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Thermal models of dyke intrusion during development of continent–ocean transition

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ABSTRACT

A consensus has emerged in recent years from a variety of geoscientific disciplines that extension during continental rifting is achieved only partly by plate stretching: dyke intrusion also plays an important role. Magma intrusion can accommodate extension at lower yield stresses than are required to extend thick, strong, unmodified continental lithosphere mechanically, thereby aiding the breakup process. Dyke intrusion is also expected to heat and thereby weaken the plate, but the spatial extent of heating and the effect of different rates of magmatic extension on the timescales over which heating occurs are poorly understood. To address this issue, a numerical solution to the heat-flow equation is developed here to quantify the thermal effects of dyke intrusion on the continental crust during rifting. The thermal models are benchmarked against a priori constraints on crustal structure and dyke intrusion episodes in Ethiopia. Finite difference models demonstrate that magmatic extension rate exerts a first-order control on the crustal thermal structure. Once dyke intrusion supersedes faulting and stretching as the principal extensional mechanism the crust will heat and weaken rapidly (less than 1 Ma).

In the Main Ethiopian Rift (MER), the majority of present-day extension is focused on ~20 km-wide Quaternary-Recent axial magmatic segments that are mostly seismogenic to mid-crustal depths and show P-wave seismic velocities characteristic of heavily intruded continental crust. When reviewed in light of our models, these observations require that no more than half of the MER's extension since ~2 Ma has been achieved by dyke intrusion. Magmatic heating and weakening of the crust would have rendered it aseismic if dyke intrusion accounted for the entire 6 mm/yr extension rate. In the older, faster extending (16 mm/yr) Red Sea rift (RSR) in Afar, dyke intrusion is expected to have had a more dramatic impact on crustal rheology. Accordingly, effective elastic plate thickness and Moho depth in the Danakil region of northernmost Afar are markedly reduced and seismicity is shallower than in the MER. Thermally driven variations in crustal rheology over time in response to dyke intrusion thus play an important role in the development of continent–ocean transition.

1. Introduction

It is well established that continental rifts develop initially in a mechanical fashion, with along axis segmentation governed by large-scale border faults defining early half-graben rift morphology (e.g., Hayward and Ebinger, 1996). A consensus is gradually emerging from a number of tectonically active rifts and rifted continental margins worldwide, however, that magma intrusion also plays an important role in extension prior to the onset of seafloor spreading (e.g., Maguire et al., 2006; White et al., 2008; Thybo and Nielsen, 2009). This is an appealing idea, since it obviates the need for large-scale tectonic forces to rupture thick, strong cratonic lithosphere: dyke intrusion can occur at lower stresses than are required for the stretching of thick continental lithosphere (e.g., Buck 2004, 2006; Bialas et al., 2010). However, the subsequent effect of magma intrusion on the thermal structure (and by inference, the strength) of the plate over time is poorly understood. It likely has important implications for the thermal evolution and subsidence history of the extending plate (e.g.,

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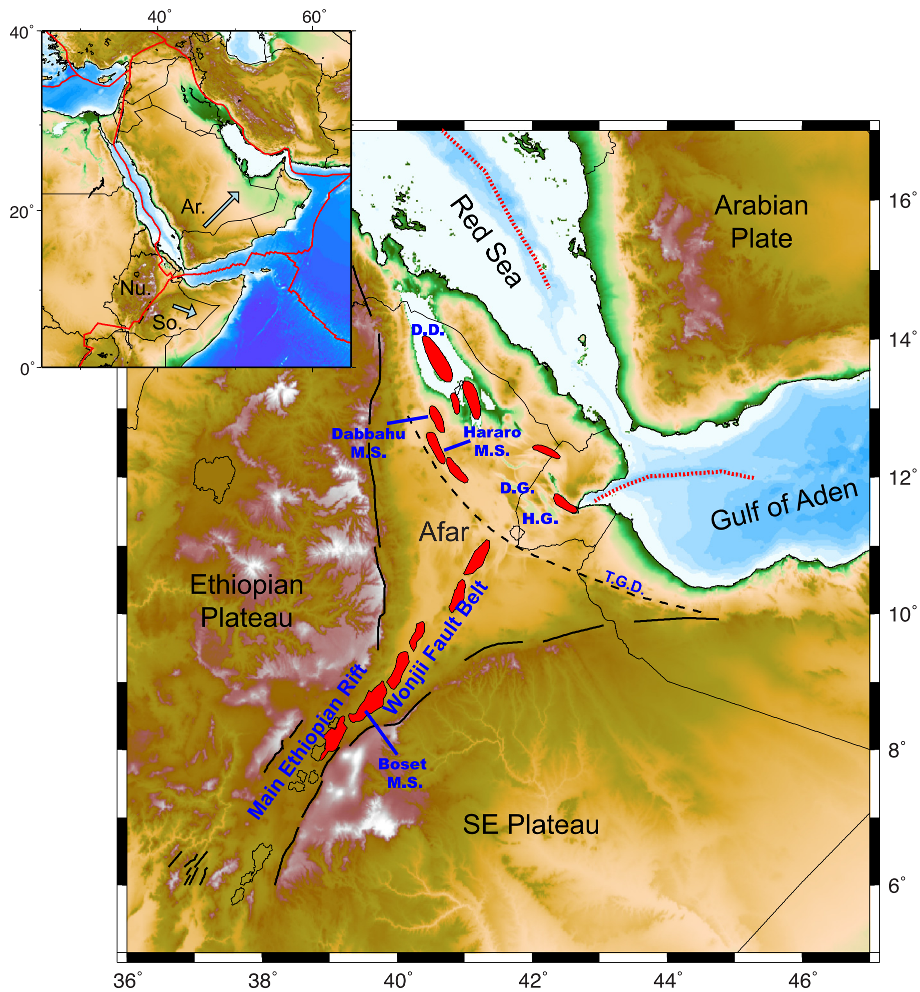

