 50 (E)	50 (A) 50 (B) 25 (C) 25 (D) 50 (E)	100 (A) 50 (B) 50 (C) 25 (D) 50 (E)	0.01	0.1	(0.01, 0.1, 0.1)	(0.1, 1, 1)	(0.1, 1, 1)	(0.1, 1, 1)	0.1	0.1	0.1
Model set 8	70	70	70	70	50	50	100	0.01	0.1	(0.01, 0.1, 0.1)	(0.1, 1, 1)	(0.1, 1, 1)	(0.1, 1, 1)	0.1 (A) 0.01 (B) 0.01 (C) 0.01 (D) 0.1 (E) 0.1 (F) 0.1 (G) 0.01 (H)	0.1 (A) 0.01 (B) 0.1 (C) 0.1 (D) 0.01 (E) 0.01 (F) 0.1 (G) 0.01 (H)	0.1 (A) 0.01 (B) 0.1 (C) 0.01 (D) 0.1 (E) 0.01 (F) 0.01 (G) 0.1 (H)
Model set 9	70	70	70	70	50	50	100	0.01	0.1	(0.01, 0.1, 0.1)	(0.1, 1, 1) (A) (0.01, 0.1, 0.1) (B) (0.01, 0.1, 0.1) (C) (0.01, 0.1, 0.1) (D) (0.01, 0.1, 0.1) (E)	(0.1, 1, 1) (A) (0.1, 1, 1) (B) (0.01, 0.1, 0.1) (C) (0.01, 0.1, 0.1) (D) (0.1, 1, 1) (E)	(0.1, 1, 1) (A) (0.1, 1, 1) (B) (0.1, 1, 1) (C) (0.01, 0.1, 0.1) (D) (0.01, 0.1, 0.1) (E)	0.1	0.1	0.1
Model set 10	70	70	70	70	50	50	100	0.01	0.1	(0.01, 0.1, 0.1)	(0.1, 1, 1)	(0.1, 1, 1)	(0.1, 1, 1)	0.1	0.1	0.1
Model set 11	70	70	70	70	50	50	100	0.01	0.1	(0.01, 0.1, 0.1)	(0.1, 1, 1)	(0.1, 1, 1)	(0.1, 1, 1)	0.1	0.1	0.1
FINAL Model	70	70	70	70	25	25	25	0.001	0.1	(0.01, 0.1, 0.1)	(0.1, 1, 1)	(0.1, 1, 1)	(0.1, 1, 1)	0.01	0.1	0.1

Graphical abstract

First-order estimate of the Canary Islands plate-scale stress field:**Implications for volcanic hazard assessment**

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Highlights

- Stress field is a key parameter controlling the distribution of volcanism
- We provide a first-order plate-scale stress field in the volcanic Canary Islands
- We also develop a regional model with archipelago-scale structural discontinuities
- Methodology useful to define potential tectonic controls of future volcanism
- Plate/regional stresses can be essential information for volcanic hazard assessment