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Geochimica et Cosmochimica Acta 185 (2016) 418–434

Geochimica et Cosmochimica Acta

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Evolution of the East African rift: Drip magmatism, lithospheric thinning and mafic volcanism

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Received 30 July 2015; accepted in revised form 21 March 2016; available online 1 April 2016

Abstract

The origin of the Ethiopian-Yemeni Oligocene flood basalt province is widely interpreted as representing mafic volcanism associated with the Afar mantle plume head, with minor contributions from the lithospheric mantle. We reinterpret the geochemical compositions of primitive Oligocene basalts and picrites as requiring a far more significant contribution from the metasomatized subcontinental lithospheric mantle than has been recognized previously. This region displays the fingerprints of mantle plume and lithospheric drip magmatism as predicted from numerical models. Metasomatized mantle lithosphere is not dynamically stable, and heating above the upwelling Afar plume caused metasomatized lithosphere with a significant pyroxenite component to drip into the asthenosphere and melt. This process generated the HT2 lavas observed today in restricted portions of Ethiopia and Yemen now separated by the Red Sea, suggesting a fundamental link between drip magmatism and the onset of rifting. Coeval HT1 and LT lavas, in contrast, were not generated by drip melting but instead originated from shallower, dominantly anhydrous peridotite. Looking more broadly across the East African Rift System in time and space, geochemical data support small volume volcanic events in Turkana (N. Kenya), Chyulu Hills (S. Kenya) and the Virunga province (Western Rift) to be derived ultimately from drip melting. The removal of the gravitationally unstable, metasomatized portion of the subcontinental lithospheric mantle via dripping is correlated in each case with periods of rapid uplift. The combined influence of thermo-mechanically thinned lithosphere and the Afar plume together thus controlled the locus of continental rift initiation between Africa and Arabia and provide dynamic support for the Ethiopian plateau.

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1. INTRODUCTION

The East African Rift System is the archetypal example of young continental rifting. It defines a 3000-km long feature where modern seismicity and volcanism are superposed on volcanic rocks and topography that date locally from the Eocene through the Oligocene (Fig. 1). As such, it provides a natural laboratory for investigating processes operating in the continental crust, the mantle lithosphere and the underlying asthenosphere that govern magmatism, uplift and rifting at both local and global scales. The East African Rift extends southward from the Afar depression and transects two areas of elevated topography, the Ethiopia and Kenya domes, separated by the highly extended Turkana depression. The modern topographic profile is commonly interpreted as reflecting thermal uplift created by upwelling material associated with the African superplume (Ebinger et al., 1989; Ritsema et al., 1999; Grand, 2002; Simmons et al., 2007; Hansen et al., 2010). Recent

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http://dx.doi.org/10.1016/j.gca.2016.03.024
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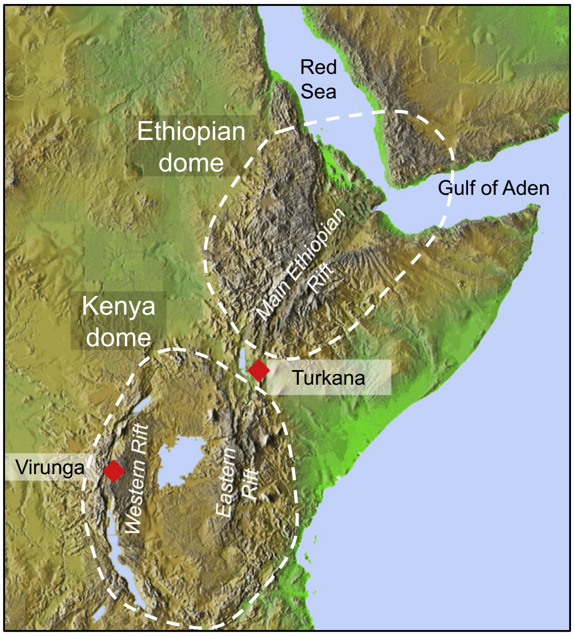

Fig. 1. Digital elevation map of Eastern Africa (http://www.open.ac.uk/earth-research/drury/files/neafrica.gif) showing approximate extent of the topographically elevated regions cut by the modern East African Rift System. Diamonds indicate the Turkana and Virunga volcanic provinces.

geophysical data provide strong support for both the existence of this major deep mantle feature and the likelihood that it contributes both heat and material across the 660 km discontinuity (Adams et al., 2012). Still, important questions remain as to the nature and extent of interaction between plume-related processes or materials and the evolving subcontinental lithospheric mantle beneath this region.

