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Geochemical evidence of mantle reservoir evolution during progressive rifting along the western Afar margin

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Abstract

The Afar triple junction, where the Red Sea, Gulf of Aden and African Rift System extension zones converge, is a pivotal domain for the study of continental-to-oceanic rift evolution. The western margin of Afar forms the southernmost sector of the western margin of the Red Sea rift where that margin enters the Ethiopian flood basalt province. Tectonism and volcanism at the triple junction had commenced by ~31 Ma with crustal fissuring, diking and voluminous eruption of the Ethiopian-Yemen flood basalt pile. The dikes which fed the Oligocene-Quaternary lava sequence covering the western Afar rift margin provide an opportunity to probe the geochemical reservoirs associated with the evolution of a still active continental margin. $^{40}Ar/^{39}Ar$ geochronology reveals that the western Afar margin dikes span the entire history of rift evolution from the initial Oligocene flood basalt event to the development of focused zones of intrusion in rift marginal basins. Major element, trace element and isotopic (Sr-Nd-Pb-Hf) data demonstrate temporal geochemical heterogeneities resulting from variable contributions from the Afar plume, depleted asthenospheric mantle, and African lithosphere. The various dikes erupted between 31 Ma and 22 Ma all share isotopic signatures attesting to a contribution from the Afar plume, indicating this initial period in the evolution of the Afar margin was one of magma-assisted weakening of the lithosphere. From 22 Ma to 12 Ma, however, diffuse diking during continued evolution of the rift margin facilitated ascent of magmas in which depleted mantle and lithospheric sources predominated, though contributions from the Afar plume persisted. After 10 Ma, magmatic intrusion migrated eastwards towards the Afar rift floor, with an increasing fraction of the magmas derived from depleted mantle with less of a lithospheric signature. The dikes of the western Afar margin reveal that magma generation processes during the evolution of this continental rift margin are increasingly dominated by shallow decompressional melting of the ambient asthenosphere, the composition of which may in part be controlled by preferential channeling of plume material along the developing neo-oceanic axes of extension.

1. INTRODUCTION

Early quantitative tectonic models explained the generation of mantle melt in extensional zones in terms of simple adiabatic decompression of the asthenosphere (e.g., White and McKenzie, 1989). However, the stresses required to rupture typical continental lithosphere may not be available from plate tectonic processes alone, and hybrid models were subsequently developed in which magma provides additional impetus for lithospheric rifting (e.g., Buck, 2004; Buck, 2006; Bialas et al., 2010). Lateral variations in lithospheric thickness and rheology may also localize strain and magmatism during rifting (e.g., Ebinger and Sleep, 1998; van Wijk et al., 2008). Upwelling, buoyant asthenosphere contributes to plate driving forces, and may generate significant volumes of melt across a broad re-

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gion (e.g., Huismans et al., 2001). The presence of buoyant melt can facilitate the intrusion of dikes into thick continental lithosphere at comparatively small extensional stresses, and this heating can significantly reduce the strength of the plate, further facilitating extension (e.g., Fialko and Rubin, 1999; Buck, 2004; Bialas et al., 2010). Thus, the initial phase of rifting above a mantle plume may be marked by a pulse of widespread dike intrusion (e.g., Renne et al., 1996; Fialko and Rubin, 1999; Klausen and Larsen, 2002). During the later stages of continental rifting, extension occurs principally by dike intrusion into a thinned lithosphere (Ebinger and Casey, 2001; Keranen et al., 2004; Rooney et al., 2005; Daly et al., 2008; Keir et al., 2009; Bastow et al., 2010; Ebinger et al., 2010; Wright et al., 2012), before a final stage of plate stretching and associated decompression melting characterizing the final stages of continent-ocean transition (e.g., Bastow and Keir, 2011). Key unresolved questions remain concerning the geochemical signature(s) of the melt sources during the initial stages of continental rifting, and the evolution of these sources as rifting continues.

The mafic lavas and dikes of continental rift margins provide a window on the evolution of the underlying mantle sources that have contributed to a developing rift. Unfortunately, most rifted margins are now at least partly submarine and relatively inaccessible. However, sustained uplift above an active mantle plume in Ethiopia has provided a sub-aerial instance of a continental rift margin in the final stages of its evolution. Observations around the Afar triple-rift junction confirm that magmatic intrusion and crustal heating have played a significant role in facilitating lithospheric extension and rupture (Berckhemer et al., 1975; Mohr, 1983a; Buck, 2004; Buck, 2006; Bialas et al., 2010; Bastow and Keir, 2011). The western margin of Afar provides an excellent site for probing the space–time relationships between magmatism and extension across a rift margin (e.g., Keir et al., 2011b). In this paper we examine the geochemical, structural, and geochronological properties of the dikes that intrude this continental margin, and explore the participation of the various mantle and lithospheric geochemical reservoirs that contribute to the evolution of this margin.

