Melt Generation from Plume Lithosphere Interactions Beneath the Rungwe Volcanic Province, East Africa

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INTRODUCTION

- The impact of a plume head beneath the lithosphere generally results in intense melting of plume materials, producing large igneous provinces (LIPs; White & McKenzie, 1995) such as in the Eastern Branch of the East African Rift (EAR) (Figure 1A) (Alayew & Gibson, 2009). However, the Western Branch of the EAR (Figure 1A) is characterized by limited and sparse magmatism and the melt source is contentious.

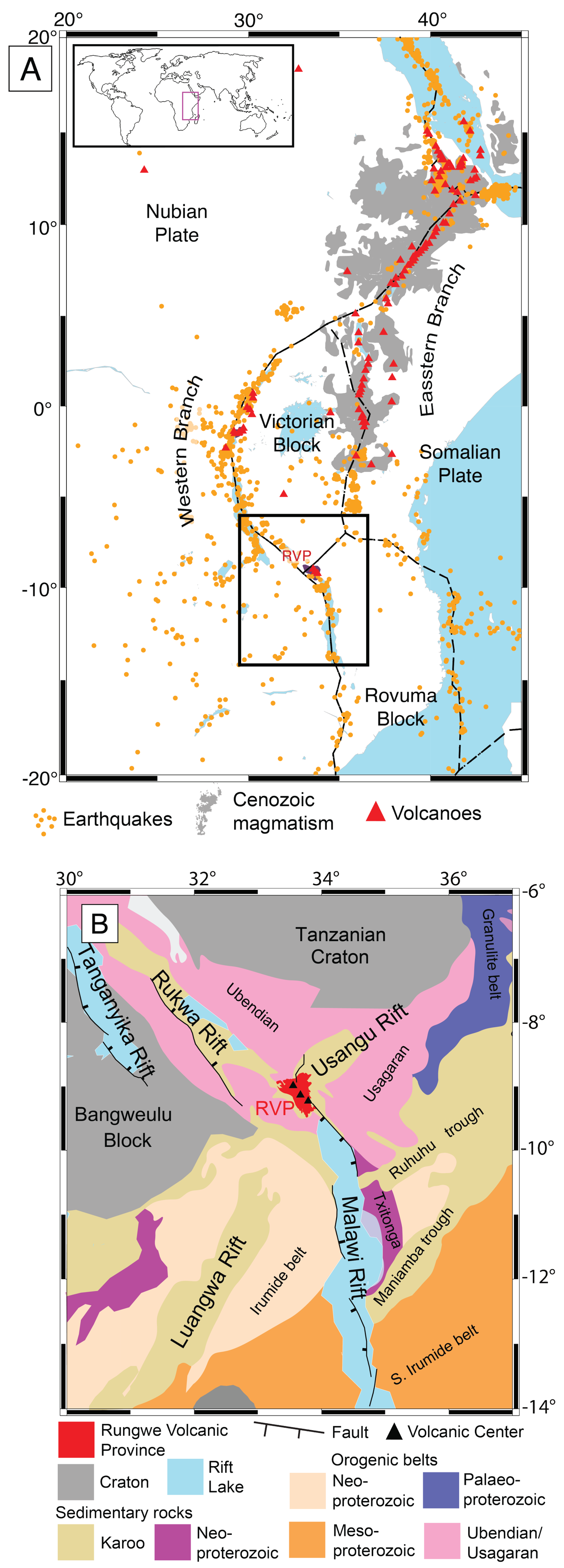

Fig.1. (A) Map of the East African Rift (EAR) showing the Eastern and Western Branches. The Western Branch of the EAR has less volcanic centers (red triangles) and more earthquakes (orange dots) than the Eastern Branch. The volcanoes are from the Smithsonian Global Volcanism Project and earthquakes from NEIC catalog (Beauval et al., 2013). The Cenozoic volcanic rocks (gray) after Thiéblemont (2016) indicate the large igneous province (LIP) in the Eastern Branch. RVP = Rungwe Volcanic Province. The black rectangle shows location of Figure 2B. Black dotted lines represent plate boundaries from Stamps et al. (2008). The inset map shows the relative location of part of the EAR (pink rectangle) on Earth. (B). Map of major terranes and geological features in the southern part of the Western Branch of the EAR after Fritz et al. (2013).

