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Lithosphere erosion and continental breakup: Interaction of extension, plume upwelling and melting

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ABSTRACT

We present the results of thermo-mechanical modelling of extension and breakup of a heterogeneous continental lithosphere, subjected to plume impingement in presence of intraplate stress field. We incorporate partial melting of the extending lithosphere, underlying upper mantle and plume, caused by pressure–temperature variations during the thermo-mechanical evolution of the conjugate passive margin system. Effects of melting included in the model account for thermal effects, causing viscosity reduction due to host rock heating, and mechanical effects, due to cohesion loss. Our study provides better understanding on how presence of melts can influence the evolution of rifting. Here we focus particularly on the role of melting for the temporal and spatial evolution of passive margin geometry and rift migration. Depending on the lithospheric structure, melt presence may have a significant impact on the characteristics of areas affected by lithospheric extension. Pre-existing lithosphere heterogeneities determine the location of initial breakup, but in presence of plumes the subsequent evolution is more difficult to predict. For small distances between plume and area of initial rifting, the development of symmetric passive margins is favored, whereas increasing the distance promotes asymmetry. For a plume-rifting distance large enough to prevent interaction, the effect of plumes on the overlying lithosphere is negligible and the rift persists at the location of the initial lithospheric weakness. When the melt effect is included, the development of asymmetric passive continental margins is fostered. In this case, melt-induced lithospheric weakening may be strong enough to cause rift jumps toward the plume location.

1. Introduction

Processes leading to extension and rifting of lithosphere result from the interaction between mantle flow and plate movements, and involve different factors acting simultaneously. Among them, heat transfer, lithosphere structure, far field stresses, mantle flow and possibly magmatism can play a major role in determining the evolution pattern of rifting areas (e.g. Koptev et al., 2015, and ref. therein). These factors are capable of interacting, with significant feedback effects as a result, which are often difficult to predict. Plate boundary forces and lithosphere distribution are strongly influenced by mantle drag (Burov et al., 2007). At the same time the lithosphere exerts a profound effect on mantle flow (e.g. Guillou-Frottier et al., 2012).

Slab pull and roll-back, ridge push and frictional resistance provide a major contribution in the force balance controlling the plate dynamics (Bott and Kusznir, 1979). However, the role of other factors in influencing rifting style and evolution is still a matter of debate. Among these, the presence of mantle plumes is recognized as capable of playing an important role during lithosphere extension (e.g. Buck, 2004). Lithosphere impingement by the plumes may produce regional uplift driving extensional stresses (e.g. Burov et al., 2007; Burov and Gerya, 2014). Furthermore, plumes are often associated with small-scale convective instability and thermos-mechanical lithosphere erosion (e.g. Fischer and Gerya, 2016). However, previous studies (e.g. Schubert et al., 2001) show that ridge push forces, associated with mantle upwelling and resulting topographic doming, are small, or progressively decrease in comparison with plate-related far field forces. Therefore, far field forces may constitute a significant component for the development of large scale rifting and may generate the driving stress field for rift evolution (Koptev et al., 2015).

In this context, stresses causing lithosphere thinning and breakup can be divided in an “active” component, generated by mantle plumes impacting against the base of the lithosphere (e.g. Bott and Kusznir, 1979), and a “passive” component, related to

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plate movement and interaction (e.g. Cloetingh and Wortel, 1986). However, many rifting areas cannot be strictly classified in terms of either one of these two end-member components (e.g. Huismans et al., 2001; Ziegler and Cloetingh, 2004, and ref. therein).

Continental breakup leads to the creation of passive margins, with a structure reflecting their rifting development (e.g. Huismans et al., 2001; Huismans and Beaumont, 2011; Franke, 2012; Brune et al., 2014, 2016; Svartman Dias et al., 2015). Particular features of passive margins to be addressed are the magnitude of lithospheric stretching, asymmetry and magmatism. These characteristics may be strongly influenced by the presence of mantle plumes, not only due to the thermo-mechanical erosion that plumes exert at the base of the lithosphere (e.g. Burov et al., 2007; Burov and Gerya, 2014), but also due to the connection between plume presence and magmatic activity in magma-rich margins. The latter is characterized by the presence of significant volumes of melts intruding into and extruding onto the lithosphere (e.g. Menzies et al., 2002). As suggested by analytical/numerical studies (e.g. Buck, 2004) and field evidence (e.g. Wright et al., 2012), an intimate relationship may exist between rifting episodes and melts emplacement, resulting in an extension accommodated by magma filling. However, melts may result from both plumes and "plume head" upwelling (Hill, 1991), and from passive upwelling related to stretching and thinning of the lithosphere (White and McKenzie, 1989). So far, the thermo-mechanical effects of magma intrusion and underplating at lithosphere-scale remain largely unquantified, although its important role in the evolution of the crust and lithosphere has long been recognized (Ziegler and Cloetingh, 2004, and ref. therein).

Another aspect that characterizes lithospheric extension is that rift areas may be non-stationary. Many examples are documented of rift migration and jumps, especially when rifting interacts with plumes (e.g. Wilson and Hey, 1995; Einardsson, 2008). The relationships between ridge position and melt presence has been investigated in previous studies (Mittelstaedt et al., 2008), but plumes may also impinge the more heterogeneous continental lithosphere, with subsequent interaction between lithospheric structure and plume material (e.g. Bosworth et al., 2005).

