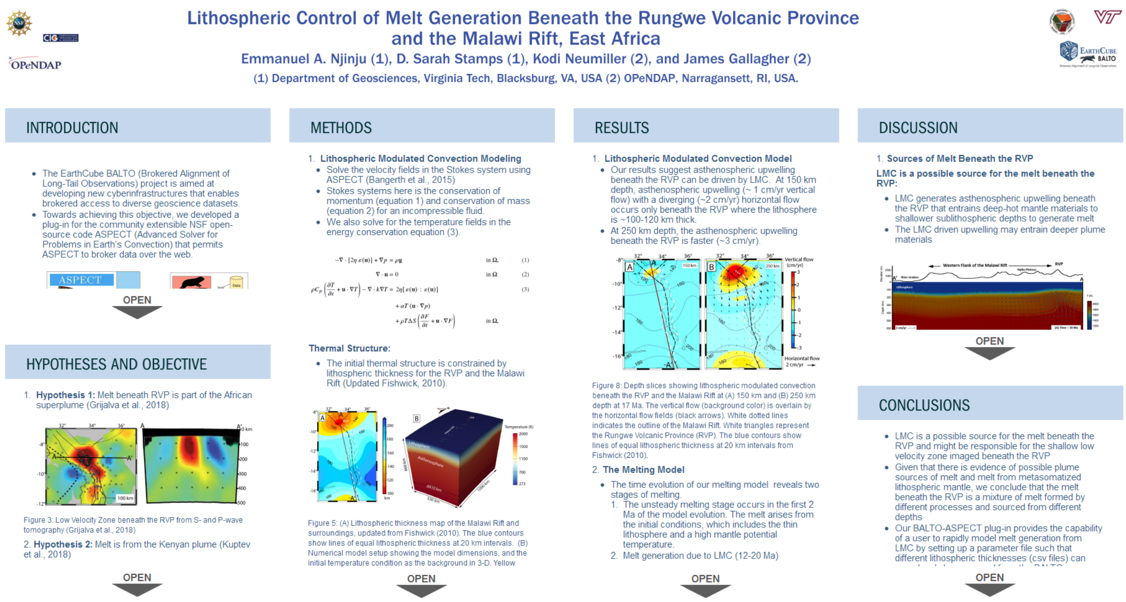
Lithospheric Control of Melt Generation Beneath the Rungwe Volcanic Province and the Malawi Rift, East Africa



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INTRODUCTION

- The EarthCube BALTO (Brokered Alignment of Long-Tail Observations) project is aimed at developing new cyberinfrastructures that enables brokered access to diverse geoscience datasets.
- Towards achieving this objective, we developed a plug-in for the community extensible NSF open-source code ASPECT (Advanced Solver for Problems in Earth's Convection) that permits ASPECT to broker data over the web.

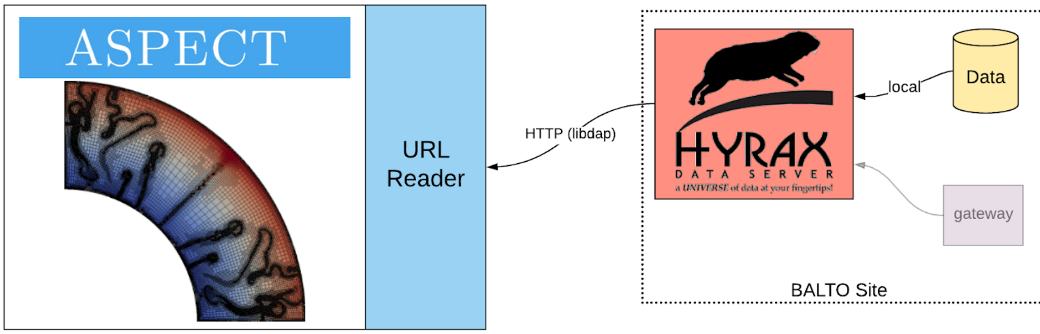

Figure 1: A flowchart of the BALTO-ASPECT plugin

- We present a use-case of the BALTO-ASPECT client, which accesses lithospheric structures from the BALTO server to constrain a 3D lithospheric modulated convection (LMC) modeling and melt generation beneath the Rungwe Volcanic Province (RVP).
- Studies suggest that magma thermally weakens the lithosphere, hence enabling rifting (magma-assisted rifting)