OBJECTIVES

- Geochemical studies of past eruptions of the RVP (Figure 1A), a volcanic center in the Western Branch, indicate plume signatures (elevated mantle potential temperatures; Rooney et al., 2011 and high $^3He/^4He$; Hilton et al., 2011). The plume signatures of the RVP remain enigmatic, mainly because the volcanism is highly localized, unlike the LIP in the Eastern Branch (Figure 1A).

- Our objective is to investigate plume-lithosphere interactions beneath the RVP, to better understand the sources of the enigmatic plume signatures.

METHODS

1. **Tomography-Based Convection Modeling**
   - Solve the velocity fields in the Stokes system using ASPECT (Bangerth et al., 2015)
   - Stokes systems here is the conservation of momentum (equation 1) and conservation of mass (equation 2) for an incompressible fluid.
   - We also solve for the temperature fields in the energy conservation equation (3).

$$-\nabla \cdot [2\eta\, \varepsilon(\mathbf{u})] + \nabla p = \rho \mathbf{g} \quad \text{in } \Omega, \qquad (1)$$

$$\nabla \cdot \mathbf{u} = 0 \quad \text{in } \Omega \qquad (2)$$

$$\rho C_p \left(\frac{\partial T}{\partial t} + \mathbf{u} \cdot \nabla T\right) - \nabla \cdot k \nabla T = 2\eta [\varepsilon(\mathbf{u}) : \varepsilon(\mathbf{u})] + \alpha T (\mathbf{u} \cdot \nabla p) + \rho T \Delta S \left(\frac{\partial F}{\partial t} + \mathbf{u} \cdot \nabla F\right) \quad \text{in } \Omega, \qquad (3)$$

Thermal Structure:

- The initial thermal structure of the lithosphere is constrained by lithospheric thickness for the RVP (Figure 2A; Updated Fishwick, 2010). While for the sublithospheric mantle, we approximate an adiabatic increase in temperature with additional temperature perturbation derived from seismic constrains (Figures 2B, C, and D).
- This is a use-case of the EarthCube BALTO (Brokered Alignment of Long-Tail Observations)-ASPECT client, which accesses lithospheric structures and seismic tomography models directly over the web