Of particular interest is the degree to which mafic lavas sample asthenospheric and lithospheric source domains over time. The Oligocene Afar and Yemeni flood basalt provinces are consistently interpreted as products of the Afar plume head, with varying contributions from both upper and lower lithospheric domains (e.g., Baker et al., 1996a; Pik et al., 1999; Kieffer et al., 2004; Furman et al., 2006a, Furman, 2007; Rogers, 2006; Meshesha and Shinjo, 2007; Beccaluva et al., 2009, 2011; Nelson et al., 2012). Here we reconsider the abundant published data on these 30 Ma flood basalts and other key eruptive provinces of the East African Rift in light of recent advances in understanding lithospheric instability related to heating with or without a mantle plume (Elkins-Tanton, 2007; Ducea et al., 2013). We seek to broaden the dialogue around East African Rift System mafic volcanism beyond the existence of one or more mantle plumes or plume offshoots and towards a richer, mechanistic model for evolution of the continents over geologic time. Specifically, we explore the role of lithospheric drip melting in generating the observed range of mafic lavas erupted along the East African Rift.

The major and trace element composition of the average continental crust is inconsistent with a one-step production from the mantle through magmatism (e.g., Rudnick, 1995). At a global scale, these major and trace element issues can be reconciled if mafic residua is lost back into the mantle through dripping and delamination; this hypothesis is based on strong physical models and makes predictions matching observations, and thus forms one of the best arguments for lithospheric foundering. An important prediction is that magmatic products from drip melting can be identified in within-plate regions where foundering is predicted to occur. Strong evidence for this argument is the eruption of potassic continental lavas in suspected areas of foundering away from plate boundaries. A broad literature shows that such magmas are the products of partial melting of peridotite with pyroxenite or other fluid and magma metasomatized lithologies. Recent work (Elkins-Tanton, 2007; Holbig and Grove, 2008; Ducea et al., 2013) shows that these magmas were melting progressively as the source region depth increased, the opposite trend of adiabatic decompression melting. These results strongly support the formation of these magmas through drip magmatism, the melting of the sinking lithosphere itself.

In this contribution we focus primarily on the Ethiopian dome to explore the geochemical evidence for lithospheric drip melting during the generation of the Oligocene flood basalt province. We then evaluate the evidence for smaller-scale lithospheric structures that may have developed in the Turkana area (Furman et al., 2004, 2006b) and more recently in the Eastern and Western Rift branches including ultra-potassic portions of the Virunga province (Rogers et al., 1992, 1998). Our results suggest that melting of descending metasomatized lithosphere in several regions of gravitational and thermal instability plays a larger role in the volcanic and topographic history of the East African Rift than has been recognized previously.

2. VOLCANIC HISTORY OF THE AFAR REGION

The Cenozoic flood basalt province in Ethiopia and Yemen is located at the junction of three rifts that formed during breakup of Africa and Arabia: the Red Sea and Gulf of Aden, both of which are floored by young mid-ocean ridge spreading centers, and the East African Rift where spreading remains confined to narrow continental volcano-tectonic zones (Fig. 1). Thick continental flood basalts in Ethiopia compose the majority of the province, covering over 600,000 km^2 with thickness up to 2000 m and an estimated total volume of 350,000 km^3 (Mohr and Zanettin, 1988).

Contemporaneous flood basalts from the Yemen conjugate margin cover an area of ~80,000 km^2 (Baker et al., 1996b; Ukstins et al., 2002). The flood basalts were emplaced over ~1–2 Ma beginning ~30 Ma (Hofmann et al., 1997), prior to significant extension (Courtillot et al., 1987; Hempton, 1987; Jestin and Huchon, 1992) but following uplift of the underlying basement by as much as 1–2 km (Bosellini et al., 1987; Şengör, 2001). Flood basalt eruption was preceded by small-volume flows in southern Ethiopia and northern Kenya (35–45 Ma; George et al., 1998; Furman et al., 2006b). Since flood basalt emplacement, the area has experienced an additional