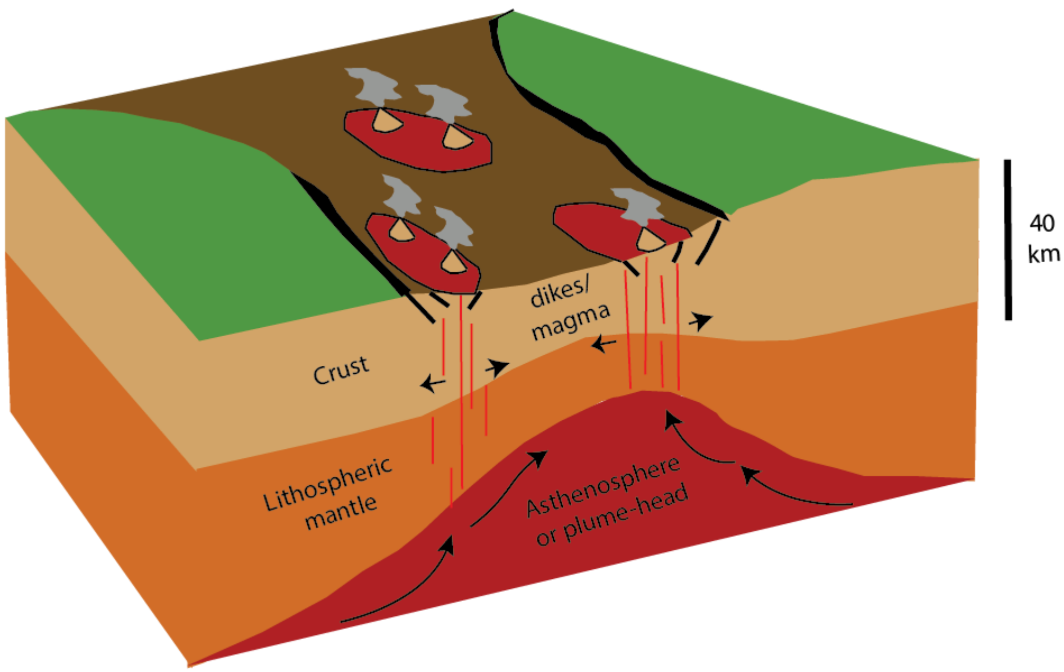

Figure 2. A conceptual model of magma-assisted rifting (After Rooney et al., 2010)

- Despite the importance of magma in rifting, the Western Branch of the East African Rift is magma-poor and there are competing hypotheses about the source of magma for the RVP in the northern Malawi Rift