2. THE WESTERN AFAR RIFT MARGIN

2.1. Setting and form

The well-studied western Afar margin separates the stable and relatively undeformed post-basement cover of the Ethiopian Plateau to the west from the Cenozoic and presently active extensional faulting, fissuring, and magmatism of the Afar depression (Gortani and Bianchi, 1937; Abbate et al., 1968; Abbate and Sagri, 1969; Mohr, 1971; Megrue et al., 1972; Gortani and Bianchi, 1973; Justin-Visentin and Zanettin, 1974; Mohr, 1983a; Hart et al., 1989; Wolfenden et al., 2005). The 800-km long western Afar margin runs in a gently curvilinear plan from Asmara in the north to Addis Ababa in the south, with the exception of a large dextral offset at latitude 13°N (Fig. 1). This coincides with the northern limit of the thick flood-lava sequence on the plateau, and also marks a structural contrast: to the north, seismically active stepped normal faults downthrown towards the rift are concentrated within a narrower margin (40 km); to the south, antithetically faulted flood-basalts cap a wider (80 km) monoclinal margin (Mohr, 1962; Abbate and Sagri, 1969; Ayele et al., 2007; Keir et al., 2011a). This southern sector of the margin can in turn be divided into two sub-sectors to either side of a proposed accommodation zone (Wolfenden et al., 2005). North of latitude 11°N, the flood-basalt pile comprises 31–29 Ma lavas and tuffs locally overlain by a cover of ~25–22 Ma flows (Justin-Visentin and Zanettin, 1974; Kieffer et al., 2004). Proceeding south from 11°N to Addis Ababa, the Oligocene flood-basalt pile is capped by progressively younger lavas that include a volumetrically significant proportion of silicic members (Zanettin, 1992; Ukstins et al., 2002). The margin transect chosen for this study is located immediately north of the chronological divide at 11°N (Fig. 1), taking advantage of the Desse-Eloa highway (Mohr, 1971; Gortani and Bianchi, 1973).

2.2. Regional stratigraphy

Expanding upon earlier studies detailing the stratigraphic and structural characteristics of the western Afar margin (Abbate et al., 1968; Gortani and Bianchi, 1973; Justin-Visentin and Zanettin, 1974; Mohr, 1983b), a new stratigraphy for the entire southern sector of the western Afar margin has been compiled by Wolfenden et al. (2005). It comprises four magmatic episodes (Table 1) which relate to a sequential, riftward production of three elongate rift-parallel volcanic basins imposed on the regional Oligocene flood-basalt pile:

The ‘Stage 1 Basin’ developed at the western end of the transect, contemporaneous with eruption of basalts and agglomerates derived from the 25–22 Ma-old Guguftu shield volcano located on the plateau rim (Kieffer et al., 2004). These Dese Formation lava flows are rarely more than a few meters thick, and lie with local unconformity on the lateritized and strongly zeolitised Oligocene pile. Characteristic lithologies are megacrystic plagioclase basalt, aphyric basalt, and subordinate olivine- and olivine-augite-phyric basalt. The pyroclastic members include fine basaltic tuff (in one instance carrying blocks of underlying, unexposed Jurassic limestone) and massive agglomerate proximate to basalt pipe vents. Silicic ash-fall and ash-flow tuff beds are restricted to the topmost part of the Dese Formation. The ‘Stage 2 Basin’ is situated near the median of the Desse-Eloa transect. Its fill of flood basalts and intercalated ignimbrites compose the early-mid Miocene Burka Formation (Wolfenden et al., 2005), again lying with unconformity on the Oligocene stratoid pile. The ‘Stage 3 Basin’ at the eastern end of the transect contains the late Miocene-Pliocene Dahla Series basalts, previously termed Fursa Basalts (Justin-Visentin and Zanettin, 1974).

2.3. Dikes and faults of the Desse–Eloa transect

Antithetic faulting parallel to the NNW regional strike of the margin has produced tilted crustal blocks typically