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Thermo-rheological aspects of crustal evolution during continental breakup and melt intrusion: The Main Ethiopian Rift, East Africa

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ABSTRACT

The Cenozoic-Quaternary Main Ethiopian Rift (MER) is characterized by extended magmatic activity. Although magmatism has been recognized as a key element in the process of continental breakup, the interaction between melts and intruded lithosphere is still poorly understood. We have performed a 2D thermo-rheological modeling study of continental crust incorporating rheological variations due to melt intrusion-related thermal perturbation. The model is calibrated based on the characteristics of lithologies occurring in the MER and its extensional history, and includes the effect of metamorphism and anatexis on crustal strength and rheological features. During Miocene early rift phases strain in the MER was mainly accommodated through rift border faults, whereas Pliocene-to-recent extension history is characterized by magma assisted rifting with most strain accommodated across magmatic segments in the rift axis. Consequently, very little strain is distributed in the old Pan-African to Paleogene crust during Pliocene to Holocene times. The magmatic activity along the rift axis created $\approx$20 km thick magmatic segments, with growth rate estimated to range from $\approx$3.5 mm yr^{-1} to $\approx$6 mm yr^{-1}. Our model suggests that the strain transfer from Miocene rift border faults to magmatic segments was favored by a moderate increase in crustal strength, due to prograde metamorphism subsequent to the melt-induced thermal perturbation. Under such conditions, crustal stretching may not constitute an effective extension mechanism, thus strain may be preferentially accommodated by melt injection along hot, partially molten magmatic segments. Anatexis has been detected in our simulations, with melt fractions sufficient to break-up the crust solid framework and migrate. This determines local variations of rheological behavior and may induce seismicity. However, resulting melt percentages are not sufficient to induce widespread, crust-derived volcanic activity. Subsequently, volcanism in the MER is mainly due to mantle-derived melts, subjected to a various degree of fractionation, with minimal contribution from crust-derived magmas.

1. Introduction

Continental break-up is an important geodynamic process occurring during plate evolution, and may mark the response of the lithosphere when it is subject to tensional stresses of a sufficient intensity and duration. Plate rupture is the final result of the thinning and heating of the lithosphere, and is associated with upwelling of mantle material, whose decompression may lead to partial melting and subsequent magmatic activity (e.g. Ebinger and Sleep, 1998; Burov et al., 2007). This process is further enhanced when the mantle is subjected to thermal anomalies, such as in hot spot areas, where the presence of mantle plumes may also lead to lithosphere doming and extension (e.g. Burov et al., 2007; Burov and Gerya, 2014). The nature of the interaction between lithosphere- and plume-related tensile stress fields is subject to extensive debate, and their effective role in causing continental thinning and rupture (e.g. Burov et al., 2007, and references therein; Cloetingh et al., 2013). However, it is well established that mantle upwelling-related magmatic activity strongly favors plate extension and breakup (e.g. Buck, 2004, 2006). This is testified to by the collocation of extension and strong magmatic activity in many different areas, including a large number of passive continental margins worldwide. In such magmatic margins, thick sequences of igneous rocks may extrude, intrude and underplate the crust (e.g. Menzies et al., 2002). In many extensional models (e.g. Buck, 1991; Davis and Kusznir, 2004), magmatism is either absent or mainly considered as a consequence of rifting. This is in contrast with observations in extensional areas, where time relationships between igneous rocks emplacement ages and extension evolution demonstrate that magmatic activity occurs prior to, or simultaneously with, extension (e.g. Buck, 2006, and references therein). In addition, magmatic activity and rifting associated deformation may focus along inherited lithospheric heterogeneities (such as former suture zones), where the plume had the function of further triggering the rupture,

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more than being the direct cause of rifting (e.g. Cloetingh et al., 2013; Buiter and Torsvik, 2014).

The presence of lithospheric heterogeneities may influence the extensional history of rifting areas. However, the evolution of plate strength and rheology, due to melt intrusion, is still poorly understood (e.g. Lavecchia et al., 2016). One of the least investigated aspects is the lithological evolution of rifting areas and their fertility (i.e. their capacity to produce melts when subjected to temperature and pressure variation). Although most magmatic products associated with rift areas are represented by mantle-derived melts, the presence of magmas characterized by a mixed (e.g. Thompson et al., 2001) or crustal origin (e.g. Kirstein et al., 2000) has been widely recognized. This testifies the profound effect that pressure and temperature conditions may exert on the same nature of the lithosphere, and, especially, on the crust.

One of the best studied rifting areas is the Main Ethiopian Rift (MER) (Fig. 1), a slowly extending continental rift constituting the northernmost section of the East African Rift System (e.g. Ebinger and Casey, 2001). Indeed, the relationship between magmatic activity, anomalous topographic swells and the presence of mantle plumes has long been recognized in the MER region (e.g. Ebinger and Sleep, 1998). However, both the evolution of the intruded crust and its response to the thermal perturbation are still poorly understood. These two elements are of a particular importance as the mantle lithosphere in this region is characterized by a marked thinning beneath the whole area (e.g. Ebinger and Sleep, 1998; Dugda et al., 2007), suggesting a major role of crust rheology in determining the strength of the whole plate.