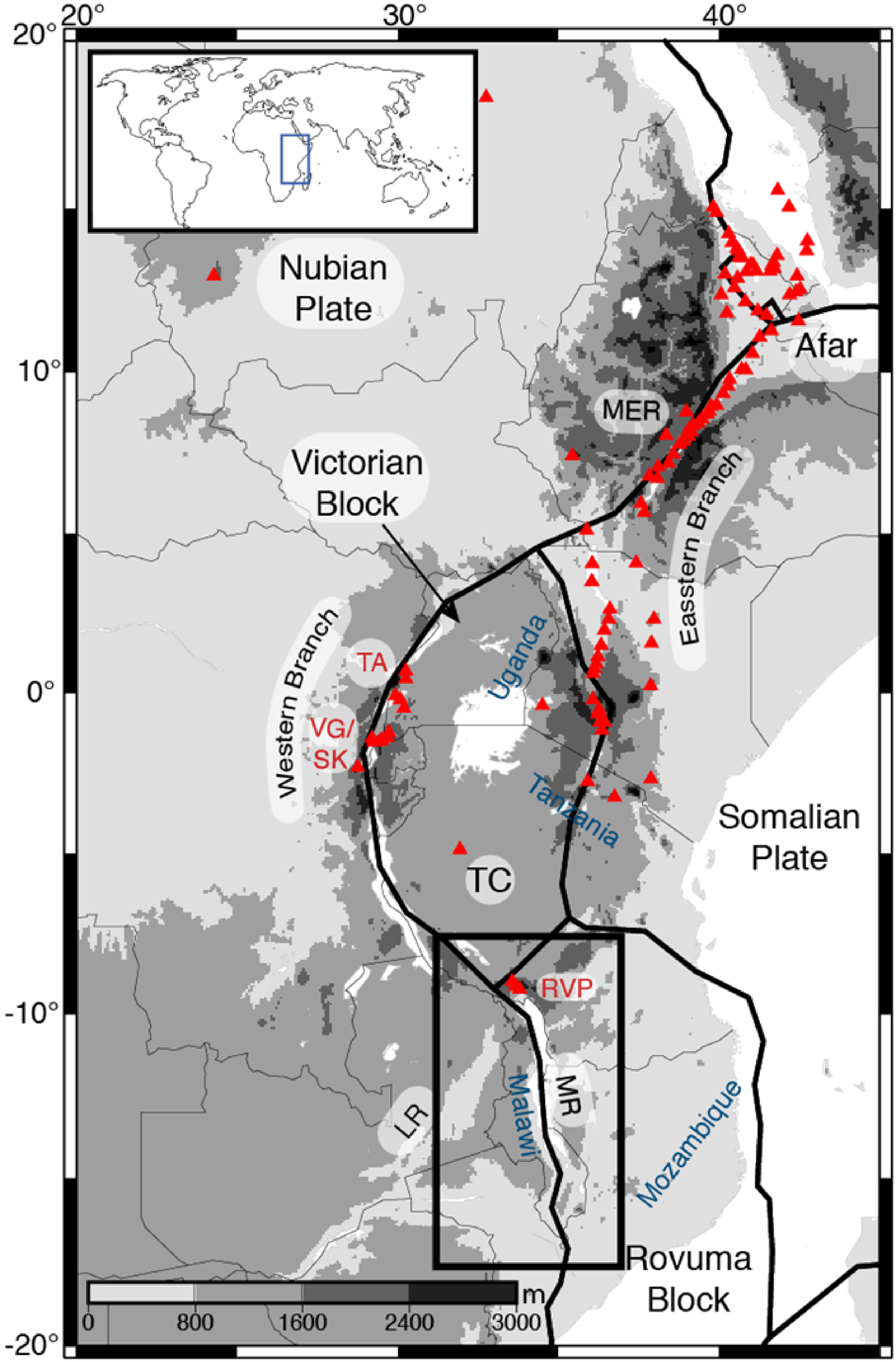

Figure 3. A digital elevation model showing the East African Rift (EAR). Black box encloses the Rungwe Volcanic Province and the Malawi Rift. The Eastern branch of the EAR shows more volcanic centers (red triangles) than the Western branch. MER = Main Ethiopian Rift. TC = Tanzanian Craton. MR = Malawi Rift. LR = Luangwa Rift. Black bold lines represent plate boundaries from Stamps et al. (2008).

HYPOTHESES AND OBJECTIVE

1. **Hypothesis 1:** Melt beneath RVP is part of the African superplume (Grijalva et al., 2018)

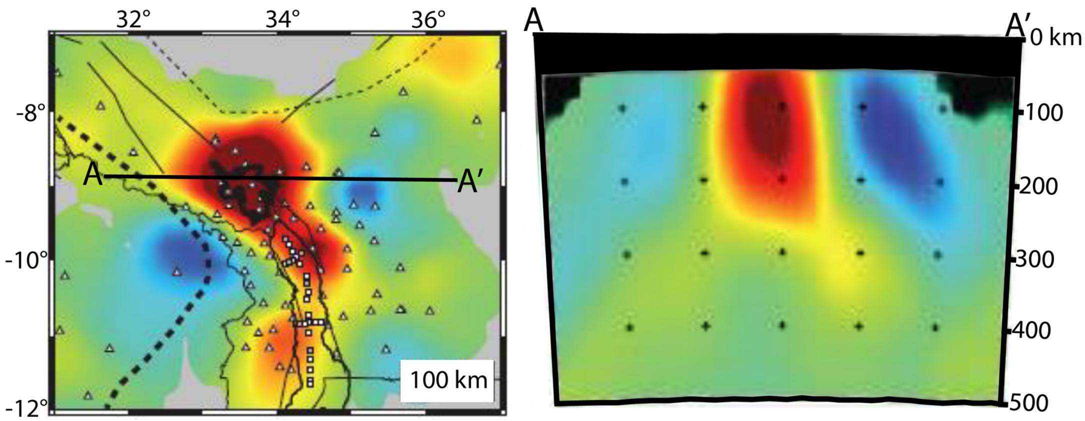

Figure 3: Low Velocity Zone beneath the RVP from S- and P-wave tomography (Grijalva et al., 2018)

2. **Hypothesis 2:** Melt is from the Kenyan plume (Kuptev et al., 2018)

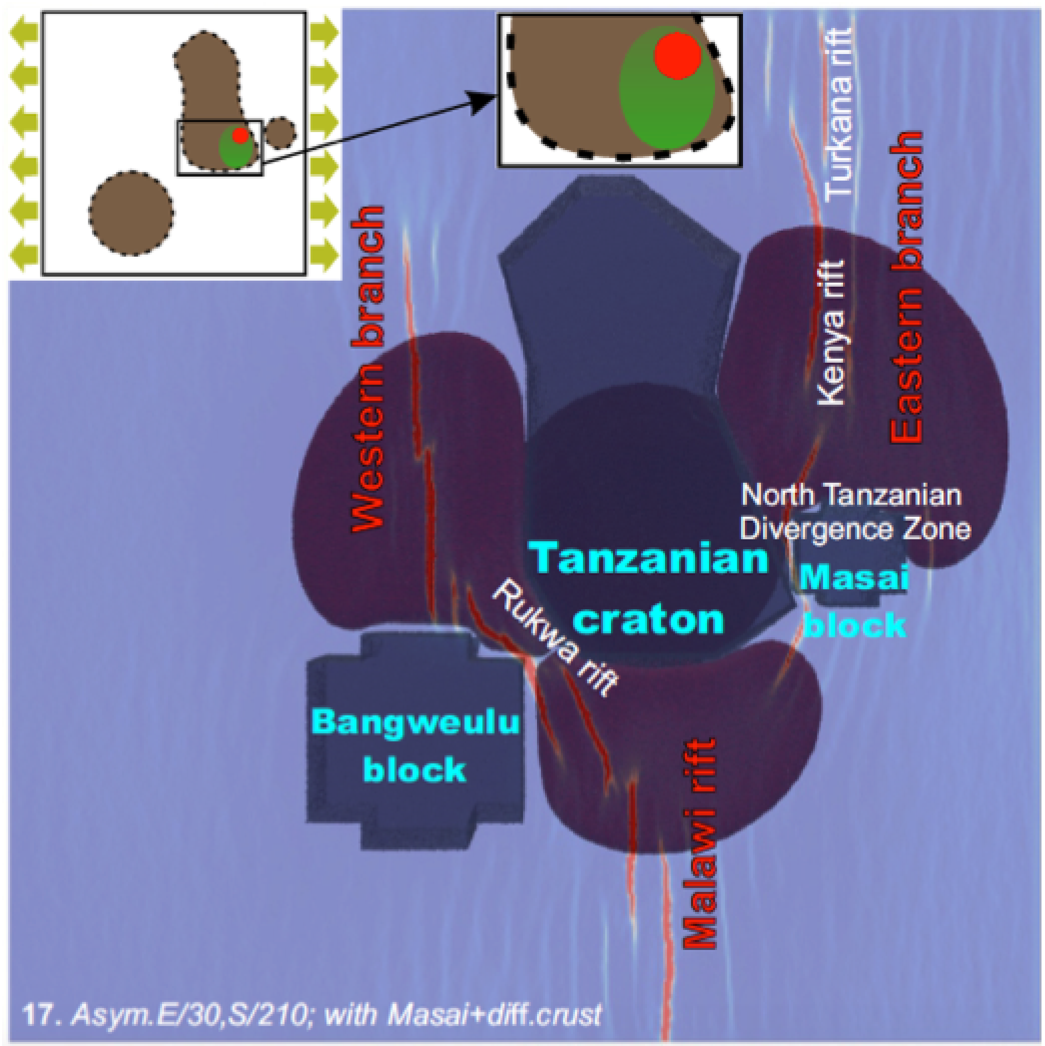

Figure 4: Kenyan plume structure around cratonic blocks from thermomechanical modeling by Koptev et al. (2018).

