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# Constraining magma storage conditions at a restless volcano in the Main Ethiopian Rift using phase equilibria models

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ABSTRACT

The Main Ethiopian Rift hosts a number of peralkaline volcanic centres, several of which show signs of recent unrest. Due to the low number of historical eruptions recorded in the region and lack of volcanic monitoring, conditions of magma storage in the Main Ethiopian Rift remain poorly constrained. Aluto is one of these restless volcanic centres and identifying magma storage conditions is vital for evaluating the significance of recent periods of unrest. Using Aluto as a case study, we explore magma storage conditions using Rhyolite-MELTS thermodynamic modelling software. We performed ~150 fractional crystallisation models using a primitive basalt as the starting composition, and for a range of pressures (50–300 MPa), initial $H_2O$ contents (0.5–3 wt%) and oxygen fugacities (QFM − 2–QFM + 1). Predicted liquid lines of descent from these models are compared with published whole-rock data and, together with new observations of natural phase assemblages and erupted mineral compositions, provide constraints on magma storage conditions.

Using a statistical approach to compare empirical data and thermodynamic model outputs, we find that compositions of evolved peralkaline rhyolites from Aluto are best reproduced by protracted (90%) isobaric fractional crystallisation from a rift-related basaltic composition, without the need for significant crustal assimilation. The required extent of fractional crystallisation suggests that much of the magmatic system may exist as a highly crystalline mush with only a small lens of rhyolitic melt. The best agreement between models and natural samples is at low pressures (150 MPa), low initial $H_2O$ concentrations (0.5 wt%) and an oxygen fugacity near the QFM buffer. The depth of magma storage derived from these results (~5.6 ± 1 km) is consistent with the source depths modelled from measured ground deformation. Data from other peralkaline volcanic centres in the Main Ethiopian Rift (Boset and Gedemsa), and other locations globally (e.g. Pantelleria, Italy) suggest that these storage conditions are a common feature of many peralkaline volcanic centres.



## 1. Introduction

At the northern end of the East African Rift system, the active Main Ethiopian Rift (MER) and the Afar Depression represent two distinct stages in the transition from a continental rift to a rift system that shares many characteristics with a slow-spreading oceanic ridge (Ebinger, 2005). Volcanic features in the MER include both focussed, caldera-forming silicic centres, and elongate rift-controlled basaltic fields, dominantly composed of monogenetic centres (Abebe et al., 2007; Corti, 2009). Volcanic activity is generally concentrated within localised segments, controlled by dense fault swarms (Corti, 2009). In the Afar region, incipient seafloor-spreading centres characterise the initiation of the Red Sea Rift, with extension largely accommodated by dikes (Wright et al., 2006; Keir et al., 2009), indicative of a more mature rift-setting.

In this study, we investigate the magmatic evolution of Aluto volcano, Ethiopia. Aluto is a peralkaline silicic volcano located in the MER, which has been active for ~500 ka and underwent a phase of major caldera-forming volcanism at ~310 ka (Hutchison et al., 2016a). Following a hiatus in activity after these caldera-forming events, volcanic activity at Aluto resumed at ~60 ka and has since been characterised by the eruption of evolved peralkaline rhyolites (Hutchison et al., 2015, 2016a, 2016b, 2016c). Aluto is one of a number of prominent restless caldera systems in the MER, showing evidence for recent ground deformation (Biggs et al., 2011; Hutchison et al., 2016b), and hosts an active hydrothermal system (Hutchison et al., 2015). Volcanic hydrothermal systems offer geothermal resources that may provide significant

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economic benefits for Ethiopia (Kebede, 2012; Younger, 2014). Evaluating the potential risks associated with developing geothermal energy plants on these restless volcanic systems requires investigation of the magma storage conditions during the most recent eruptive periods. Improving our understanding of how and where magmas evolve beneath peralkaline volcanic centres is particularly important, given the potential hazards posed by the infrequent explosive eruptions at these volcanic systems. Aluto is currently showing signs of unrest (Biggs et al., 2011; Hutchison et al., 2016b), and recent geophysical observations allow comparison of the present magmatic activity with that inferred for past eruptive episodes.

Here we explore the hypothesis that the composition of Aluto's volcanic products can be generated by closed-system, isobaric fractional crystallisation (i.e. without crustal assimilation) and aim to determine the conditions of magma storage before recent eruptions. We approach this by calculating potential liquid lines of descent across a wide range of potential magmatic storage conditions (i.e. pressure, oxygen fugacity [$fO_2$], initial $H_2O$ content) using the Rhyolite-MELTS thermodynamic modelling software (Gualda et al., 2012) and comparing model outputs with whole-rock compositions of natural samples. We develop a statistical test to quantitatively assess the fit between modelled liquid lines of descent, and empirical whole rock data. On identifying the best fitting magma storage conditions (i.e. the model parameters that best predict the natural melt compositions), we compare these petrological constraints with the interpreted depth of melt accumulation from geophysical measurements of recent ground deformation and seismic activity at Aluto. A comparison between current activity and the petrologically derived magma storage conditions of past eruptions has not previously been attempted at Aluto and may provide important information regarding the potential scale and eruptive style of future activity.