In this paper we present a thermo-mechanical model for continental lithospheric extension, characterized by the presence of intra-lithospheric heterogeneities and impinged by a mantle plume. The novel aspect of this model is the incorporation of partial melting for mantle materials, as a response to pressure–temperature variations. Melts migrate upwards in response to a density difference and are emplaced at the base of the lithosphere, when their density is higher than the host rocks. Where intruded, their presence leads to a decrease of the temperature-dependent viscosity and a loss of cohesion of host rocks. Our model allows assessment of the importance of melts during the evolution of rifting areas, including the most favorable conditions that maximize their effects.

2. Model setting

2.1. Model geometry and governing equations

We constructed a 2D visco-plastic model, simulating a continental lithosphere subjected to a constant, extensional velocity, where an upper mantle layer and a plume at the base of the model are incorporated (Fig. 1). The model has a width of 1000 km and a thickness of 400 km (that is, the base of the model is constrained to the top of the mantle transition zone). It comprises 1) a two-layered crust with thickness 40 km, corresponding to an average continental crust thickness (e.g. Philpotts and Ague, 2009), where both the upper and lower crust have the same thickness (20 km), 2) a mantle lithosphere with a thickness of 80 km (e.g. Philpotts and Ague, 2009), and 3) a 280 km thick upper mantle. The shape of the plume at the onset of the simulation is a semicircle with a radius of 100 km (cf. e.g. Burov et al., 2007; Burov and Gerya, 2014). In addition, a lithosphere weakness is introduced at the boundary between lower crust and lithospheric mantle, as a square of dimension 10 km constituted by a different material from the lithosphere (see Table 1). The adopted configuration is designed for case studies where lithospheric heterogeneities occur due to the pre-rift tectonic history of the study areas. This is the case of Afar Rift, where Pan-African orogenic structures are reactivated during the Tertiary tectonic evolution, regardless of the relative plume position northward (e.g. Chorowicz et al., 1998; Bosworth et al., 2005, and ref. therein).

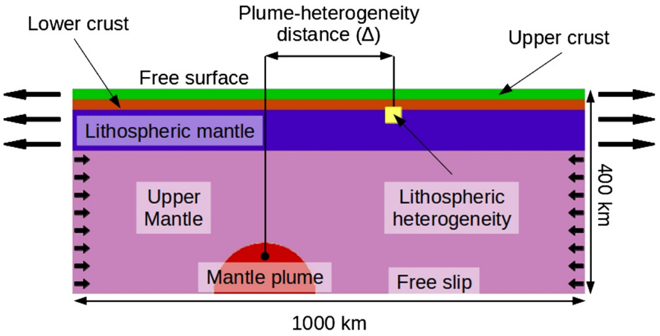

Fig. 1. Schematic representation of the model. The black arrows indicate the direction of applied velocity and relative mass outflow/inflow (see Table 1 for the adopted value).

The centers of the plume and the lithospheric weakness are equidistant from the central vertical axis of the model, and their mutual distance Δ is a parameter investigated in different simulation sets (Fig. 1). The lithosphere is subjected to an extensional velocity of 5 mm/yr at both sides of the model, compatible with slow spreading ridges and breakup areas (e.g. Wolfenden et al., 2004; McClusky et al., 2010). This velocity is appropriate for the initial configuration of the model, since larger velocities would determine a well-defined rifting area before the arrival of the plume at the base of the lithosphere, solely controlled by the position of the lithospheric weakness. Such a configuration would limit the study of the interaction between plume and lithosphere structure. The applied velocity on the lithosphere results in a mass outflow at both lateral boundaries of the model, and is counterbalanced by a mass inflow that keeps the simulation volume constant (Fig. 1). The bottom boundary condition is free slip, while a free surface is incorporated at the top boundary. Other parameters are listed in Table 1.

The code used for our simulation sets is ELEFANT, a nonlinear fluid Arbitrary Lagrangian–Eulerian (ALE) code, specifically designed for the solution of visco-plastic flow at lithospheric scale. The code is based on the algorithm already implemented in FANTOM (e.g. Thieulot, 2011), and assumes that, at a regional scale of observation and at geologic time scale, earth materials may be treated within the realm of continuum mechanics and inertial forces may be neglected (i.e. the flow Reynold number is ≈0) (e.g. Gerya, 2010). It derives that the momentum equation may be expressed as:

$$\nabla \cdot \boldsymbol{\sigma} + \rho \mathbf{g} = \mathbf{0} \tag{1}$$

where $\boldsymbol{\sigma}$ is the stress tensor, ρ is the density and $\mathbf{g}$ is the gravity acceleration vector. Materials are assumed incompressible, implying zero divergence of the velocity $\boldsymbol{v}$ tensor:

$$\nabla \cdot \boldsymbol{v} = 0 \tag{2}$$

The stress tensor $\boldsymbol{\sigma}$ can be separated into a spherical part $p\mathbf{1}$ and a deviatoric part $\boldsymbol{s}$, as follows: