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Upper mantle temperature and the onset of extension and break-up in Afar, Africa

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ABSTRACT

It is debated to what extent mantle plumes play a role in continental rifting and eventual break-up. Afar lies at the northern end of the largest and most active present-day continental rift, where the East African Rift forms a triple junction with the Red Sea and Gulf of Aden rifts. It has a history of plume activity yet recent studies have reached conflicting conclusions on whether a plume still contributes to current Afar tectonics. A geochemical study concluded that Afar is a mature hot rift with 80 km thick lithosphere, while seismic data have been interpreted to reflect the structure of a young, oceanic rift basin above mantle of normal temperature. We develop a self-consistent forward model of mantle flow that incorporates melt generation and retention to test whether predictions of melt chemistry, melt volume and lithosphere–asthenosphere seismic structure can be reconciled with observations. The rare-earth element composition of mafic samples at the Erta Ale, Dabbahu and Asal magmatic segments can be used as both a thermometer and chronometer of the rifting process. Low seismic velocities require a lithosphere thinned to 50 km or less. A strong positive impedance contrast at 50 to 70 km below the rift seems linked to the melt zone, but is not reproduced by isotropic seismic velocity alone. Combined, the simplest interpretation is that mantle temperature below Afar is still elevated at 1450 °C, rifting started around 22–23 Ma, and the lithosphere has thinned from 100 to 50 km to allow significant decompressional melting.

1. Introduction

The Afar region in northern Ethiopia forms the northern tip of the largest and most active present-day continental rift, where the Main Ethiopian Rift (MER) intersects the Red Sea Rift and the Gulf of Aden (Fig. 1). Beneath the Red Sea Rift, crust is thinned to about 15 km (Markis and Ginzburg, 1987; Hammond et al., 2011), volcanism is much more wide spread than in the MER, and much of the region has subsided below sea level in the past few million years, observations that point to the region being in transition from rifting to spreading (Markis and Ginzburg, 1987; Hayward and Ebinger, 1996; Bastow and Keir, 2011).

Afar is generally considered as a classic example of plume involvement in rifting, as it is flanked by ∼30 million year old flood basalts that erupted as rifting started in the Gulf of Aden and Red Sea (Hofmann et al., 1997). Past and recent volcanism exhibits geochemical characteristics generally found in ocean island basalts, such as high ^{3}He/^{4}He ratios, and trace element and isotopic enrichments (Schilling et al., 1992; Pik et al., 2006; Ferguson et al., 2013). Furthermore, seismic velocities in the mantle below Afar are extremely low, as might be expected for high temperatures (e.g. Bastow and Keir, 2011). Yet, recent observations have questioned whether a plume is still involved in the present-day tectonics of the region.

Based on seismic *S*-to-*P* receiver functions and geodynamic modelling, Rychert et al. (2012) proposed that lithosphere–asthenosphere structure beneath the Afar is similar to a mid-ocean ridge system: with shallow melt generation (<80 km) due to adiabatic decompression of mantle with a potential temperature of roughly

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1350 °C. Seismic travel-time tomography (Hammond et al., 2013) finds low seismic velocities under Afar consistent with such a shallow melt zone. At the other end of the debate, Ferguson et al. (2013) used the trace element composition of mafic lavas from Afar and petrogenetic modelling to argue that the erupted magmas are predominantly generated below a still thick lithosphere, at depths greater than 80 km, and at mantle potential temperatures close to 1450 °C. This temperature is more consistent with major element composition of lavas within the northern part of the East African Rift system, which suggest an elevated potential temperature of between 1370 and 1490 °C for rocks erupted in the last 10 Ma (Rooney et al., 2012b).

A central question is therefore whether there is still currently active rifting and the up-welling of deep and hot (>1400 °C) mantle material, which is possibly rooted in the African Superplume (e.g. Nyblade, 2011). The other possibility is that today Afar has evolved to the point of steady passive up-welling of the asthenosphere. Although estimates of the mantle potential temperature beneath Afar for these respective scenarios both lie between 1350 and 1490 °C, this range represents the difference between either minimal volcanism or the generation of a significant amount of melt (White and McKenzie, 1995; Armitage et al., 2010). Knowledge of how mantle temperature and lithospheric thinning have evolved in Afar is therefore essential to understanding which key tectonic and/or magmatic processes are driving the continued development of this rift system.

In this study we attempt to reconcile the seemingly contradictory geochemical and geophysical observations with a single tectonic scenario. We develop a set of models of lithospheric extension and mantle melting and compare the model predictions to observations of melt volume, melt chemistry, bulk seismic velocities and discontinuities of the lithosphere–asthenosphere. We focus on three regions of Afar where both seismic and geochemical constraints are available: (1) the Erta Ale rift zone, within the northern Danakil Depression, which is near the northwestern end of the main active rift, (2) the Dabbahu magmatic segment in central Afar, near the border of the rift zone, and (3) the Asal rift zone at the southeastern end of the Afar rift zone and the western edge of the Gulf of Aden (Fig. 1).