### *1.1. Genesis of peralkaline magmas*

Peralkaline magmas are defined as having a peralkalinity index ($PI = (Na + K)/Al) > 1$ (Macdonald, 1974), with peralkaline rhyolites further sub-divided into comendites (high $Al_2O_3$ and low FeO) and pantellerites (low $Al_2O_3$ and high FeO). Peralkaline magmas occur globally and are commonly associated with ocean islands (e.g. Socorro Island, Mexico; Bohrson and Reid, 1997), localised extension in collisional settings (e.g. Pantelleria; Civetta et al., 1988; White et al., 2009) and continental rifts (e.g. Gedemsa; Peccerillo et al., 2003). Isotopic and trace element analysis of peralkaline volcanic products suggests that fractional crystallisation is the dominant mechanism by which peralkaline rhyolites are generated (e.g. Peccerillo et al., 2003; Ronga et al., 2009; LeMasurier et al., 2011; Field et al., 2012; Neave et al., 2012; Rooney et al., 2012), though in some systems (e.g. Gedemsa and Olkaria) radiogenic isotope ratios point to a limited role for crustal contamination (e.g. Davies and Macdonald, 1987; Black et al., 1997; Peccerillo et al., 2003; Giordano et al., 2014).

Phase equilibrium experiments indicate that the generation of peralkaline magmas may be favoured by low pressure conditions, characteristic of the upper crust (Caricchi et al., 2006). Experimental data indicates that fractional crystallisation from a transitional basaltic parent cannot produce melt compositions that cross the subaluminous/peralkaline divide at $P > 0.5$ GPa. Phase equilibrium experiments by Di Carlo et al. (2010) suggest that pantellerite magmas may evolve at depths as shallow as $5 \pm 1$ km. Low pressures stabilise plagioclase feldspar and inhibit amphibole crystallisation, leading to an increase in the peralkalinity index of the residual melt (Caricchi et al., 2006). The phase relationships of peralkaline rhyolites are also consistent with crystallisation under relatively reduced conditions (<QFM – Quartz-Fayalite-Magnetite buffer), since the peralkalinity of the magma increases as crystallisation of calcic clinopyroxene is inhibited under these conditions (Scaillet and Macdonald, 2001, 2003).

## 2. Geological setting

The MER is a ~500 km long zone of active continental rifting between the Nubian and Somalian plates (Fig. 1; Corti, 2009), and is considered a type example of an active continental rift (Ebinger,

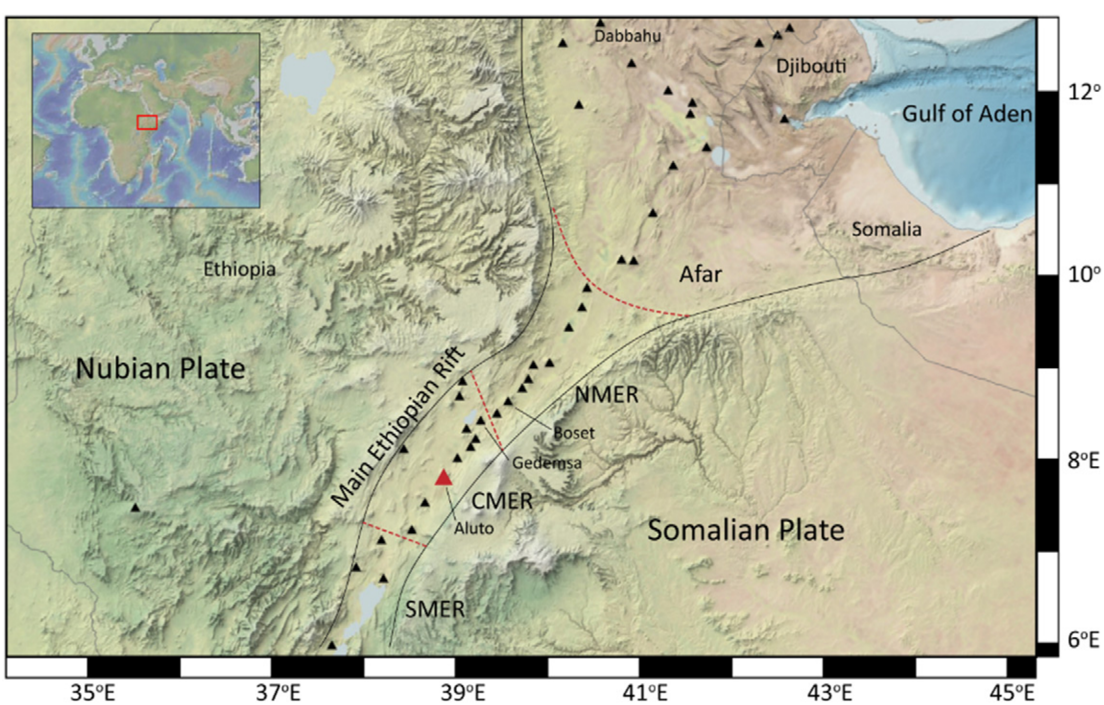


**Fig. 1.** Topographic map of the East African Rift system. The location of the Main Ethiopian Rift and Afar depression are identified by the black lines. Red dashed lines indicate the divisions between the South Main Ethiopian Rift (SMER), Central Main Ethiopian Rift (CMER), North Main Ethiopian Rift (NMER) and the Afar region (after Corti, 2009). Volcanic centres are represented by the small grey triangles (data from the Smithsonian Global Volcanism Program; Siebert and Simkin, 2002). The location of Aluto is marked by the larger red triangle. Inset is taken from GeoMapApp (Ryan et al., 2009; http://www.geomapapp.org/).