Title: Insights into plume-ridge-transform fault interactions as derived from 3D numerical geodynamic modelling of the Azores Triple Junction

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Highlights

Insights into plume-ridge-transform fault interactions as derived from 3D numerical geodynamic modelling of the Azores Triple Junction

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- The configuration of the present-day Azores domain is the result of a complex interaction between a ridge, a transform fault and a mantle plume.
- Due to a shift in tectonic forcing, these interactions promoted the formation of a new intraoceanic rift system.
- The diffuse nature of the Eurasia-Nubia plate boundary in the Azores can be explained by plume-induced strain delocalization.

Insights into plume-ridge-transform fault interactions as derived from 3D numerical geodynamic modelling of the Azores Triple Junction

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Abstract

The Azores Archipelago is an igneous province located in the centre of the Atlantic Ocean marked by a large bathymetric plateau with a complex tectonic history. Over the last 10 Myr, this region has been shaped by the interaction between the Azores plume, the Mid-Atlantic Ridge (MAR), and the Gloria Fault zone. This complex interaction was characterised namely by the transition from a ridge-ridge-transform (R-R-T) triple junction to a diffuse complex triple zone, with the implied tectonic stresses being accommodated along several right-lateral oblique extensional structures, including the Terceira Rift. An understanding of the main geodynamic mechanisms behind this transition is still lacking.

This work explores how the Azores system may have been shaped by these complex plume-ridge-transform fault interactions by running 3D viscoelastoplastic geodynamic models using the LaMEM code. We base our initial modelling setup on previously proposed reconstructions for Azores during the Early Miocene, and implement a complying shift from spreading to right-lateral regional strain rate conditions. We further implemented a plume rising below the MAR to gain additional insight on the nature of the main geodynamic process-interactions governing this system.

Our results suggest that the present-day geometric configuration of the Azores, as well as the formation of the Terceira Rift, are strongly conditioned by the interactions between plume-ridge-transform fault system under the right-lateral relative motion between Eurasia and Nubia, as well as by the growth of the Azores Plateau. Under our modelling conditions, a thicker and weaker Azores Plateau, interfering with a mantle plume, promotes the localisation of deformation along its edges which act as rheological boundaries. As a consequence, the global shift in tectonic forcing is shown to be capable of strongly localize strain along the NE edge of the plateau, closely mirroring the present-day location of the Terceira Rift.

Keywords: Azores, mantle plume, ridge-plume interactions, geodynamics, numerical modelling

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1. Introduction

The Azores Archipelago is located at the centre of the Northern Atlantic Ocean (Fig. 1) and is the expression of a broad triple zone of distributed deformation (Fig. 1), with the Nubia and Eurasian plates to south- and north-east respectively, and the North American plate to the west. It is also the home of its namesake mantle plume, which has been suggested as a partial source of the volcanism in the region, with the other being the Mid-Atlantic Ridge (MAR) (e.g., Beier et al., 2022).

The Azores plume is a well established and studied feature of this region, from a geophysical (e.g., Bowin et al., 1984; Silveira et al., 2006; Yang et al., 2006; Pilidou et al., 2005), geochemical (e.g., Beier et al., 2022), and geodynamic (e.g., Arnould et al., 2019) point of view. Its exact geometry and location are relatively unclear, varying significantly according to different published works. For instance, using seismic tomography, Silveira et al. (2006) argued that the plume is no longer rooted in the lower mantle, with the characteristic low velocity anomaly being confined mostly to the top 200 km of the upper mantle; while the work from Yang et al. (2006) suggests that the plume stem is rooted below 400 km, and can be traced throughout the upper mantle. The authors further suggest that the plume head is presently located below Terceira Island, which is also in accordance with the studies conducted by Gente et al. (2003). A more recent work, Arnould et al. (2019), explored this region using seismic tomography and argued that this plume is strongly asymmetric. To this extent, they show that the plume has an elliptical shape which spans ca. 2000 km south and 600 km north along the axis of the MAR, and link this shape to the relative motion between the three involved plates and a slight northward drift of the plume itself. While the absolute motion of the plume may be small, reconstruction works conducted by Beier et al. (2022) and Gente et al. (2003) show a more significant relative position change over the past 50 Ma, mostly due to surface tectonic plate reconfigurations. Regarding its influence at the surface, it has been shown that the arrival and spread of the plume below the Azores lithosphere has induced widespread volcanic activity over several million years, being the major contributor to the formation and growth of the Azores Plateau (e.g., Beier et al., 2022).

The Azores Plateau is a small igneous province which is marked by a large bathymetric swell (Fig. 1). It has been proposed to be the result of a two-staged interaction between the Azores plume and the MAR, with the older volcanic materials (> 4 Ma) being mostly plume-related (Beier et al., 2022), whereas later materials (< 2 Ma) being mostly the result of the rifting processes in the region (Storch et al., 2020; Beier et al., 2022). It is bissected by the MAR, limited to the south by the East Azores fracture zone (EAFZ) and to the north(-

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east) by the Terceira Rift (Fig. 1). The latter represents a NW-SE striking structure connecting the MAR to the western Gloria Fault (GF) zone and presently undergoing ultraslow dextral transtension (e.g., Vogt and Jung, 2004; Fernandes et al., 2006; DeMets et al., 2010; Marques et al., 2013; Weiß et al., 2015; Storch et al., 2020). This transtensional behaviour has been attributed to the relative right-lateral global motion between the Eurasia and Nubia plates (Weiß et al., 2015), which locally induces NW-SE compression and NE-SW extension along this segment of the plate boundary (e.g., Luis and Miranda, 2008; Fernandes et al., 2003; Lourenço et al., 1998).

To this day, the geodynamic constraints behind the formation of the Terceira Rift are not fully understood, with different formation mechanisms having been proposed to explain it. The early neotectonic studies on the region (Madeira and Ribeiro, 1990, and references therein) sustained an interpretation of this feature as a "leaky transform", derived from the stress partitioning effect between the right-lateral GF and the spreading at the MAR, resulting in a transtensional component between them (shown in Fig. 8 of Madeira and Ribeiro, 1990). Later works regarding bathymetric (Lourenço et al., 1998) and gravimetric (Luis et al., 1998) surveys of the Azores Archipelago agreed with Madeira and Ribeiro (1990) that the Terceira Rift was accommodating extension, but argued that it consisted instead of an extensional strike-slip fault.

By compiling gravitational, sediment and plate kinematics data, Gente et al. (2003) suggested that the capture and migration of the Azores plume between 20 and 10 Ma caused the disruption of the Pico-Gloria fault zone (an earlier fault zone which comprised the GF and Pico Fault) and the migration of the plate boundary northwards, creating a weak zone broadly located where the present day Terceira Rift can be found. By contrast, Vogt and Jung (2004) argue that the morphology of the Terceira Rift strongly resembles "hyper-slow" ridges (with spreading rates < 2 mm/yr) around the world. In their view, the Terceira Rift represents the most recent (ca. 1 Ma) of a series of ultra-slow spreading centres formed in this region due to the motion between the Eurasia and Nubia plates. In their numerical modelling study of the mantle dynamics of triple junctions, Georgen and Sankar (2010) use the Terceira Rift as one of the branches of a possible R-R-R Azores Triple junction, albeit while acknowledging that a strike component of motion may exist.

Another modelling study, conducted by Neves et al. (2013), used 2- and 3-D elastoplastic models to argue that the broadly NW-SE alignments of volcanic edifices (e.g., the Pico-Faial islands or the Princess Alice basin, Fig. 1), as well as the formation of the Terceira Rift were the consequence of a brittle fracturing pattern developed as the GF propagated towards the MAR. According to the authors, this pattern is controlled by the shearing induced by the GF, by locally variable elastic thickness, and by the drag exerted by the mantle.

Using high resolution bathymetry and seismic multichannel data from this region (Weiß et al., 2015) proposed timelines for the formation/development of different features in the Azores Archipelago, which were broadly in agreement with the modelling study by Neves et al. (2013). The work from Weiß et al. (2015) was also found to be in general agreement with the study conducted by Beier et al. (2022), in which bathymetric, seismic, petrological and geochemical data obtained for the archipelago was used to propose a timeline for the growth of the Azores Plateau. In agreement with Neves et al. (2013), both Weiß et al. (2015) and Beier et al. (2022) propose NW-SE oriented fracturing under broadly transtensional conditions, albeit with different timing (e.g., Weiß et al., 2015 shows the formation of the Terceira Rift at 25-20 Ma, while Beier et al., 2022 proposes its formation at 1.5-1 Ma).

Among the various proposed formation mechanisms for the Terceira Rift (and other extensional features in the region, such as the Princess Alice Basin or the northern King's Trough, (e.g., Kidd et al., 1982; Srivastava et al., 1990), one consistent characteristic is the shift in tectonic forcing induced by the Early Miocene right-lateral motion between Eurasia and Nubia (e.g., Potter and Szatmari, 2009; Jolivet and Faccenna, 2000), which resulted in transpressive/transtensive conditions along this plate boundary (e.g., Hensen et al., 2019). In this work, we use 3D state-of-the-art viscoelastoplastic geodynamic models to simulate the effects of a regional tectonic forcing change in a triple junction setting. To this extent, we use an initial model setup which is broadly based on reconstructions for the Azores system during the Early Miocene (e.g., Gente et al., 2003), simulating a generic oceanic ridge-transform-ridge system in which one of the transform faults is longer and extends further away from the ridge (Fig. 2). Using this setup, we imposed a shift from rift-orthogonal spreading, between North America and Eurasia plates, to right-lateral transcurrent shearing, between Eurasia and Nubia, to assess whether this global plate kinematics change could locally induce the birth of a new dextral transtensional plate boundary. To complement this approach, we also run models in which we include a positive thermal anomaly at the base of the model close to the MAR (Fig. 2A). This induces the formation of a mantle plume, allowing us to explore whether the tectonic reconfiguration that took place in the Azores was essentially the result of global plate kinematics change or if a local mantle plume could have also played a pivotal role in this evolution.

The aim of this study is, therefore, to gain new insights on the geodynamic processes and forces that interacted to shape the Azores Triple Junction into its present configuration and, in the process, derive valuable new understanding on how plumes, ridges, and transform faults may interact in 3D/4D to form complex triple junctions. We also aim to understand how rigid entities, such as oceanic plateaus, may

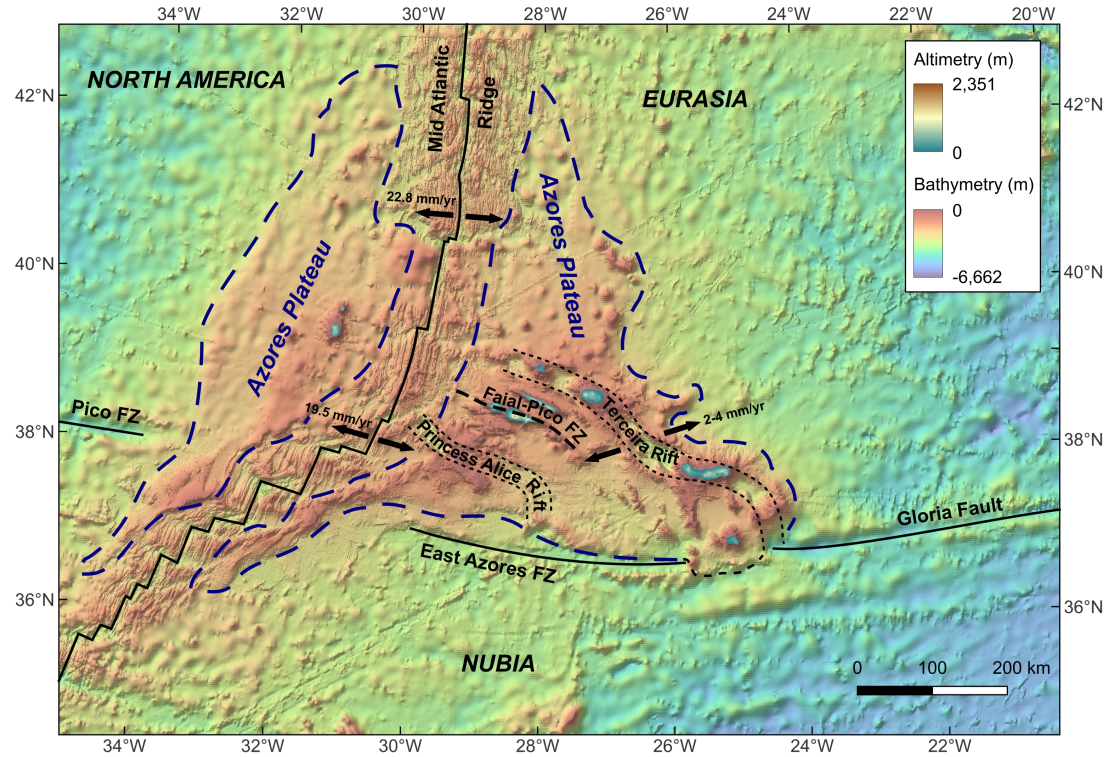

Figure 1: **Overview of the Azores system with the major tectonic features highlighted.** The Azores Plateau is marked by the blue contoured region. The major NE-SW features are highlighted in black lines, with fault zones being marked by thick dashed lines and extensional features being delimitated by thin dotted lines. The thick arrows indicate present-day spreading/extensional rates from DeMets et al., 2010. Bathymetry from the EMODnet project (www.emodnet-bathymetry.eu); subaerial topography was generated from a 1:5000 scale digital altimetric database from Secretaria Regional do Turismo e Transportes of the Azores Government. FZ - Fracture Zone

influence or condition the geometry and position of ridge jumps and the generation of transtensional diffuse plate boundaries, such as the one found in the Azores between Eurasia and Nubia.

2. Methods

2.1. Numerical approach

The conducted numerical models were run using the LaMEM code (Kaus et al., 2016), using internally imposed global strain rate conditions to simulate the seafloor spreading and the shift in tectonic forcing due to the right-lateral motion between Eurasia and Nubia. No compressibility was assumed for these modelling runs. LaMEM employs a finite difference staggered grid discretization which is coupled with a particle-in-cell approach (Kaus et al., 2016) to obtain numerical solutions for the equations of conservation of mass, momentum, and energy (Eq. 1-3).

$$\frac{\partial \boldsymbol{v_i}}{\partial x_j} = 0 \tag{1}$$

$$-\frac{\partial P}{\partial x_i} + \frac{\partial \tau_{\mathbf{ij}}}{\partial x_j} + \rho \mathbf{g_i} = 0 \tag{2}$$

$$\rho C_p \left(\frac{\partial T}{\partial t} + \boldsymbol{v_i} \frac{\partial T}{\partial x_i} \right) = \frac{\partial}{\partial x_i} \left(\kappa \frac{\partial T}{\partial x_i} \right) + H_R + H_S \tag{3}$$

Here, $\boldsymbol{v_i}$ represents the velocity, x_i the cartesian coordinates, P the pressure, $\tau_{\mathbf{ij}}$ the shear stress, ρ the density, $\mathbf{g}$ the gravitational acceleration, C_p the specific heat, T the temperature, t the time, κ the thermal conductivity, and H_R and H_S represent the radiogenic and shear heating components, respectively. The shear heating component is defined as:

$$H_S = \tau_{\mathbf{ij}} \left(\dot{\varepsilon}_{\mathbf{ij}} - \dot{\varepsilon}_{\mathbf{ij}}^{elastic} \right), \tag{4}$$

with $\dot{\varepsilon}_{\mathbf{ij}}$ as the total strain rate tensor and $\dot{\varepsilon}_{\mathbf{ij}}^{elastic}$ the strain rate imposed by the elastic deformation.

All presented models were run using non-linear viscoelastoplastic rheologies, with the following constitutive equations (Kaus et al., 2016; Piccolo et al., 2020):

$$\dot{\varepsilon}_{ij} = \dot{\varepsilon}_{ij}^{viscous} + \dot{\varepsilon}_{ij}^{elastic} + \dot{\varepsilon}_{ij}^{plastic} = \frac{\tau_{\mathbf{ij}}}{2\eta_{eff}} + \frac{\overset{\diamond}{\tau}_{\mathbf{ij}}}{2G} + \dot{\gamma} \frac{\partial Q}{\partial \tau_{\mathbf{ij}}}, \tag{5}$$

$$\overset{\diamond}{\tau}_{\mathbf{ij}} = \frac{\partial \tau_{\mathbf{ij}}}{\partial t} + \tau_{\mathbf{ik}} \omega_{\mathbf{kj}} - \omega_{\mathbf{ki}} \tau_{\mathbf{kj}}, \tag{6}$$

$$\omega_{\mathbf{ij}} = \frac{1}{2} \left(\frac{\partial \mathbf{v_j}}{\partial x_i} - \frac{\partial \mathbf{v_i}}{\partial x_j} \right), \tag{7}$$

with η_{eff} as the effective viscosity, $\overset{\diamond}{\tau}_{\mathbf{ij}}$ the Jaumann objective stress rate, $\omega_{\mathbf{ij}}$ the spin tensor, G the elastic modulus and Q the plastic flow potential.

The creep viscosity, η_{vs}, is calculated as:

$$\eta_{vs} = \frac{1}{2} A^{-\frac{1}{n}} \times \dot{\varepsilon}_{II}^{\frac{1}{n}-1} \times \exp\left(\frac{E_a + V_a P}{nRT} \right), \tag{8}$$

with A as the diffusive or dislocation pre-exponential factor, n the stress exponent, $\dot{\varepsilon}_{II}$ the second invariant of the strain rate tensor (Eq. 5), E_a the activation energy, V_a the activation volume and R the gas constant.

Plastic creep is ensured by employing a Drucker-Prager yield criterion (Drucker and Prager, 1952):

$$\sigma_Y = C \cos(\phi) + P \sin(\phi), \tag{9}$$

with σ_Y as the yield stress tensor, ϕ the internal friction angle and C the cohesion. The onset of plastic weakening takes place once mantle materials accumulate at least 10% of total plastic strain and this effect halts after at least 60% of total plastic strain has been accumulated. During softening, the materials' cohesion and internal friction angles are linearly reduced until they reach 1% of their initial values. The effective viscosity (η_{eff}) of the individual phases is obtained by calculating the minimum between the calculated viscoelastoplastic viscosity and the Newtonian viscosity.

The age dependence of the thermal profiles of the plates follows the half-space cooling model:

$$T = T_{surface} + (T_{mantle} - T_{surface}) \times erf\left(\frac{y}{\sqrt{Kt}}\right). \tag{10}$$

Here, $T_{surface}$ represents the temperature at the surface of the model (273 K), T_{mantle} is the temperature at the lithosphere-asthenosphere boundary (1523 K), y is the depth, K the diffusivity, and t is the age of the plate. The effective (rheological) lithosphere thickness throughout the model is set by the 1523 K (1250 °C) isotherm. The upper mantle thermal profile follows the mantle adiabat, with a gradient of 0.5 K/km. All material densities are temperature and pressure dependent:

$$\rho = \rho_0 + \alpha(T - T_0) + \beta(P + P_0). \tag{11}$$

Here, ρ_0 is the density of the material at the reference temperature T_0, α is the thermal expansibility and β is the compressibility.

