Earth and Planetary Science Letters 489 (2018) 203–218

Contents lists available at ScienceDirect

Earth and Planetary Science Letters

www.elsevier.com/locate/epsl

The evolution of magma during continental rifting: New constraints from the isotopic and trace element signatures of silicic magmas from Ethiopian volcanoes

William Hutchison [a,b,*], Tamsin A. Mather [a], David M. Pyle [a], Adrian J. Boyce [c], Matthew L.M. Gleeson [d], Gezahegn Yirgu [e], Jon D. Blundy [f], David J. Ferguson [g], Charlotte Vye-Brown [h], Ian L. Millar [i], Kenneth W.W. Sims [j], Adrian A. Finch [b]

[a] Department of Earth Sciences, University of Oxford, South Parks Road, Oxford OX1 3AN, UK
[b] School of Earth and Environmental Sciences, University of St Andrews, KY16 9AL, UK
[c] Scottish Universities Environmental Research Centre, Rankine Avenue, East Kilbride G75 0QF, UK
[d] Department of Earth Sciences, University of Cambridge, Downing Street, Cambridge CB2 3EQ, UK
[e] School of Earth Sciences, Addis Ababa University, P.O. Box 1176, Addis Ababa, Ethiopia
[f] School of Earth Sciences, University of Bristol, Wills Memorial Building, Queens Road, Bristol BS8 1RJ, UK
[g] School of Earth and Environment, University of Leeds, Leeds LS2 9JT, UK
[h] British Geological Survey, The Lyell Centre, Research Avenue South, Edinburgh EH14 4AP, UK
[i] NERC Isotope Geosciences Laboratory, Keyworth, Nottingham, NG12 5GG, UK
[j] Department of Geology and Geophysics, University of Wyoming, Laramie, WY 82071, USA

ARTICLE INFO

Article history:
Received 10 November 2017
Received in revised form 16 February 2018
Accepted 22 February 2018
Available online xxxx
Editor: M. Bickle

Keywords:
rift
magmatism
assimilation
peralkaline
Ethiopia
oxygen isotopes

ABSTRACT

Magma plays a vital role in the break-up of continental lithosphere. However, significant uncertainty remains about how magma-crust interactions and melt evolution vary during the development of a rift system. Ethiopia captures the transition from continental rifting to incipient sea-floor spreading and has witnessed the eruption of large volumes of silicic volcanic rocks across the region over ∼45 Ma. The petrogenesis of these silicic rocks sheds light on the role of magmatism in rift development, by providing information on crustal interactions, melt fluxes and magmatic differentiation. We report new trace element and Sr–Nd–O isotopic data for volcanic rocks, glasses and minerals along and across active segments of the Main Ethiopian (MER) and Afar Rifts. Most $\delta^{18}O$ data for mineral and glass separates from these active rift zones fall within the bounds of modelled fractional crystallization trajectories from basaltic parent magmas (i.e., 5.5–6.5‰) with scant evidence for assimilation of Pan-African Precambrian crustal material ($\delta^{18}O$ of 7–18‰). Radiogenic isotopes ($\varepsilon_{Nd} = 0.92$–6.52; $^{87}Sr/^{86}Sr = 0.7037$–0.7072) and incompatible trace element ratios (Rb/Nb <1.5) are consistent with $\delta^{18}O$ data and emphasize limited interaction with Pan-African crust. However, there are important regional variations in melt evolution revealed by incompatible elements (e.g., Th and Zr) and peralkalinity (molar $Na_2O + K_2O/Al_2O_3$). The most chemically-evolved peralkaline compositions are associated with the MER volcanoes (Aluto, Gedemsa and Kone) and an off-axis volcano of the Afar Rift (Badi). On-axis silicic volcanoes of the Afar Rift (e.g., Dabbahu) generate less-evolved melts. While at Erta Ale, the most mature rift setting, peralkaline magmas are rare. We find that melt evolution is enhanced in less mature continental rifts (where parental magmas are of transitional rather than tholeiitic composition) and regions of low magma flux (due to reduced mantle melt productivity or where crustal structure inhibits magma ascent). This has important implications for understanding the geotectonic settings that promote extreme melt evolution and, potentially, genesis of economically-valuable mineral deposits in ancient rift-settings. The limited isotopic evidence for assimilation of Pan-African crustal material in Ethiopia suggests that the pre-rift crust beneath the magmatic segments has been substantially modified by rift-related magmatism over the past ∼45 Ma; consistent with geophysical observations. We argue that considerable volumes of crystal cumulate are stored beneath silicic volcanic systems (>100 km^3), and estimate that crystal cumulates fill at least 16–30% of the volume generated by crustal extension under the axial volcanoes of the MER and Manda Hararo Rift Segment (MHRS) of Afar. At Erta Ale only ∼1% of the volume generated due to rift extension is filled by cumulates, supporting previous seismic evidence for a greater role of

* Corresponding author at: School of Earth and Environmental Sciences, University of St Andrews, KY16 9AL, UK.
E-mail address: wh39@st-andrews.ac.uk (W. Hutchison).

https://doi.org/10.1016/j.epsl.2018.02.027

plate stretching in mature rifts at the onset of sea-floor spreading. We infer that ~45 Ma of magmatism has left little fusible Pan-African material to be assimilated beneath the magmatic segments and the active segments are predominantly composed of magmatic cumulates with $\delta^{18}O$ indistinguishable from mantle-derived melts. We predict that the $\delta^{18}O$ of silicic magmas should converge to mantle values as the rift continues to evolve. Although current data are limited, a comparison with ~30 Ma ignimbrites (with $\delta^{18}O$ up to 8.9‰) supports this inference, evidencing greater crustal assimilation during initial stages of rifting and at times of heightened magmatic flux.