2. Methods

We use a relatively straightforward 2-D geodynamic model of extension of a viscous lithosphere–asthenosphere system and decompressional melting to explore the effect of mantle temperature on rift evolution. Modelling extension within the region of the Danakil Depression and Asal Rift as a 2-D process is reasonable given that extension is perpendicular to the rift axis (Fig. 1).

2.1. Geodynamic model

Evolution of upper mantle temperature and flow is modelled as Stokes flow driven by a divergent upper velocity boundary condition and a temperature difference between the surface and model base (Armitage et al., 2010). The most likely rheology for continental lithosphere and sublithospheric mantle is a temperature and pressure dependent dislocation creep (e.g. Lévy and Jaupart, 2011). We use a formulation that includes the effect of melt-weakening and dehydration strengthening (see Supplementary Material; Armitage et al., 2010). Thermal state and non-Newtonian viscous flow are solved in the finite-element code CitCom (Moresi et al., 1996). We use a 2800 km wide by 700 km deep 2-D Cartesian domain containing 512 by 512 equally spaced nodes, providing a resolution of 5.6 by 1.4 km.

Solid-mantle density in the models changes as a function of temperature, melt retention, and melt depletion, providing buoyant flow due to melt generation. Melt production is calculated as a function of temperature, pressure and previous depletion (Scott, 1992; Phipps Morgan, 2001; Nielsen and Hopper, 2004; see Supplementary Material). Melt starts once the hydrous solidus is crossed, where up to 2% melt can be generated until temperature exceeds the dry solidus. We include a hydrous solidus as there is evidence of some water within the volcanics in Afar (e.g. Pik et al., 1999). Melt generated is assumed to be transported vertically by Darcy flow, using the methods described in Goes et al. (2012), for more explanation see the Supplementary Material.

Solid mantle-flow boundary conditions are a prescribed symmetric divergent-flow velocity condition on the top and free slip on the sides and base. Temperature boundary conditions are fixed temperature at the base (a mantle potential temperature of 1350, 1450 or 1550 °C) and the top (0 °C), and a zero normal temperature gradient at the sides. The initial condition is a 100, 150 or 200 km thick lithosphere defined by a linear increase in melt depletion (from 0% at the base to 50% at the surface) and reduction in temperature from the basal temperature condition at 100 km depth to 0 °C at the surface. The high buoyancy is to keep the high viscosity lithosphere at the top of the model domain. This material, due to its buoyancy, does not participate in the melting as it remains above the solidus and is moved to the sides due to the divergent boundary condition.

2.2. Melt chemistry

Partitioning of REEs between the solid mantle and partial melt is calculated from the melt depletion, temperature and pressure within the melt region assuming incremental batch melting (see Dean et al., 2008; Gibson and Geist, 2010; Armitage et al., 2011; and the Supplementary Material). Geochemical and isotopic evidence from erupted melts shows that mantle source beneath Afar is fertile compared to the depleted upper mantle source of MORBs (e.g. Schilling, 1973; Schilling et al., 1992; Barrat et al., 1998; Rooney et al., 2012a; Ferguson et al., 2013), and that this fertile source has been a long-lived feature of the mantle here (Pik et al., 1999). To examine how the extent and depths of melting evolve during rift development we calculate the REE concentration of melts generated by partial melting of mantle upwelling beneath the extending lithosphere. For the source we use a fertile mantle composition from McDonough and Sun (1995).

2.3. Conversion to seismic velocities

The models are converted to synthetic seismic structure (compressional velocity, V_P, shear velocity, V_S, density, and shear attenuation, Q_S) following the methods described in Goes et al. (2012). A thermodynamic formulation is used to determine elastic parameters and density as a function of temperature, pressure, composition, and phase, using the mineral parameter compilation of Xu et al. (2008), and the code PerPleX from Connolly (2005). For the fertile mantle we use a peridotite composition, and for the depleted mantle a harzburgite, both from Xu et al. (2008). Seismic velocities are not sensitive to more detailed variations in composition, so we linearly grade between these compositions as a function of degree of depletion (see Goes et al., 2012). Subsequently, we correct for shear attenuation using a semi-empirical temperature, pressure and dehydration dependent Q model, Q_g in Goes et al. (2012). We assume that the reference mantle is damp, as estimated for an MORB-source (1000 H/10^6 Si; Hirth and Kohlstedt, 1996).

The presence of melt is in most models assumed to only affect the elastic response (Hammond and Humphreys, 2000a; Gribb and Cooper, 2000). We chose the melt derivatives for cuspate melt geometries from Hammond and Humphreys (2000b): a 7.9%