2.2. Initial setup and boundary conditions

This work was conducted by running 3D viscoelastoplastic numerical models to investigate if the shift in tectonic forcing caused by the onset of right-lateral motion between Eurasia and Nubia could have induced a rearragement of the R-R-T Azores triple junction, as well as the role played by the Azores plume in this evolution. This plume influence is evaluated by implementing a corresponding mantle anomaly at the base of the model. The initial configuration of the model was based on reconstructions of the Azores system during the Early Miocene, such as the one proposed by Gente et al. (2003). To this extent, we simulate a ridge-transform-ridge triple junction system, in which the southernmost transform is prolonged away from the ridge (Fig. 2), bordering the south of the Azores Plateau. To ensure that we assess the individual effect of each studied parameter, we always modified our models in a systematic manner, changing only one variable per model run, resulting in a total of 5 models (see Table 1).

The prescribed model domain was 1500 km long, 900 km wide and 315 km thick and was discretized along a 256x256x128 resolution grid. To prevent boundary condition issues, as well as instabilities within

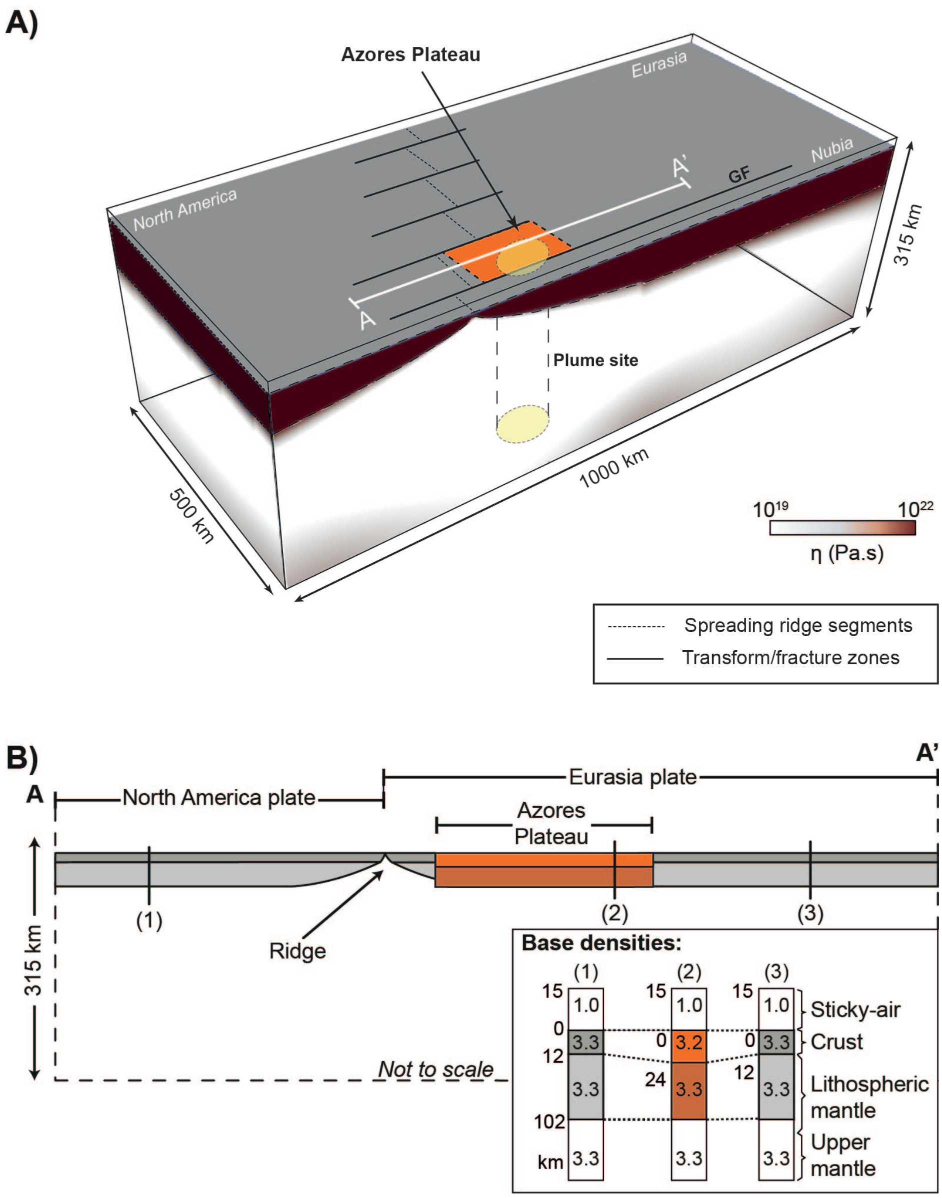

Figure 2: **Initial setup for the conducted models. A) Model setup for the experimental initial state**: Schematic representation of the geometric configuration, model dimensions and rheology. The viscosity scale applies to the front- and left-facing wall. To avoid undesired boundary effects due to material accumulation and over stress at the corners of the model, as a consequence of the adopted shear boundary conditions, this region does not correspond to the entire model domain but just a prescribed high resolution domain. **B) Cross section AA' cutting through the Azores Plateau**. Inset shows the initial density structure of the oceanic plates vs. the plateau (units in g/cm^3). Rheologies detailed in the text, and on Supplementary Table S1. GF - Gloria Fault

Table 1: List of models run in the present study. Model 1 (in bold) is considered the reference model.

Model number	Pre-existing plateau	Active plume	Additional constraints
1	**Yes**	**No**	**-**
2	No	No	-
3	No	Yes	No imposed strain rates
4	No	Yes	-
5	Yes	Yes	-

the model, this discretization is non-uniform, with a central high-resolution region (shown in Fig. 2A) surrounded by a low resolution box. The model included a 15 km thick sticky-air layer, which acts as a free surface, allowing for the formation of topography. Furthermore, the top boundary is open, ensuring a free movement of this layer. All other model boundaries were defined as free slip, which allows for motion along the boundary surface but not across it.

The rheology of the oceanic crust follows a dry olivine creep law (Ranalli, 1997) and has a variable thickness which depends on its distance to the spreading ridge (following the half-space cooling model, Eq. 10). The lithospheric mantle also follows a dry olivine creep law, differing in behaviour from the crustal material due to a higher temperature (Eq. 8).

The Azores Plateau was prescribed with a weaker but thicker crust to mimic the volcanic nature of this region, in this case, following a diabase law (Mackwell et al., 1998). To reflect the accumulation of plume-derived material at the base of the lithosphere, the plateau interrupts the normal plate growth from the ridge, resulting in a locally thicker lithospheric mantle close to it as is illustrated in the cross-section shown in Fig. 2B. The transform faults are implemented in the models as thin planar bodies with a constant Newtonian viscosity of 10^{20} Pa·s as to achieve high strain localization within them. All rheological parameters made available in Appendix Table S1. The Azores plume was prescribed in our models by injecting hotter (ca. 250 K) material through a point in the bottom boundary with a constant rate of 5 cm/yr. The injection site is 100 km wide and is located approximately below the Azores Plateau (Fig. 2A). The composition of the plume material is identical to the surrounding upper mantle (see Supplementary Table S1) and ascends to the surface due to its positive thermal buoyancy. As prior works have argued that the nature of the plume (i.e., chemical vs. thermal vs. thermochemical) does not influence the dynamics of ridge-plume interaction (e.g., Ribe et al., 1995), we adopted the simplification of implementing a thermal anomaly at the lower boundary of our model. Consequently, we obtained a relatively consistently shaped mushroom-shaped mantle plume throughout all models which allows for a straightforward comparison between them.

The dynamics of the system are controlled by a two-phase regionally imposed strain rate (Fig. 3), which

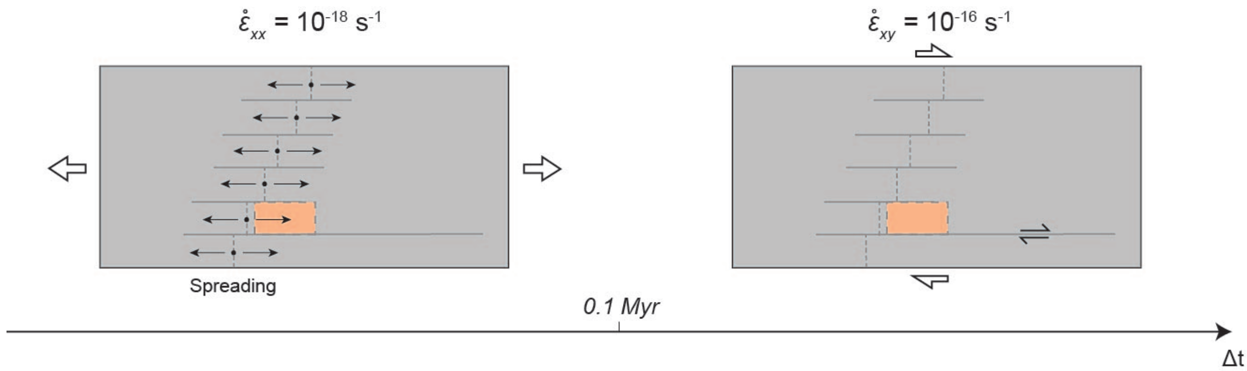

Figure 3: **Top-view illustration of the imposed two-phase regional strain rates, implemented during the entire model evolution.** During a first phase, lasting 100 kyr, the model evolves under regional spreading conditions with a $\dot{\varepsilon}_{xx}$ of 10^{-18} s^{-1}. After that, we impose a right-lateral simple shear regional strain rate ($\dot{\varepsilon}_{xy}$) of 10^{-16} s^{-1} (corresponding to a right-lateral strike slip velocity of ca. 1 cm/yr), simulating the transcurrent motion of Eurasia and Nubia, which is locally capable of inducing transpressional and transtensional strain in the Azores plateau domain. The large white arrows represent the imposed strain conditions, while the thin black arrows represent the resulting local kinematic conditions.