1. Introduction

Magmatism fundamentally alters the thermal, chemical and mechanical properties of the crust and plays a key role in the break-up of continental lithosphere (Buck, 2006; Bialas et al., 2010). However, uncertainty remains about whether magmatic differentiation and crustal interactions vary spatially between different rift segments, and whether there are significant secular variations during rift evolution. Studies of the petrogenesis of rift magmas offer insights into these questions.

The petrologic diversity of volcanic rocks is generated by numerous processes. Among the most important are: interaction with the crust via partial melting or assimilation; and fractional crystallization of the parental magma (e.g., Macdonald et al., 2008; Deering et al., 2008). Partial crustal melting strongly depends on the thermal state of the crust (Dufek and Bergantz, 2005; Annen et al., 2006) and the availability of fusible crustal materials. In active rifts, the potential for partial melting will be amplified in regions of elevated temperatures and will coincide with zones of highest magmatic intrusion (Karakas and Dufek, 2015). Partial melting is also favoured in regions of fusible crust, while more refractory regions, that have already been heavily intruded, are less likely to be remelted or assimilated by later intrusions. Fractional crystallization will be amplified in rift settings where magma flux and crustal temperatures are lower, and there is an absence of fusible crust.

Geochemical techniques can discriminate between partial crustal melting and fractional crystallization. Oxygen isotopes ($\delta^{18}O$) are a powerful tool for investigating crustal interactions (provided the $\delta^{18}O$ of crust is distinct from mantle-derived rocks and cumulates), while incompatible trace elements (e.g., Ba, Sr, Th, Zr) are particularly sensitive to fractional crystallization. Geochemical studies in active rift zones, notably Iceland, have successfully linked silicic magma petrogenesis to the thermal state of the crust (Martin and Sigmarsson, 2010). On the axis of the Icelandic Rift, where magma flux is high and the crust is hot, silicic magmas exhibit $\delta^{18}O$ evidence for assimilation of fusible hydrothermally-altered metabasaltic crust with low $\delta^{18}O$ (< 2‰). While in cooler off-rift settings, magmatic flux is lower, assimilation is limited (samples exhibit normal magmatic $\delta^{18}O$, 5.0–6.5‰, Eiler, 2001), and silicic melts undergo extensive fractional crystallization. In continental rift zones further complexity is expected because vestigial pre-rift continental crust may also be present.

Ethiopia exposes several stages of rift development from continental rifting in the Main Ethiopian Rift (MER) to nascent seafloor spreading in the Afar Rift (Fig. 1, Hayward and Ebinger, 1996), providing a unique opportunity to study connections between magma petrogenesis and geotectonic setting. Here, geochemical data can be interpreted in the context of geophysical constraints on crustal structure and composition (Keranen et al., 2004; Bastow and Keir, 2011; Hammond et al., 2011), and magmatic intrusion volumes (Dessisa et al., 2013; Keir et al., 2015). Further, magmatism in Ethiopia has been taking place since ~45 Ma (Rooney, 2017) permitting the development of a temporal understanding of magma evolution and crustal interactions as rifting proceeds.

Previous studies in Ethiopia focused on geochemistry of mafic magmas of the MER and found evidence for spatio-temporal variations in crustal assimilation and fractionation (Rooney et al., 2007; Section 2). However, silicic volcanism is a key component of rift magmatism and a common feature across different rift zones. Although previous authors have investigated individual complexes (e.g., Gedemsa, Peccerillo et al., 2003; Dabbahu, Field et al., 2013) it is unclear whether silicic magmagenesis varies spatially across different rift settings and whether there have been secular variations since the onset of rifting. Answering these questions has important implications for understanding ongoing rift volcanism; and the links between petrogenesis, rift setting and mineral resources. Silicic melts generated in continental rifts by protracted fractional crystallization tend to be enriched in economically-valuable elements (including, rare earth elements, REE, Zr, Nb and Ta). Identifying rift settings that favour extreme differentiation (i.e., mature versus immature continental rifts, or on-versus off-axis locations) provides valuable insights into the geotectonic settings that may host economically significant ore bodies.

In this paper we integrate new and published Sr–Nd–O isotope and trace element data from six MER and Afar Rift volcanic systems (Fig. 1a, b). We evaluate the relative importance of fractional crystallization and crustal melting at each and compare this to their rift setting (crustal thickness and crustal compositions, Fig. 1) and eruptive flux. We show that:

i) despite significant variations in magma flux and crustal structure there is limited evidence for Pan-African crustal assimilation in Ethiopian Quaternary magmas
ii) there are variations in fractional crystallization between the different volcanic systems, and melt evolution is amplified in less mature rifts with lower magma flux
iii) the relative importance of fractional crystallization and crustal melting in the genesis of silicic magmas should vary as a continental rift develops and the pre-rift crust is modified by magmatic intrusions

2. Geological setting

Magmatic activity in East Africa began in the Eocene. Recent reviews (Rooney, 2017) suggest multiple pulses of magmatism since ~45 Ma, with the most volumetrically-significant flood basalt and silicic eruptions taking place in the Oligocene (~33.9 to 27 Ma, Hofmann et al., 1997; Ayalew et al., 2002). Rift magmas have intruded through a continental lithosphere that comprises Precambrian schists and granitoids assembled during the Neoproterozoic Pan-African crust building event (Teklay et al., 1998). Initiation of major rift zones was diachronous: ~35 Ma in the Gulf of Aden (d'Acremont et al., 2005); ~28 Ma in the Red Sea (Wolfenden et al., 2005) and 15–18 Ma in the MER (Wolfenden et al., 2004). Each rift zone shows a comparable evolutionary history, with early deformation accommodated on border faults, and later extension and magmatic intrusions localized along 20 km wide and