3. **Hypothesis 3:** Decompression melts arise from asthenospheric upwelling due to LMC

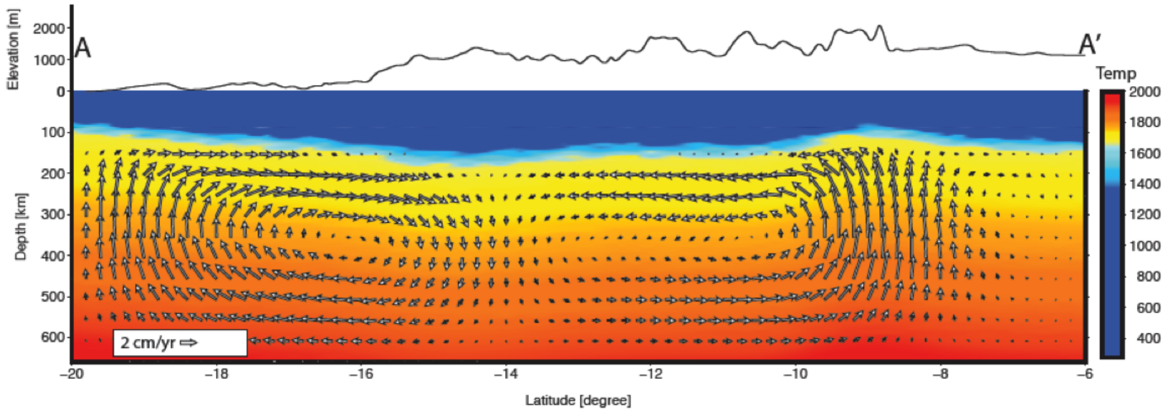

Figure 4: A profile showing LMC

Our main objective is to investigate hypothesis 3 in order to better understand the source of the melt beneath the RVP and the role of melt in magma-poor rifting.

METHODS

1. **Lithospheric Modulated 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).

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

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

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

Thermal Structure:

- The initial thermal structure is constrained by lithospheric thickness for the RVP and the Malawi Rift (Updated Fishwick, 2010).