simulates the change in tectonic forcing imposed by the right-lateral motion between the Eurasian and Nubia plates during the Middle Miocene (e.g., Fernandes et al., 2003; Schettino and Macchiavelli, 2016; Potter and Szatmari, 2009; Duarte et al., 2013), which is locally capable of triggering transtensional and transpressive strain in the Azores plateau domain. As we cannot be sure on the exact magnitude of strain during the Miocene, we adopted the simplification of considering a strain rate equivalent to the one observed in the Present day (closely corresponding to the ca. 1 cm/yr strike-slip velocity between Eurasia and Nubia). The models are ran for 100 kyr under regional spreading conditions to ensure the establishment of the MAR and the initiation of the mantle upwelling beneath the ridge, followed by a regional simple shear component with $\dot{\varepsilon}_{xy} \approx 10^{-16}$ s^{-1}, which locally induces transpressional and transtensional strain conditions in the Azores plateau domain. This specific strain rate value was chosen to ensure that the right-lateral motion in the region reflects the known Eurasia-Nubia relative motions.

For simplification, our reference conditions include both the Azores Plateau and the shift in regional strain rate. Although the former did not exist at the time of the change in tectonic forcing (ca. 10 Ma), it was formed shortly after (e.g., Beier et al., 2022; Weiß et al., 2015) which could be sufficient to significantly alter the local rheology contrasts.

3. Results

3.1. Models without an active mantle plume

All models without an active mantle plume showed a similar sequence of events, which is represented in Fig. 4 and Supplementary Video 1. During the first 100 kyr (Fig. 4A), the MAR is opened, which induces upper mantle upwelling below it (simulating an active mid-ocean ridge). After the prescribed change in the general strain rate regime occurs (Fig. 3), a weak strain localization band is immediately formed (Fig. 4B) connecting the GF and the MAR. As the model evolves (Fig. 4C), this band becomes more localized with its strain rate being two orders of magnitude higher than the background. Once this connection between the GF and the northern segments of the MAR is established, an isolated low strain domain can be observed between these three features (Fig. 4D). This domain is bordered to the north by the newly formed shear zone, which acts as a slow transtensional boundary. Here, the Eurasian plate is separated into two distinct zones, the "original" Eurasia and the new Azores domain. Although both domains are moving away from the MAR, the NE domain moves ca. 3 mm/yr faster, producing intra-oceanic rifting that evolves into a slow spreading centre (Fig. 5).

In models in which the Azores Plateau was absent (Model 2, Fig. 6 and Supplementary Video 2), we observed that after the main prescribed change in the strain tectonic regime ($\Delta t \approx 100$ kyr), no particular localization of strain occurs, and consequently, no clearly defined shear zone develops. Instead, a large triangular diffuse high strain rate area develops adjacent to the spreading ridge (to the east of the MAR). This increased strain rate area is maintained throughout the entire modelling run, without strong localization ever developing.

3.2. Models with an active plume

In order to assess the influence which could be exerted by the Azores plume alone, the main strain regimes (and the induced shift between them) that were prescribed in all other models were disabled in Model 3 (Fig. 7A and Supplementary Video 3). Thus, in this model, all observed surface strain is the result of the mantle plume head encroaching at the base of the lithosphere, with a minor contribution from ridge push. Consequently, the strain magnitudes are significantly lower than the ones observed in both Models 1 and 2 (as seen in Fig. 7A). During the first ca. 500 kyr, the majority of strain is localized at the MAR and associated weak zones while the plume ascends through the upper mantle. Upon arriving at the base of the lithosphere (600-800 kyr) the plume head temporarily disrupts the MAR by forcefully inducing the opening of two ridge segments (Fig. 7A1). However, as the plume head spreads beneath the lithosphere (0.8-1.1 Myr), the two segments are re-established at their initial positions and the surface deformation effects of the plume stop being visible (Fig. 7A2).

The regionally imposed strain rates were implemented again in Model 4 (Fig. 7B) in order to assess how the shift in tectonic forcing could enhance or inhibit the surface strain caused by the mantle plume. Under these conditions, we once again observe the same event sequence as in the models without the active plume.

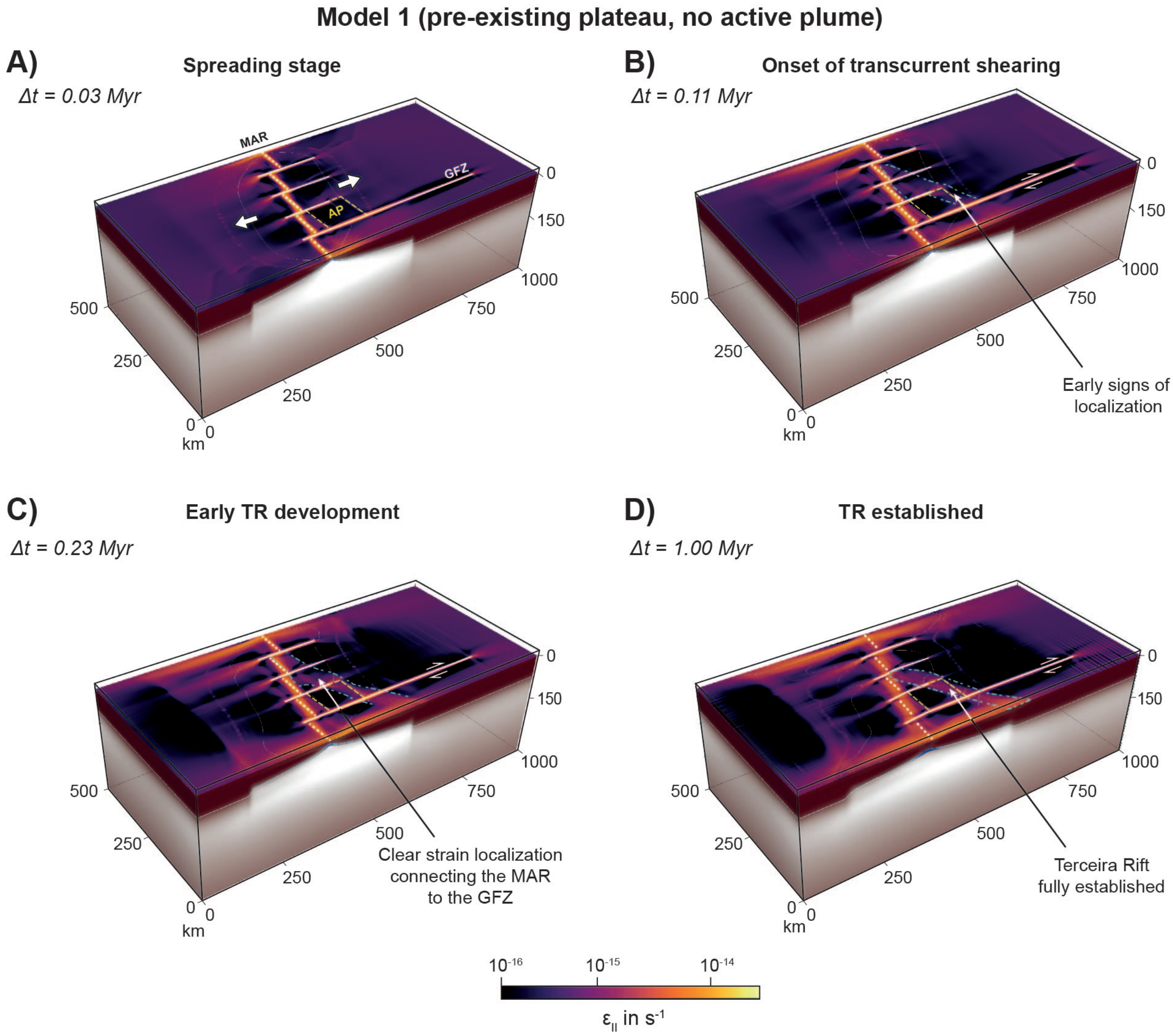

Figure 4: **Evolution of the reference model (Model 1) over 1 Myr. A) Spreading phase.** The upwelling of the mantle below the MAR is induced, allowing for the establishment of the weak zones associated with this feature (such as the central valley). **B) Shift in tectonic forcing.** After 100 kyr have elapsed, the regional simple shear conditions are imposed on the model. There is an immediate establishment of a narrow shear zone that localizes transtensional strain and connects the GF to the MAR. This also results in the isolation of a small triangular domain between this shear zone, the GF and the MAR. **C) Early development of the TR.** After another ca. 100 kyr, strain localization is further developed, with increased transtensional strain and simultaneous narrowing of the forming shear zone. It is also noticeable that the isolated triangular domain is characterized by a low strain rate, implying that the newly formed band is acting as a plate boundary (much like the Terceira Rift). **D) Final deformation state.** After ca. 1 Myr of evolution, the new transtensional shear band is fully developed, with a geometry and kinematics compatible with the one observed for the natural Terceira Rift. MAR - Middle-Atlantic Ridge; GF - Gloria Fault; AP - Azores Plateau; TR - Terceira Rift.