Fig. 1. Tectonic setting of the East African rift system in the Horn of Africa. Solid black lines show Oligocene–Miocene border faults of the Red Sea, Gulf of Aden and East African rifts. Red segments show the Quaternary–Recent sub-aerial rift axes. DD: Danakil Depression. TGD: Tendaho-Goba'ad Discontinuity. MS: magmatic segments. DG: Dobi Graben. HG: Hanli Graben. Dashed red lines are sea-floor spreading centres in the Red Sea and Gulf of Aden. Top left inset: topography of NE Africa and Arabia. Arrows show plate motions relative to a fixed Nubian plate. Red lines are plate boundaries.

Thybo and Nielsen, 2009), including whether or not continent–ocean transition is heralded by an abrupt episode of continental plate thinning and subsidence after a period of heating and weakening by protracted magma intrusion (Bastow and Keir, 2011; Keir et al., 2013).

To address these issues, a thermal model is developed to understand better the evolution of continental crust during extension by dyke intrusion. The model space is parameterised as an array of cells for which the heat-flow equation is solved numerically by finite difference scheme. The effects of variable magma temperature, dyke injection frequency and size, and geothermal gradient on the thermal evolution of the crust over time during rifting are tested by mapping the solidus and 600 °C isotherm (representing the brittle–ductile transition temperature) positions. In a tectonically active rift this is a testable hypothesis seismically, since crustal seismicity is not expected to develop at temperatures greater than ∼600 °C (e.g., Maggi et al., 2000a).

To ground-truth the thermal models and input parameters, this study draws on geoscientific constraints from on-going extension in the East African (EAR) and Red Sea (RSR) rift systems in Ethiopia (Fig. 1). The region exposes sub-aerially several sections of asynchronous rift sector development above a hot (e.g., Rooney et al., 2012; Ferguson et al., 2013), low wavespeed (Bastow et al., 2008) mantle; from embryonic continental rifting in the slowly (∼6 mm/yr) extending Main Ethiopian rift (MER) in the south (Kogan et al., 2012), to incipient oceanic spreading in the more rapidly extending RSR and Gulf of Aden Rift in Afar (e.g., Hayward and Ebinger, 1996; McClusky et al., 2010). Real-time geodetic and seismic observations of dyke intrusion episodes (Wright et al., 2006; Keir et al., 2009; Grandin et al., 2011) are available from the region, offering considerable advantage over studies of extinct or buried rifted margins in constraining when and how dykes intrude the crust. The region is also well-understood geophysically, with detailed constraints on parameters such as crustal thickness, effective elastic plate thickness and P-wave seismic velocity structure all available (for reviews, see e.g., Bastow et al., 2011; Keir et al., 2013).

In the MER, a combination of GPS surveys and structural geology studies point towards ∼80% of present-day strain being accommodated at least partly by magma intrusion within a relatively narrow (∼20 km) rift-axial zone, also known as the Wonji Fault Belt (WFB: Mohr, 1967; Ebinger and Casey, 2001). However, precisely what proportion of extension has been accommodated by dyke intrusion into the still-thick MER crust since ∼2 Ma is uncertain. In the Danakil depression, where crustal thickness is markedly thinner than elsewhere in Afar (Makris and Ginzburg, 1987), it has been proposed that Pliocene–Recent basin development and voluminous Quaternary volcanism are the result of a late-stage of plate stretching following a protracted period of localised magma-intrusion (Bastow and Keir, 2011; Keir et al., 2013). This study explores whether episodes of dyke intrusion during continental breakup are capable of heating the continental crust sufficiently