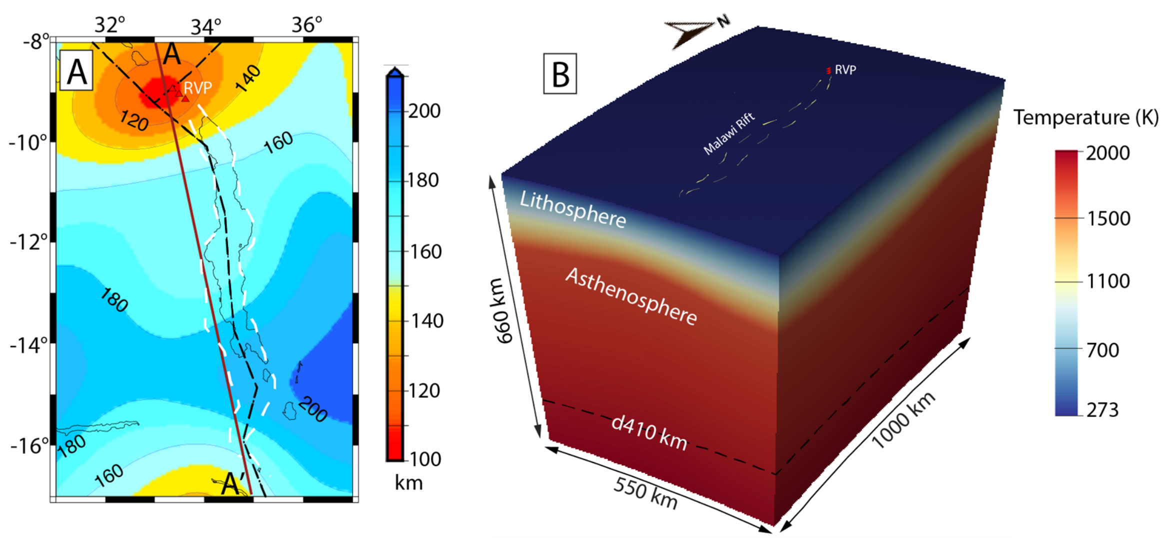

Figure 5: (A) Lithospheric thickness map of the Malawi Rift and surroundings, updated from Fishwick (2010). The blue contours show lines of equal lithospheric thickness at 20 km intervals. (B) Numerical model setup showing the model dimensions, and the initial temperature condition as the background in 3-D. Yellow dotted lines shows the outline of the Malawi Rift. RVP = Rungwe Volcanic Province.

- By implementing our BALTO-ASPECT plugin, ASPECT dereferences a URL using libdap and brokers the CSV ASCII data. It stores this data as a series of vectors. ASPECT then goes through these vectors and appends the values onto a stringstream and uses its existing sub-systems to read the data just as it would a local file.

Rheology:

- We implement a rigid lithosphere (10^{23} Pa.s)

- The asthenosphere is governed by a composite rheology flow law for dry olivine material parameters that includes porosity weakening (Jadamec & Billen, 2010).

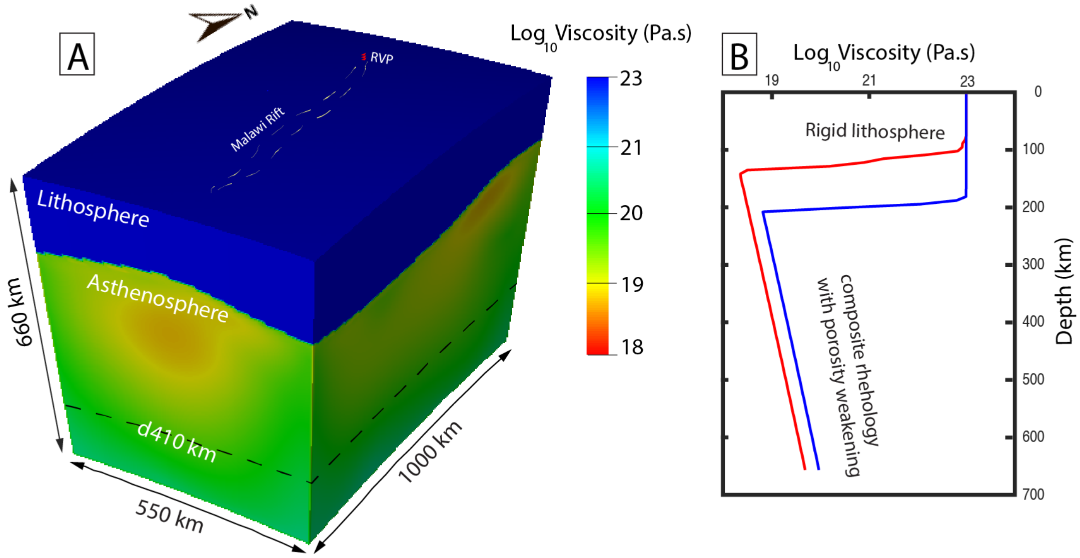

Figure 6: (A) Three-dimensional representation of the initial viscosity field. Yellow dotted lines show the outline of the Malawi Rift. RVP = Rungwe Volcanic Province. (B) One-dimensional initial viscosity depth profiles for a lithospheric thickness of 100 km (red) and 200 km (blue).