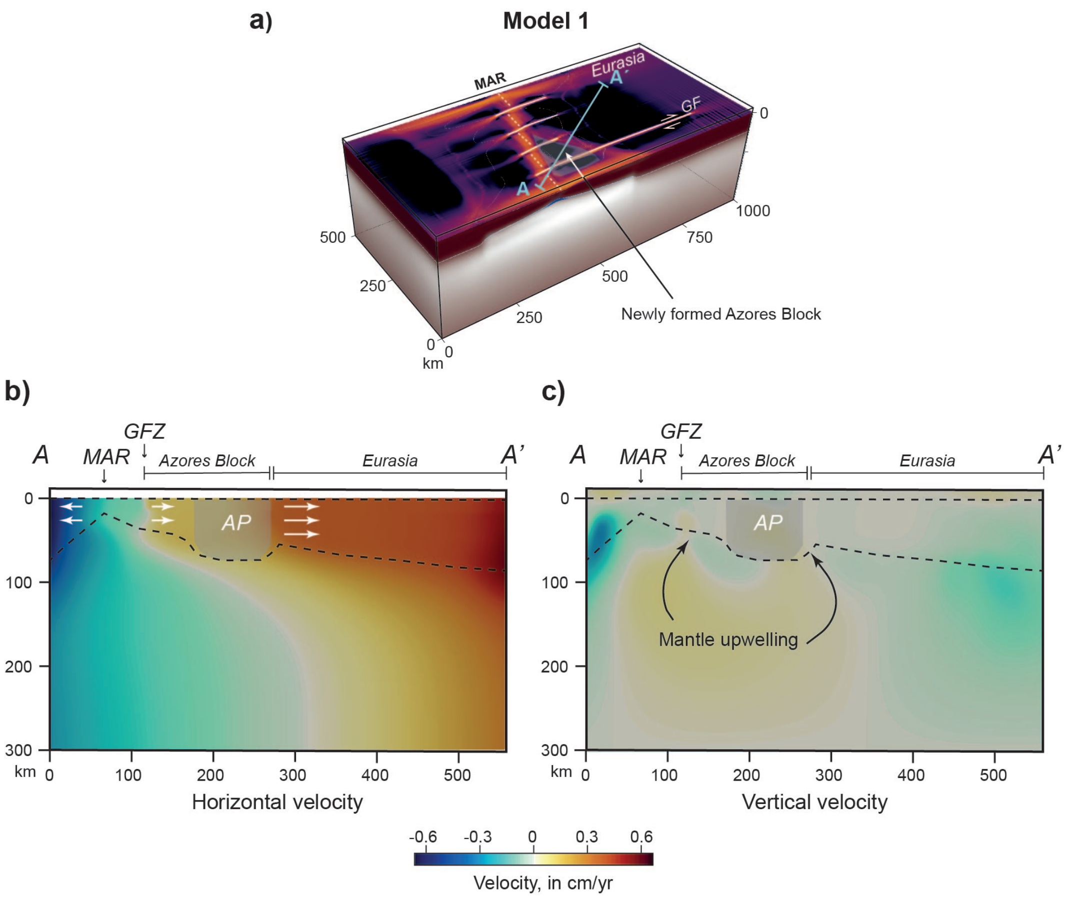

Figure 5: **Newly formed transtensional shear zone boundary (corresponding to the Terceira Rift). A) Model 1 after 1 Myrs, depicting the location of the cross sections orthogonal to the newly formed transtensional shear zone. B) Cross section AA': horizontal velocity output.** Note that the horizontal velocity displays a jump in magnitude towards the NE (i.e., to the right) across the newly formed shear zone, denoting marked extensional strain localization along the NE boundary between the triangular Azores Block and the rest of the Eurasia plate. The Eurasia plate has been separated into two separated strong blocks, the "original" Eurasia plate (to the NE), and the new Azores Block domain. While both are moving away from the MAR, the north-eastern Eurasia region is moving ca. 3 mm/yr faster, producing a slow spread along this new boundary. **C) Cross section A-A': viscosity output.** The separation observed in the previous cross-section is accompanied by two small mantle upwelling sites, under the GF and the TR-like shear zone, showing some degree of mantle accommodation to the transtensional deformation in the region. MAR - Middle-Atlantic Ridge; GF - Gloria Fault.

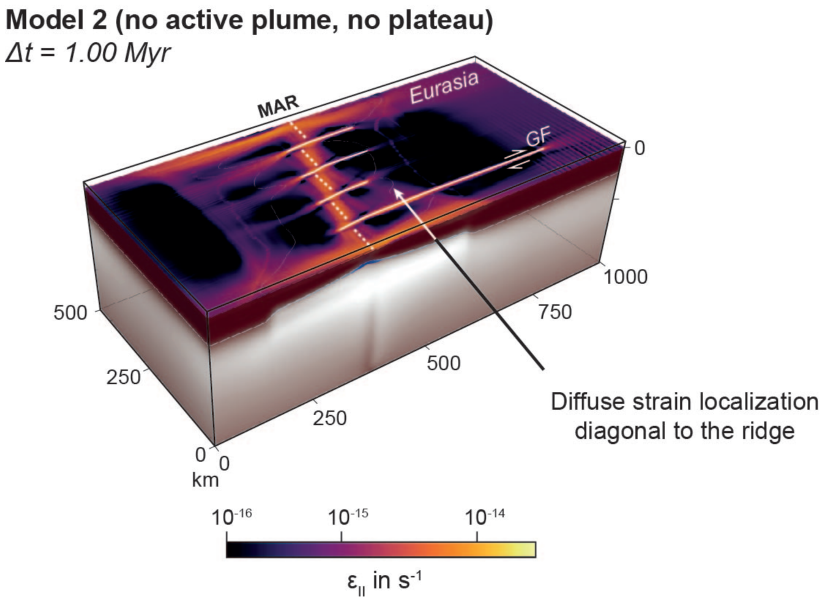

Figure 6: **Final deformation state in Model 2.** Diffuse strain distribution occurs throughout the entire Azores domain (between the GF, the MAR and the Eurasia plate to the NE). MAR - Middle-Atlantic Ridge; GF - Gloria Fault.

However, and unlike Model 3, the MAR is never disrupted during plume ascension (see Supplementary Video 4). Furthermore, a wider high strain rate region is formed in these models when compared to Model 3 (Fig. 7A vs. 7B).

Lastly, in Model 5 (Fig. 7C), we added the Azores Plateau to assess how the complete set of geodynamic constraints would affect the evolution of this system. This model shows the combined features from all the previous models. We observe a broadly triangular-shaped high strain rate domain bounded by the MAR and the GF as in Models 1 and 2 (Fig. 4 and 6), without any low strain rate zones being formed.

4. Discussion

4.1. The effects of the right-lateral motion between Eurasia and Nubia

One of the primary objectives of this work was to explore how the change in relative motion between the Eurasian and Nubian plates (e.g., Weiß et al., 2015) could influence the formation of the Terceira Rift. To simulate these changes, we begin with an initial setup which is based on geological reconstructions for the region (Fig. 8A) and simulates the shift from orthogonal rift spreading to dextral simple shear, induced by the onset of right-lateral strike-slip movement between Eurasia and Nubia plates along the GF. (Fig. 3). This imposed strain rate regime is induced by the relative right-lateral motion along the GF (e.g., DeMets et al., 2010; Fernandes et al., 2006), in which Eurasia moves eastwards relative to Nubia. This shift in the overall governing strain rate regime expresses a reorientation of the regional stress field, with the principal