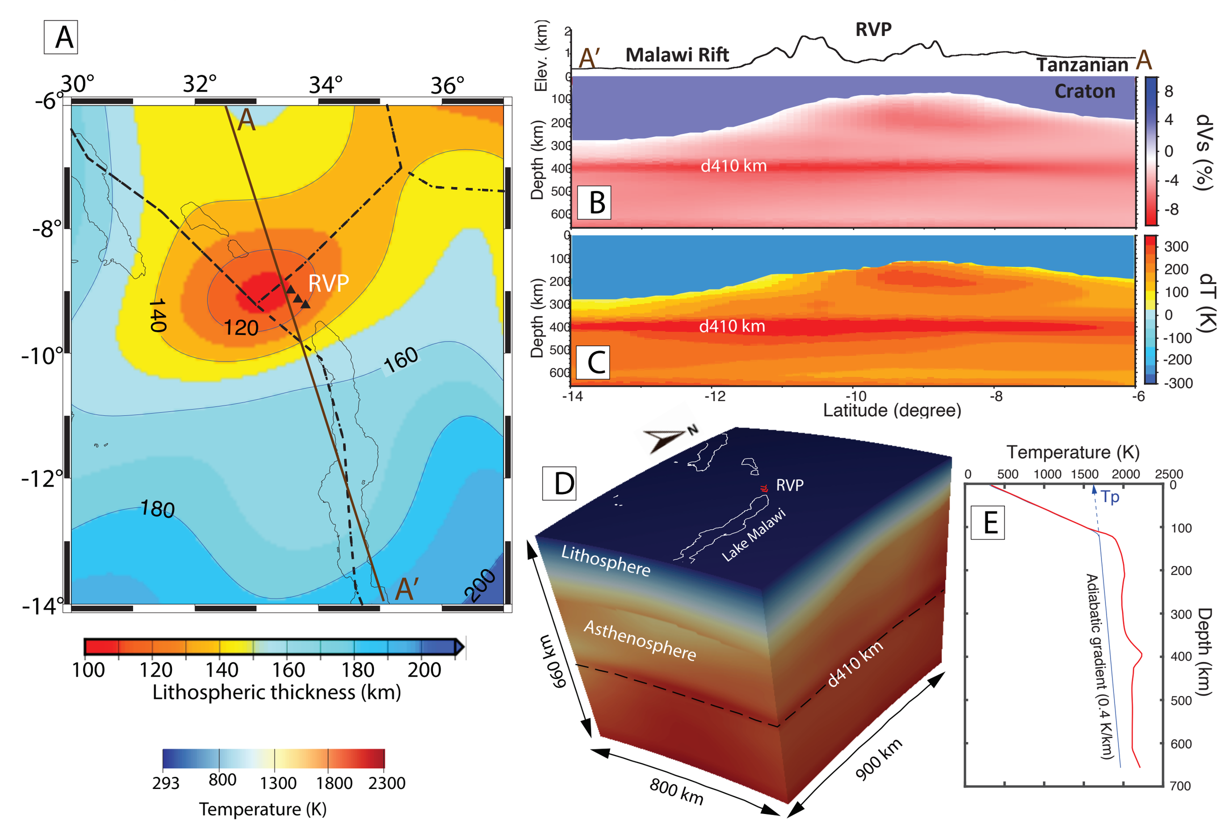

Fig.2. (A) Lithospheric thickness map of the Rungwe Volcanic Province (RVP, black triangles) and surroundings, updated from Fishwick (2010) which we use as input in this study. The blue contours show lines of equal lithospheric thickness at 20 km intervals. Black dotted lines represent plate boundaries from Stamps et al. (2008). Brown line AA' is the profile location for Figures 3B and C. (B) Cross section of seismic velocity perturbation after Emry et al. (2018). The velocities are relative to the AK135 global average Earth Model (Kennett et al., 1995). (C) Temperature perturbation derived from the velocity perturbation in Figure 2C. (D) Numerical model setup showing the model dimensions and the initial temperature condition as the background in 3D. (E) Initial temperature-depth profile beneath the RVP (red line). Blue line represents the 0.4 K/km adiabat. Tp = mantle potential temperature.

Rheology:

- We implement a rigid lithosphere (10^{23} Pa.s), while the sublithospheric mantle is governed by a composite rheology flow law for dry olivine material parameters that includes porosity weakening (Jadamec & Billen, 2010).

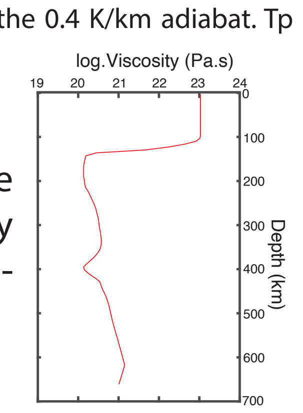

Fig.3. One-dimensional initial viscosity depth profiles beneath the RVP.

2. **Partial Melting**
   - We model melting of anhydrous peridotite according to Katz et al. (2003) where the solidus and liquidus have a quadratic relationship with pressure.
   - The generated melt is proportional to the temperature in excess of the solidus

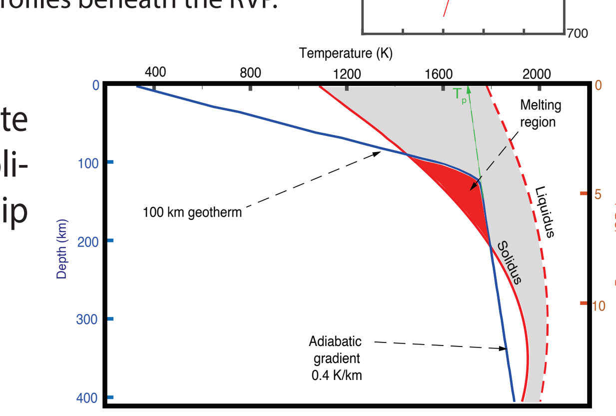

Fig.4. A combined plot of temperature-depth profiles (blue solid lines; beneath the RVP) and a pressure-temperature phase diagram depicting shallow melting of anhydrous peridotite parameterized from Katz et al. (2003).