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

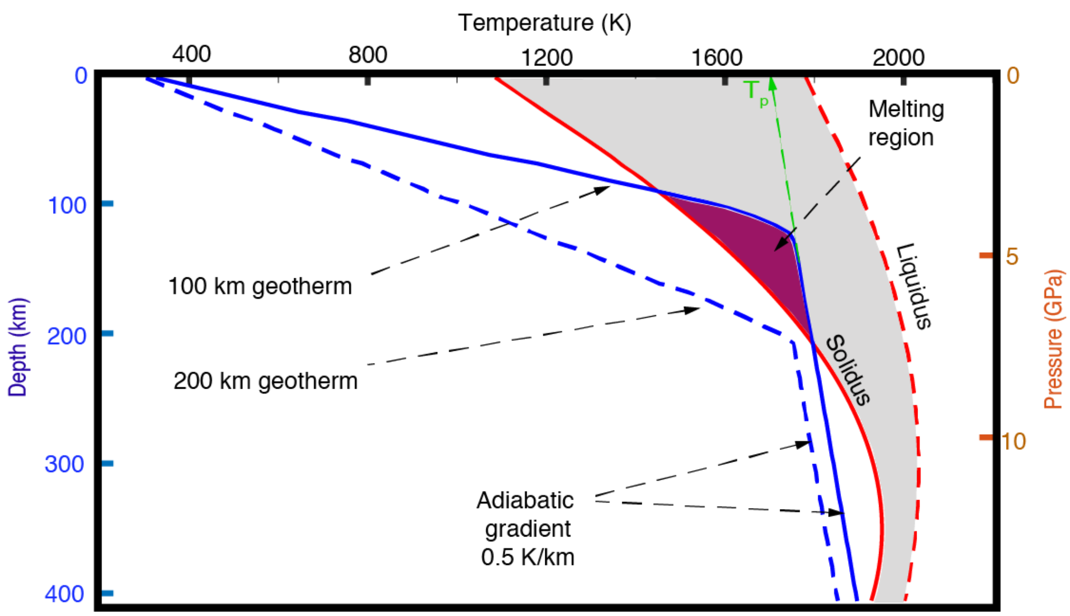

Figure 7: A combined plot of temperature-depth profiles (blue solid lines for a 100 km thick lithosphere and blue-dashed lines for a 200 km thick lithosphere) and a pressure-temperature phase diagram depicting shallow melting of anhydrous peridotite parameterized from Katz et al. (2003).

RESULTS

1. **Lithospheric Modulated Convection Model**

- Our results suggest asthenospheric upwelling beneath the RVP can be driven by LMC. At 150 km depth, asthenospheric upwelling (~ 1 cm/yr vertical flow) with a diverging (~2 cm/yr) horizontal flow occurs only beneath the RVP where the lithosphere is ~100-120 km thick.
- At 250 km depth, the asthenospheric upwelling beneath the RVP is faster (~3 cm/yr).