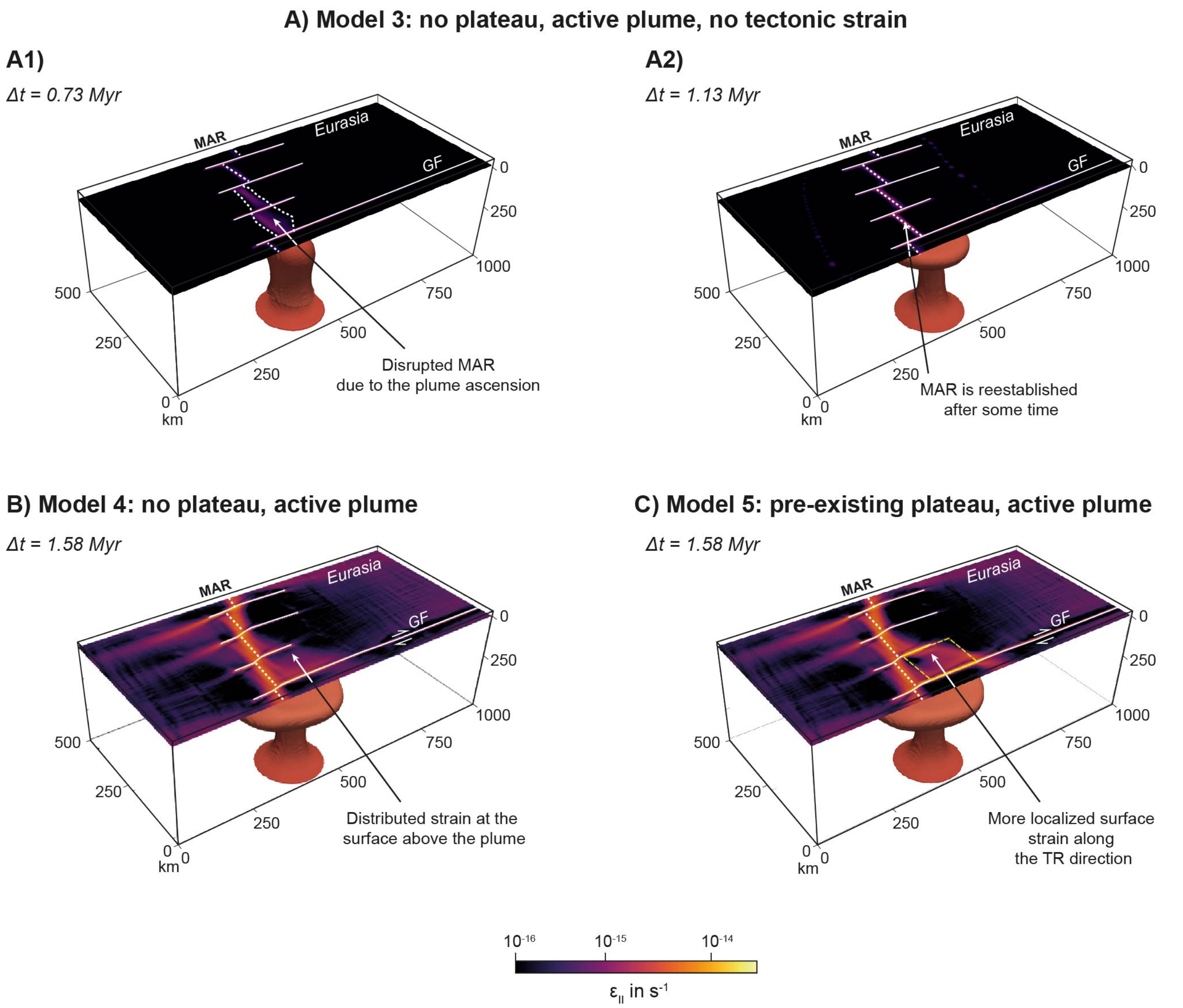

Figure 7: **Evolution and final states of the plume models (Models 3 to 5). A1. Disruption of the MAR in Model 3.** Upon arrival of the plume head to the base of the lithosphere, there is a disruption of the MAR, as illustrated by the broadening of spreading centres in two of the MAR segments. **A2. Reestablishment of the MAR.** Over time, the MAR is reformed in its original position as the result of the lack of regional shearing. **B) and C) Final deformation states in Models 4 and 5.** The arrival of the plume in these models with a pre-imposed regional strain rate shows surface patterns similar to Model 2 (Fig. 6). However, strain distribution is in this case more diffuse, without any significant localization along any narrow shear bands (compare with Fig. 4D). MAR - Middle-Atlantic Ridge; GF - Gloria Fault.

extension direction rotating from E-W to NE-SW, compliant with the known NW-SE oriented extensional features, such as the Terceira Rift, the Princess Alice Rift, the King's Trough (e.g., Gente et al., 2003; Kidd et al., 1982; Srivastava et al., 1990) and the volcanic alignments in the region (e.g., Neves et al., 2013; Weiß et al., 2015, Fig. 1). We also explored how the presence or absence of the Azores Plateau could influence the evolution of the system. This stems from the overlap between the age of formation for this feature, ca. 15-10 Ma (e.g., Beier et al., 2022), and the acceleration of the orthogonal convergence between these two plates in the Mediterranean region, ca. 15-10 Ma (e.g., Potter and Szatmari, 2009; Rosenbaum et al., 2002; Jolivet and Faccenna, 2000) , which imposes the dextral transcurrent kinematics along the GF.

Our models without active mantle plumes (Fig. 4 and 6) allow us to obtain some insights concerning the impact of two geodynamic constraints: the existence of the Azores Plateau and change in tectonic forcing) on the evolution of the Azores system. First and foremost, once the tectonic forcing shift takes place, a strain localization boundary is formed at an $\approx 45°$ angle to the MAR and connects it to the GF. The appearance of this boundary can be linked to NE-SW reorientation of the main extensional direction, which thus facilitates this NW-SE MAR-GF connection. The degree of strain localization south along this new boundary is directly correlated with the presence of the Azores Plateau (compare Fig. 4 and 6), as models ran without this feature more distributed strain rate within the same domain. By contrast, when the plateau is present, most strain is localized along a narrow shear zone (Fig. 4) which forms close to the edge of the plateau. This suggests that the rheologically distinct (see Supplementary Table S1) and thicker plateau crust plays a fundamental role in the evolution of the Azores system. On this, prior works concerning the effects of rheologically distinct bodies on transtensional systems have shown that their edges are prime sites for strain localization due to acting as strong rheological boundaries (e.g., Calignano et al., 2015; Willis et al., 2019). Additionally, it has been shown that localized bodies with thicker crusts (i.e., weak layers) tend to favour both extensional stresses (Lynch and Morgan, 1987) and delocalized deformation (Keppler et al., 2013).

Our results suggest that this rheological boundary localization effect may be acting in our models. Under our modelling conditions, despite its inherent weak rheology (see Table S1), the cold nature of the imposed Azores Plateau makes it act as a strong body. This promotes the localization of stress along its boundaries, facilitates the creation of the observed strain shadow zones (compare Figs. 4 and 6) and the shear zone which connects the MAR and the GF (Fig. 4). Over time, this shear zone begins to act as an active transtensional plate boundary in our models, isolating a new triangular domain from the surrounding plates (Fig. 8B). We argue that this isolated area represents the Azores domain (Fig. 8B), which was formed between the

Terceira Rift, the MAR and the EAFZ (an older, deactivated segment of the Gloria-Pico Fault, Luis and Miranda, 2008, shown in Fig. 8B). This comparison can be strengthened by the kinematic measurements shown in Fig. 5, namely the ca. 3 mm/yr horizontal difference across this boundary, which is in-line with the magnitude of the slow rifting rates observed for the region which range from ca. 1.5 (e.g., Fernandes et al., 2003, 2004) to 3 mm/yr (e.g., Vogt and Jung, 2004).

The evolution of our modelled triple junction from its original R-R-T (Fig. 8A) to the final diffuse R-R-R configuration (Fig. 8B) closely follows plate reconstructions for this region (e.g., Gente et al., 2003; Luis and Miranda, 2008; Beier et al., 2022). This triple junction configuration change due to a change in global tectonic forcing is in-line with prior work which suggested that these features are inherently unstable, constantly adapting and reacting to the existing tectonic stresses (Cronin, 1992). In the present case, a change in global tectonic forcing resulted in the establishment of a new transtensional site which, in time, could evolve into an independent ridge site. Thus, our results suggest that the formation of new intraoceanic rift (or oblique extensional) sites are the result of the local expression of a change in global tectonics.

4.2. The mantle plume contribution

Around the world, many plumes are located below or close to mid ocean ridges (Ribe et al., 1995), such as Iceland, Afar, Galapagos or the Azores. This overlap has sparked a plethora of studies in the past which have versed on the interactions between these major geological features (e.g., Ribe et al., 1995; Albers and Christensen, 2001; Pilidou et al., 2005; Mittelstaedt et al., 2011; Gibson et al., 2015; Whittaker et al., 2015; Sun et al., 2021; Pang et al., 2023, among many others). It has been argued that, among other things, plumes can be both captured by ridges (e.g., Schilling, 1991, and references therein) as well as induce new ridge sites (e.g., Whattam and Stern, 2015). They are also known to induce strong geoid and dynamic topography anomalies (e.g., Wang, 2021). Nevertheless, to the best of our knowledge, no modelling study has tackled the combined effects of a ridge-plume-transform interaction triggered by the onset of right-lateral strike-slip motion and its related shearing. As previously shown, our plume head is positioned close to the MAR (Fig. 2 and 7), which influences the development of the Terceira Rift in two main ways. First, the arrival of the plume head to the base of the lithosphere induces a temporary disruption of the MAR (i.e., a forced opening of individual segments). Secondly, the edges of the plume head promote the accumulation/localization of strain along specific directions at the surface.

We argue that the disruption effect of the MAR, observed in Model 3, represents an attempt at initiating a change in ridge configuration, a process commonly occurring at plume-ridge interaction sites, called a ridge jump (e.g., Mittelstaedt et al., 2011; Gibson et al., 2015; Whittaker et al., 2015). Previous research on this