RESULTS

1. **Tomography-Based Convection Model**
   - Our results of TBC indicate sublithospheric mantle upwelling beneath the RVP and the northern Malawi Rift at 250 km depth. The TBC at 250 km depth is characterized by a relatively rapid upwelling (~4 cm/yr) with a diverging horizontal flow (~3 cm/yr). At 150 km depth, upwelling is focused only beneath the RVP

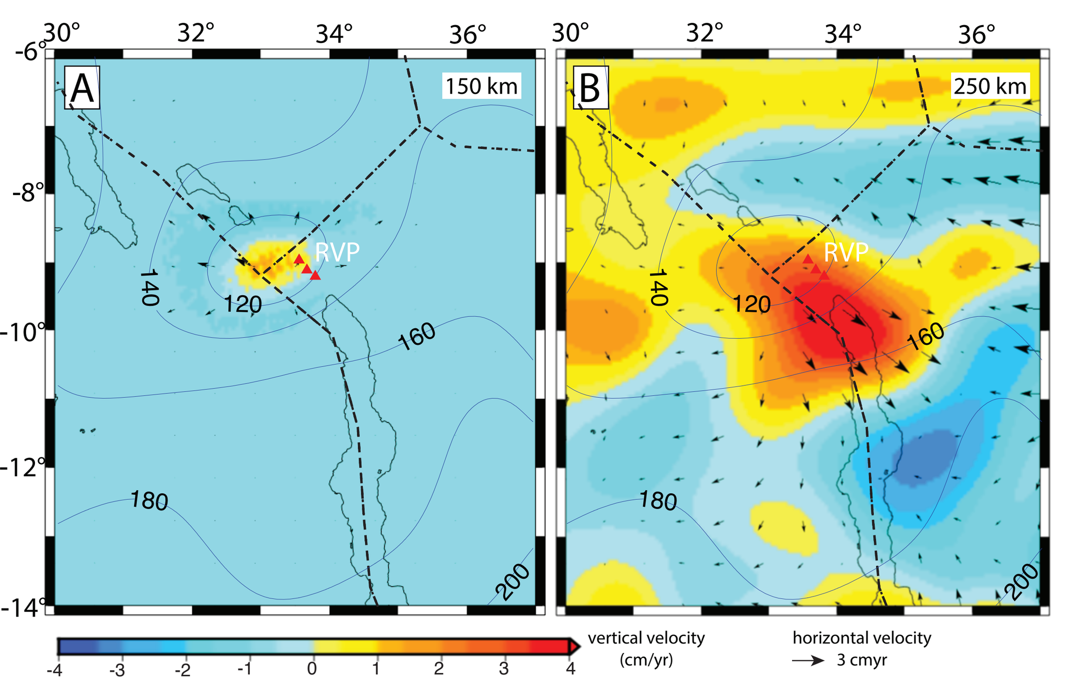

Fig.5. Depth slices showing plume-driven convection beneath the RVP at (A) 150 km and (B) 250 km depth. The vertical flow (background color) is overlain by the horizontal flow fields (black arrows). White triangles represent the Rungwe Volcanic Province (RVP). The blue contours show lines of equal lithospheric thickness at 20 km intervals from Fishwick (2010).

2. **Melt Generation from PDC**
   - Upwellings from TBC bring deep-hot mantle materials to shallower sublithospheric depths to generate melt
   - Melt is generated just below the lithosphere at depth from 105-200 km