In this paper, we present a thermo-mechanical model with the aim to examine the rheology variations of a continental crust subjected to a melt intrusion-related thermal perturbation. Our model includes temperature-induced metamorphic variations in crustal mineralogical association. The model characteristics have been calibrated adopting MER lithological and geometrical constraints, with the aim to better understand the evolution of the Ethiopian continental crust during the development of magma segments characterizing the axial rifting area.

2. Tectonic setting

The Main Ethiopian Rift (MER) (Fig. 1) constitutes the northern part of the East African Rift System (e.g. Ebinger and Casey, 2001) and converges, together with the Red Sea and Gulf of Aden rifts, in the Afar area. Among the three branches, it is the youngest and least evolved (e.g. Bastow et al., 2011, and references therein). The onset of extension in the MER is dated at ≈11–10 Ma (e.g. Ukstins et al., 2002; Wolfenden et al., 2004) within the Precambrian metamorphic crustal basement of the Pan-African Mozambique belt (Kazmin et al., 1978) and was mostly accommodated along mid-Miocene border faults delineating half-grabens (Morley, 1988; Wolfenden et al., 2004). The last phases of extension are characterized by an intense magmatic activity, leading to the construction of approximately 20 km thick, right-stepping, en echelon magmatic segments during the Pliocene-Pleistocene time (Ebinger and Casey, 2001; Beutel et al., 2010, and references therein; Bastow et al., 2011).

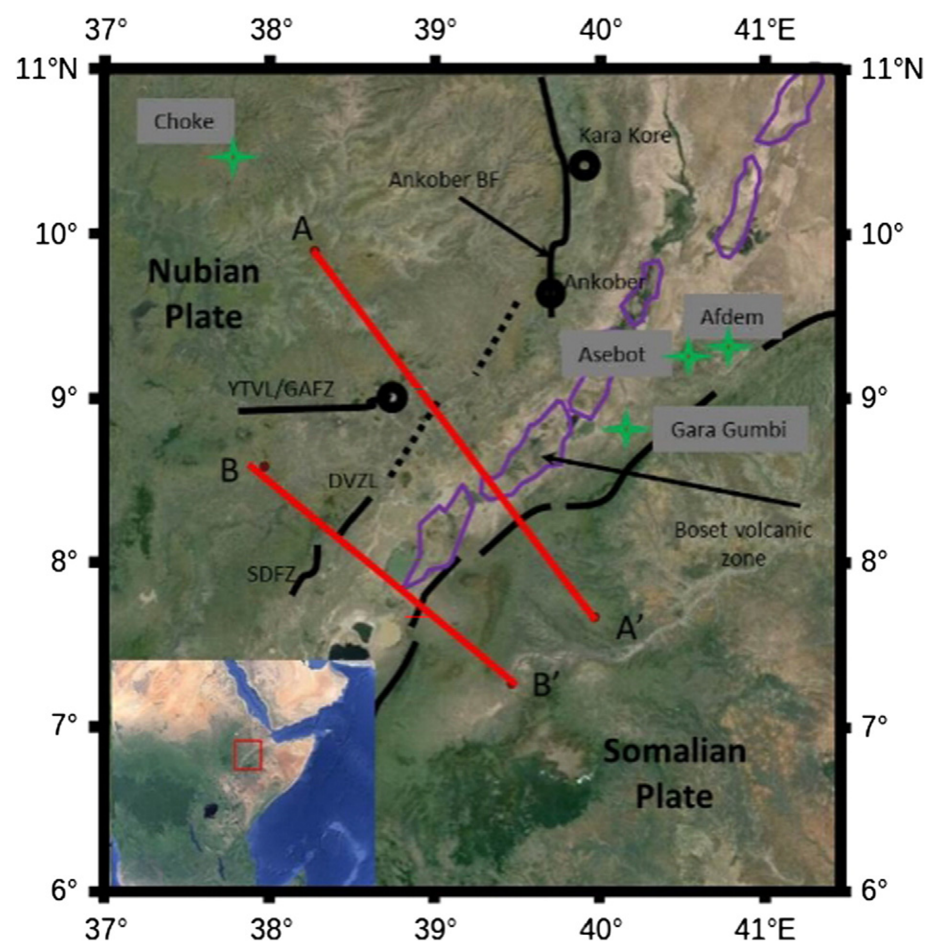

Fig. 1. Sketch map of Afar Rift and northern Main Ethiopian Rift (after Bastow et al., 2011, modified). Violet closed lines represent magmatic segments and solid black lines depict major mid-Miocene border faults. Dashed lines are faulted monoclines. Green stars are selected Cenozoic volcanoes. Red lines are the traces of gravimetric cross sections adopted for simulations (AA″: Cornwell et al., 2006; BB′: Mahatsente et al., 1999; see Fig. 2). SDFZ—Silti Debre Zeyit fault zone; GAFZ—Guder Ambo fault zone; YTVL—Yerer-Tullu Wellel volcanotectonic lineament. BF—Border Fault; DZVL—Debre Zeit Volcanic Lineament.