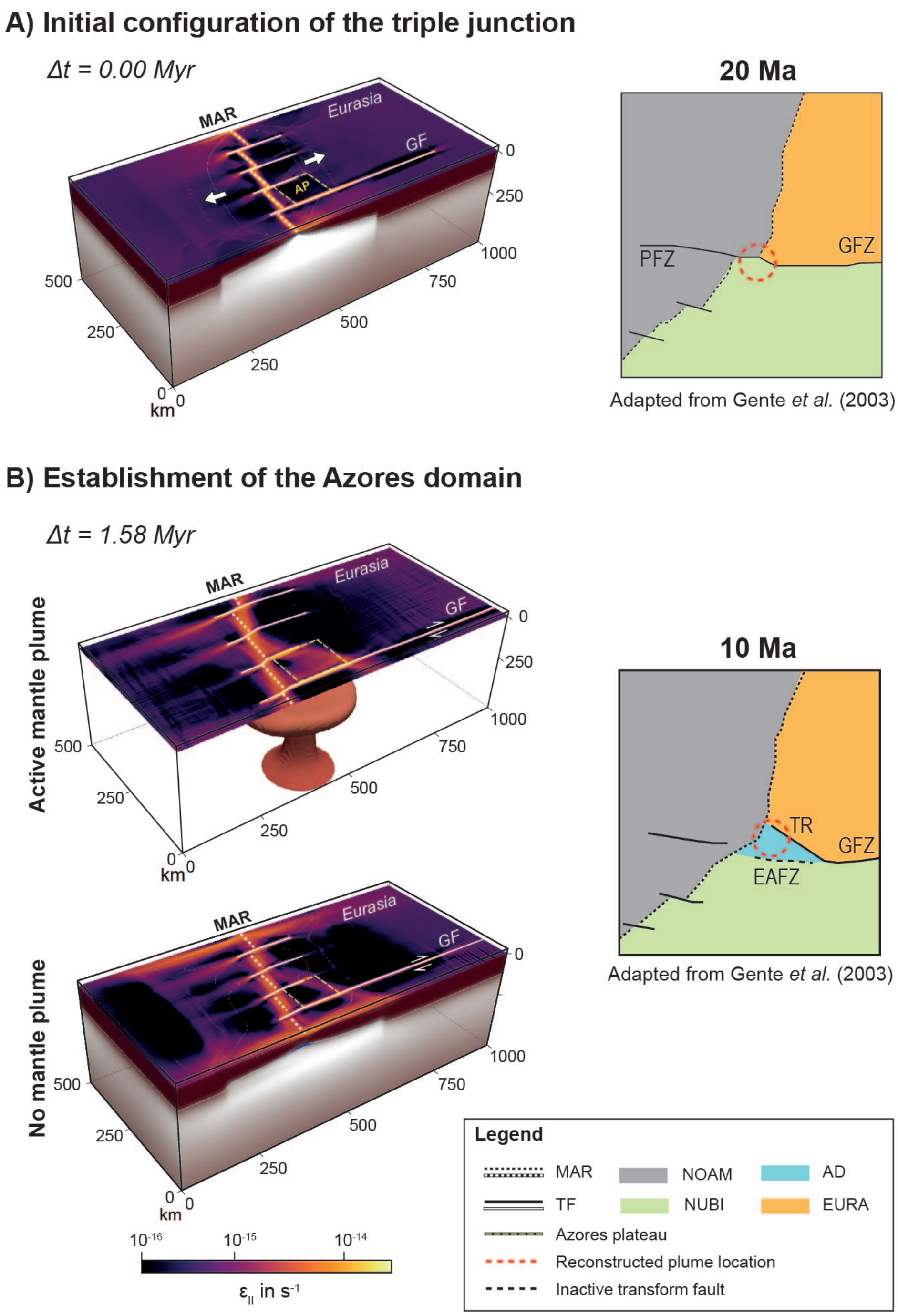

Figure 8: **Comparison of the model results with the evolution of the Azores system. A) Initial configuration of the Azores triple junction.** Our initial setup was based on the reconstructions for the region (such as the one from Gente et al., 2003). During the Early Miocene, the GF was not an isolated fault but instead part of the Pico-Gloria Fault (PF-GF) system. **B) Formation of the Azores domain due to the regional tectonic forcing.** Plate reconstructions for the region propose that the Azores domain (AD) was established in the late Miocene (ca. 10 Ma, Gente et al., 2003) during the tectonic reconfiguration imposed by the relative motion between the Eurasia-Nubia plate (e.g., Potter and Szatmari, 2009). In our results, a similar change from spreading to right-lateral shearing conditions leads to opening of the Terceira Rift, here mimicked by a narrow band of high strain localization which links the MAR to the GF. The deactivation of the EAFZ segment is not simulated in our models due to the simplified implementation of the weak zones as simple isoviscous shapes (a discussion of this can be found in Appendix A - Model Limitations). PF: Pico Fault; GF: Gloria Fault; EAFZ: East Azores Fracture Zone; AP: Azores Plateau; TR: Terceira Rift; NUBI: Nubia plate; EURA: Eurasia plate; NOAM: North America plate; MAR: Mid-Atlantic Ridge; and TF: Transform Fault.

topic has suggested that ridge jumps are the result of the coexistence between a weakening of the lithosphere around a mid-ocean ridge and a rift-inducing stress field (Mittelstaedt et al., 2011, and references therein). Under the conditions of Model 3, no ridge jump is observed suggesting that one or both of these factors are not present. Although not visible in Fig. 7A, the encroaching mantle plume induces a small degree of off-axis deformation (and, consequently, localized weakening), represented by rings of increased strain rate ring around the ridge (see Sup. Fig. S1). Albeit on a different geodynamic setting, this observation is in accordance with the works of Whattam and Stern (2015) and Stern and Dumitru (2019) on plume-induced subduction initiation. In these works, the authors show that the edges of a plume induce a deformation ring at the surface, along which new subduction zones can be triggered. Accordingly, the stress induced along by the edges of mantle plumes is likely compressive, the opposite of the extensional conditions required for any rift to be formed. When this factor is combined with the lack of far-field tectonic forcing in Model 3, the only extensional stress present derives from the thermal upwelling at the ridge. Ultimately, this is likely the reason behind the observed re-establishing of the MAR at its initial position in this model.

By contrast, all models in which the shift in global strain rate regime was simulated show the incipient formation of a new transtensional site (Fig. 7B and C), with the NW-SE oriented shear zone acting as a plate boundary which connects the MAR to the GF. As previously shown, the encroachment of the plume head alone is sufficient (albeit with minor effects) to induce deformation in the lithosphere surrounding the MAR. When this is coupled with the NE-SW extension imposed by the regional strain field (as illustrated in Fig. 3), all requirements for a ridge jump are present. However, the formation of an transtensional shear boundary with NW-SE orientation (i.e., similar to the Terceira Rift) can be formed simply by the shift in tectonic forcing. This, therefore, not only begs the question of what the contribution of the plume to the evolution of this system is; but also of how much of the observed deformation can be attributed to this feature. One way to assess this is by comparing the results between models with and without a mantle plume while maintaining the remaining features (i.e., Fig. 7B and C vs Fig. 6 and 4, respectively). In both cases – with and without Azores Plateau – the values observed for the strain rate in the Azores domain are higher under the influence of the plume. Not just this, but the absence of the plateau causes a significant drop in the definition of the new shear zone and complete disappearance of the triangular Azores low strain domain (corresponding to a relatively stronger block, compare in Fig. 7C vs 4D). We argue that, in both cases, the increased strain rate within the Azores domain is the result of plume-induced deformation, with the impingement of the plume head causing an upwards deflection (i.e., bulging) of the lithosphere (Burov and Guillou-Frottier, 2005) and increased deformation at the surface (Wang, 2021). This is further reinforced by the relatively confined nature of this strain rate increase, as it is limited to the new Azores domain (Fig. 7B-D) and above the injection spot (Fig. 2). Despite its ability to localize strain along its edges, the interior of the Azores Plateau also contributes towards delocalization when under the effect of an encroaching mantle plume, albeit at a lower rate than standard oceanic lithosphere. As the plume impinges on the base of the lithosphere, it produces a large thermal anomaly, gradually heating up the lithosphere of the plateau, reducing its effective strength. With this decreased strength, the localization effect observed in previous models (e.g., Fig. 4) is less efficient, resulting in an overall more diffuse higher strain rate within the plateau. We suggest that this diffuse straining of the Azores Plateau, induced by lithosphere upwelling and the plume-derived thermal anomaly, could provide an explanation for the uncertainty regarding the exact location of the boundary between Nubia and Eurasia in this region (e.g., Marques et al., 2013; Fernandes et al., 2006).

There is one additional effect that can be gleaned from comparing the plume models with and without the Azores Plateau, which could be relevant for the evolution of the Azores system. As discussed previously, when the plateau is present, there is a strong strain localization effect along its edges due to the existence of rheological boundaries. By contrast, its absence promotes the existence of the diffuse high strain region. Thus, we can infer from these results that it is likely that a growing plateau would induce the migration of the deformation towards its edges. Thus, and as the formation of the Azores Plateau was not a single event but instead spread over several magmatic phases over ca. 10 Ma (e.g., Beier et al., 2022), its growth led to the systematic migration of the active deformation sites following its edges. At an early stage (ca. 10 Ma), as the motion between Eurasia and Nubia shifts and induces the present-day right-lateral motion (Potter and Szatmari, 2009; Rosenbaum et al., 2002), the Azores Plateau is represented by a small crustal thickening close to the MAR. As the stress field rotated during this period, the first NW-SE extensional features are formed, such as the Princess Alice Rift and minor volcanic edifices at the SE edge of the plateau. Over time, as the plateau grows and the crustal thickening becomes more widespread, these extensional features become inactive and most of the deformation concentrates along the NE edge of the plateau (Fig. 8B). We argue that these events are a reflection of the strain localization effects observed in the models with the Azores Plateau (both with and without mantle plumes) and can provide an explanation for the observed changes in the plate boundary in this region (e.g., Neves et al., 2013).

5. Conclusions

With this numerical modelling work, we aimed to explore how the complex interaction between a ridge-plume-transform system and the right-lateral motion between Eurasia and Nubia led to the opening of the Terceira Rift and the gradual shift from a R-R-T to a diffuse R-R-R triple junction.

Our results suggest that the principal mechanism controlling the formation and extension of the Terceira Rift (and other NW-SE oriented features) is the change in tectonic forcing imposed by the change in motion between Eurasia and Nubia during the Early Miocene, acting in tandem with the strain localization effects of the Azores Plateau. The shift towards a relative right-lateral motion between these plates induced a rotation of the local stress field, promoting the localization of transtensional shear along the edges of the plateau which, eventually, evolves into the Terceira Rift. Furthermore, under our modelling conditions, the plume-ridge-transform interaction results in the establishment of a diffusively strained Azores domain, where no distinct plate boundary can be defined. This is in-line with the presently uncertain/indistinct plate boundary between Eurasia and Nubia in the Azores.