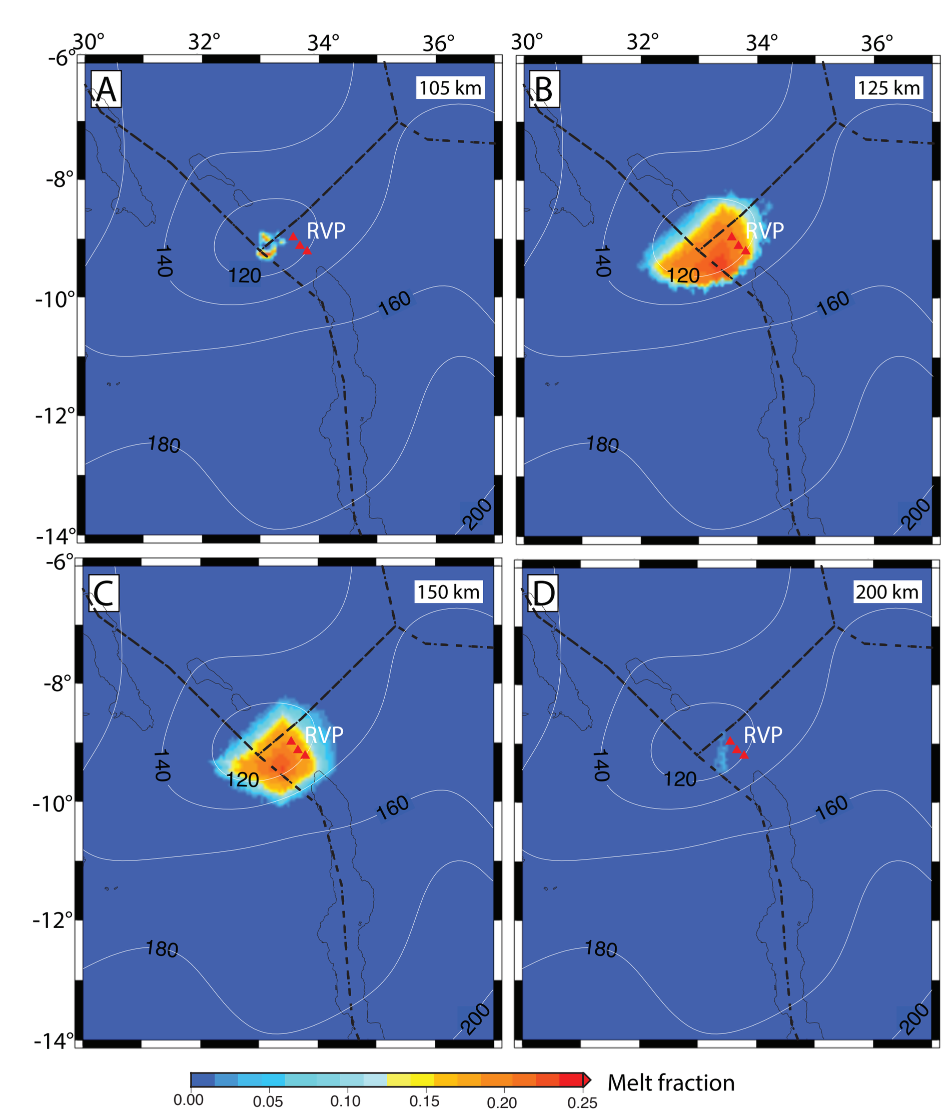

Fig.6. Depth slices showing initial melt fractions beneath the RVP at (A) 105 km, (B) 125 km, (C) 150 km and (D) 200 km depth.

DISCUSSION

- TBC generates upwelling of hot plume materials beneath the RVP to shallower sublithospheric depths to generate melt.
- Upwellings of plume materials generate decompression melts beneath the RVP where the lithosphere is thinnest
- Compared to previous studies of melt generation from lithospheric modulated convection (LMC; Njinju et al., 2020) in which melt is generated below the lithosphere at depth from 130-155 km; there is deeper (105-200 km) melting from TBC
- Although previous study demonstrates that LMC (Njinju et al., 2020) could generate melt beneath the RVP, however it required an elevated mantle potential temperature which still suggest the presents of a plume
- Lithospheric architecture has a first-order control on the localization of magmatism beneath the RVP
- The presents of a plume material beneath the RVP is required for sublithospheric melt generation

CONCLUSIONS

- TBC is a possible source for the melt beneath the RVP and might be responsible for the observed plume signatures in the RVP
- Melt generate from TBC might be responsible for the shallow low velocity zone imaged beneath the RVP
- Our BALTO-ASPECT plug-in provides the capability of a user to rapidly model melt generation from TBC by setting up a parameter file such that different lithospheric thicknesses (csv files) can seamlessly be accessed from the BALTO server as inputs to constrain the initial temperature conditions.
- This use-case demonstrates the capability of the BALTO-ASPECT client to read input data from the BALTO brokering server for modeling of plume-lithosphere interactions beneath the RVP

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