Overall, and considering the broader tectonic implications, our models suggest that these plume-ridge-transform systems should not be interpreted as isolated systems, as they are strongly influenced by the tectonic setting in which they occur. In natural systems, any ridge-plume system will be under a constant far-field forcing, imposed by the tectonic setting at stake, which will control the orientation and distribution of any geometric reorganization which is forced due to the plume-induced MAR disruption. There are over 20 possible configurations of triple junctions and more than 100 examples on Earth today (Cronin, 1992). However, only a few have been studied with the depths of the Azores. Understanding how the Azores is evolving thus provides a unique opportunity to understand how triple junction evolve. In particular, because they are unstable and sensitive to large-scale plate reorganization. Furthermore, intra-oceanic rifts, such as the Terceira Rift, are rare and have important implications for the evolution of Earth-like plate tectonics. Understanding how they nucleate and evolve are also of key importance. In this case, the new rift seems to have formed as the result of the interaction of a plume with a triple-junction during an episode of plates reorganization.

From this, we hope that future works aim to explore this problematic in other plume-ridge-transform triple junction sites, such as the Galapagos, as well as assess how a growing oceanic plateau could impact the evolution of these systems. Such work will be fundamental in understanding how the everchanging changing global tectonic settings influence the evolution of oceanic basins.

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7. Credit statement

Conceptualization: JA, JD, FR, RR, RF; **Data curation:** JA, JD, FR, RR, RF; **Formal analysis:** JA, JD, FR, RR, RF; **Funding acquisition:** RF; **Investigation:** JA, JD, FR, RR, RF; **Methodology:** JA, JD, FR, RR, RF; **Project administration:** RF; **Validation:** JA; **Visualization:** JA; **Writing – original draft:** JA, RF; **Writing – review & editing:** JA, JD, FR, RR, RF

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Appendix A. Model limitations

The presented models aim to explore how the Azores system may have been shaped by the complex interactions between a mantle plume, the MAR and the relative motions between Eurasia and Nubia. However, as with most models, any conclusion drawn must take into consideration the limitations of the methodology.

One of the limitations pertains to an existing uncertainty in the rheology of the upper mantle (e.g., King, 2016; Jain and Korenaga, 2020, and references therein). While there is some variability on the choice of rheological parameters (e.g., Table S1), it should be expected that slight variations of these parameters could lead to different results. For instance, a change in the viscosity of the ascending plume materials could result in the faster or slower ascent through the mantle, or even on determining the formation of a narrower vs. wider plume head.

On the topic of mantle plumes, there is another degree of uncertainty regarding the position of the Azores plume, specifically concerning the location of the stem in the past and the exact root depth of the plume itself (e.g, Gente et al., 2003; Silveira et al., 2006; Yang et al., 2006). Given this uncertainty, our selection of injection spot represents a compromise that may ultimately influence the evolution of our models, as a more distant injection of the plume would likely result in a different outcome.

Additionally, under our modelling setup, no two-phase flow is included. Mantle plumes are known to induce partial melting within the lithosphere (e.g., Manglik and Christensen, 2006), which not only introduces a liquid phase into the system but also weakens the local rheology (e.g., Whattam and Stern, 2015). As stated before, a weaker rheology of the Azores Plateau directly causes a wider distribution of the strain in this domain. It is likely that by adopting two-phase flow this effect would be more impactful, which suggests that our results might represent an underestimation of the strain rate in the Azores.

Furthermore, there are also some limitations regarding the initial geometry for the Azores domain used for the initial setup. As stated previously, the initial geometry selected for this study was based on the plate reconstructions for the Azores domain during the Early Miocene (e.g., Madeira, 1998; Gente et al., 2003; Miranda et al., 2015). However, there is a degree of uncertainty on any reconstruction that may influence the way through which the system will evolve. Furthermore, we assume a relatively uniform composition of the oceanic plates in our models, with no smaller scale features (such as individual formations and/or earlier fractures). While we expect these individual second-order features to not significantly contribute to the outcome of the models, their collective behaviour may contribute towards the degree of strain localization.

Another limitation is the rheology of the prescribed weak zones to simulate the fracture zones and the transform faults, all of which have been designed as being isoviscous (i.e., constant Newtonian viscosity) regions. In nature, fracture/fault zones are heterogeneous with a complex mixture of blocks and gouge which, when the stress is dropped, inevitably are cemented together to form a consistent lithology. In order to accurately replicate this type of complex rheology it is important to apply extremely fine resolutions on top of these features. As our objective was to simulate how a weak zone could influence the development of a new transtensional boundary, and not specifically simulate the dynamics of fault zones, as well due to computer power limitations to include such heterogeneities, we have adopted this simplification of assuming isoviscous rheologies.

Finally, regarding the choice of boundary conditions which usually consist of adopted kinematic impositions with the aim to replicate natural dynamics. For instance, although natural mid-ocean ridges are mostly driven by (far-field) slab-pull, ridge-push and mantle convection forces (e.g., Coltice et al., 2017), non-whole Earth models simulate the formation and evolution of these features by either directly impose known kinematic conditions (e.g., Georgen and Lin, 2002) or derive them from regional strain rates (e.g., Püthe and Gerya, 2014). While this simplification changes the effective forces in the system (e.g., removing the compression imposed by an opening ridge), it is a forceful one due to the computation power required to simulate the entire Earth system when compared to the study of a small region such as the Azores Triple Junction.

Appendix B. Complete set of modelling parameters

Table S1: Physical parameters applied in the models, for each of the different phases. The softening parameters are found in Methods section. The two values for density in the Oceanic crust column represent the plateau and general oceanic domains, respectively.

Properties	Parameters	Oceanic Crust	Weak zones	Mantle plume	Upper Mantle
Density	ρ_0 - kg/m^3	3260 / 3300	3300	3300	3300
Dislocation creep	B_n - Pa^{-n}/s^{-1}	8	-	2.50x10^4	2.50x10^4
	n	4.7	-	3.5	3.5
	E_n - J/MPa/mol	4.85x10^5	-	5.30x10^4	5.30x10^4
	V_n - m^3/mol	0	-	1.35x10^{-5}	1.35x10^{-5}
Diffusion creep	B_I - Pa^{-n}/s^{-1}	-	-	1.50x10^9	1.50x10^9
	n	-	-	1	1
	E_I - J/MPa/mol	-	-	3.75x10^5	3.75x10^5
	V_I - m^3/mol	-	-	1.35x10^{-5}	1.35x10^{-5}
Plastic flow	Cohesion - MPa	30	10	30	30
	Softened cohesion - MPa	0.3	-	-	0.3
	ϕ - degrees	0.1	15	20	20
	Softened ϕ - degrees	0.001	0.068	-	0.2
Elasticity	G - Pa	5.00x10^{10}	5.00x10^{10}	5.00x10^{10}	5.00x10^{10}
Thermal properties	Expansivity (α) - 1/K	3x10^{-5}	3x10^{-5}	3x10^{-5}	3x10^{-5}
	Conductivity (κ) - W/m/k	3	3	3	3
	Heat capacity - J/kg/K	1050	1050	1050	1050

631 ## Appendix C. Supplementary Figures

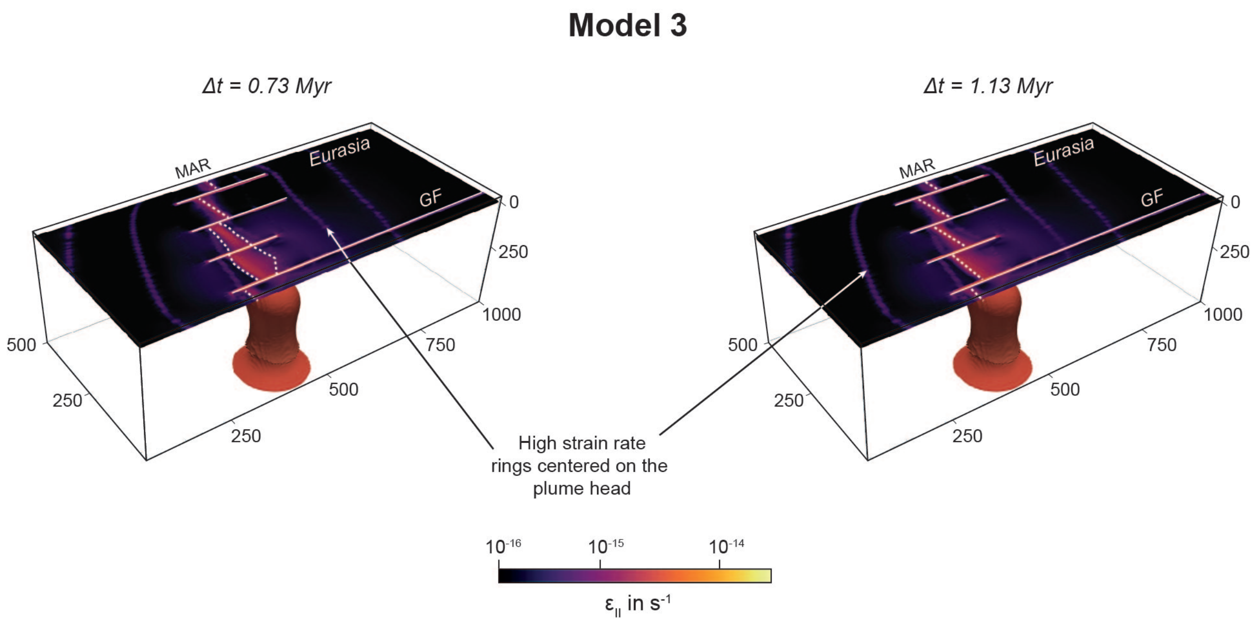

Figure S1: **Model 3 with a narrower strain rate colouring.** By observing Model 3 with a narrower range of strain rate values (compare with the ones in Fig. 7A) it is possible to observe the higher strain rate rings centred on the plume head, signalling its impact on the oceanic lithosphere above.