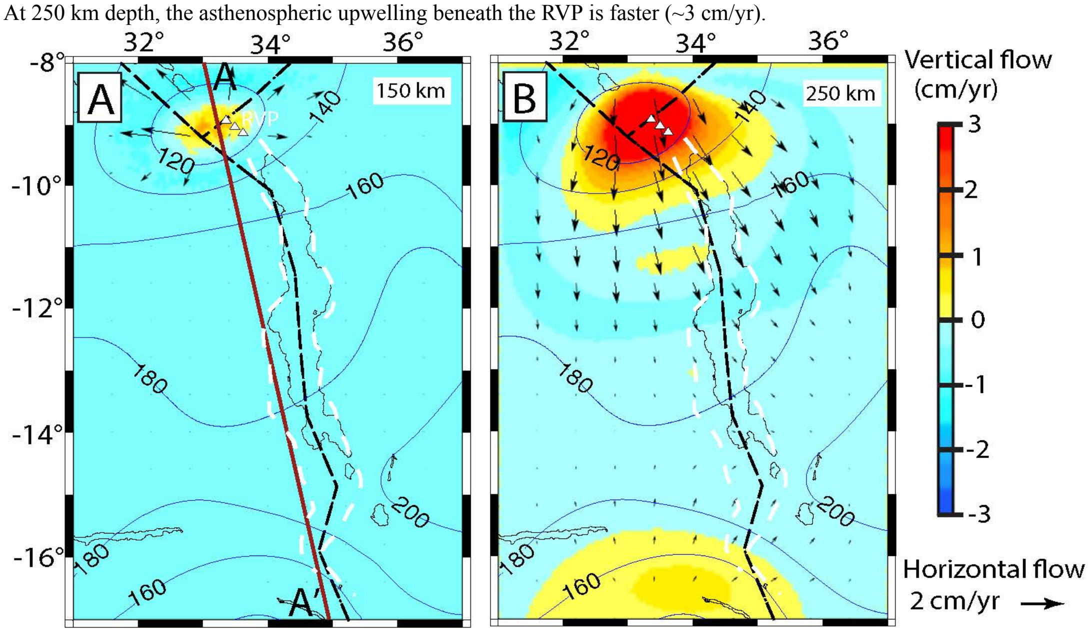

Figure 8: Depth slices showing lithospheric modulated convection beneath the RVP and the Malawi Rift at (A) 150 km and (B) 250 km depth at 17 Ma. The vertical flow (background color) is overlain by the horizontal flow fields (black arrows). White dotted lines indicates the outline of the Malawi Rift. 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. **The Melting Model**

- The time evolution of our melting model reveals two stages of melting.
    1. The unsteady melting stage occurs in the first 2 Ma of the model evolution. The melt arises from the initial conditions, which includes the thin lithosphere and a high mantle potential temperature.

2. Melt generation due to LMC (12-20 Ma)

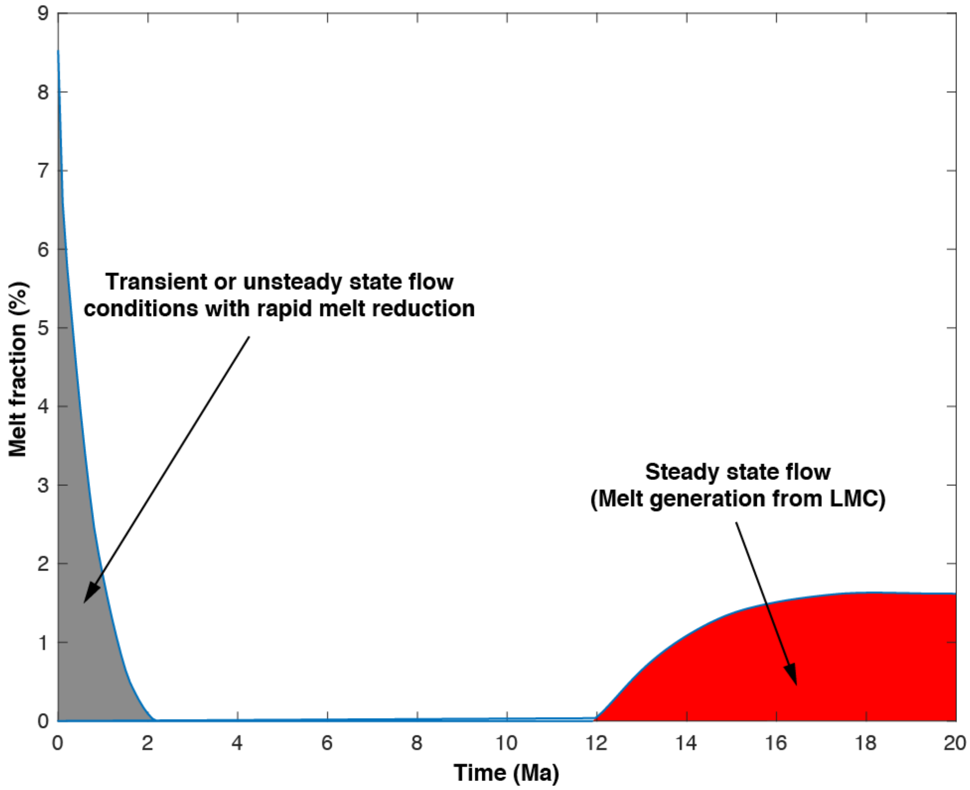

Figure 9: A plot of melt fraction versus time showing the evolution of melt in the model.

3. **Melt generation due to LMC**

- Steady-state LMC generates asthenospheric upwelling capable of bringing deep-hot mantle materials to shallower sublithospheric depths to generate melt

- Melt is generated just below the lithosphere at depth from 130-155 km

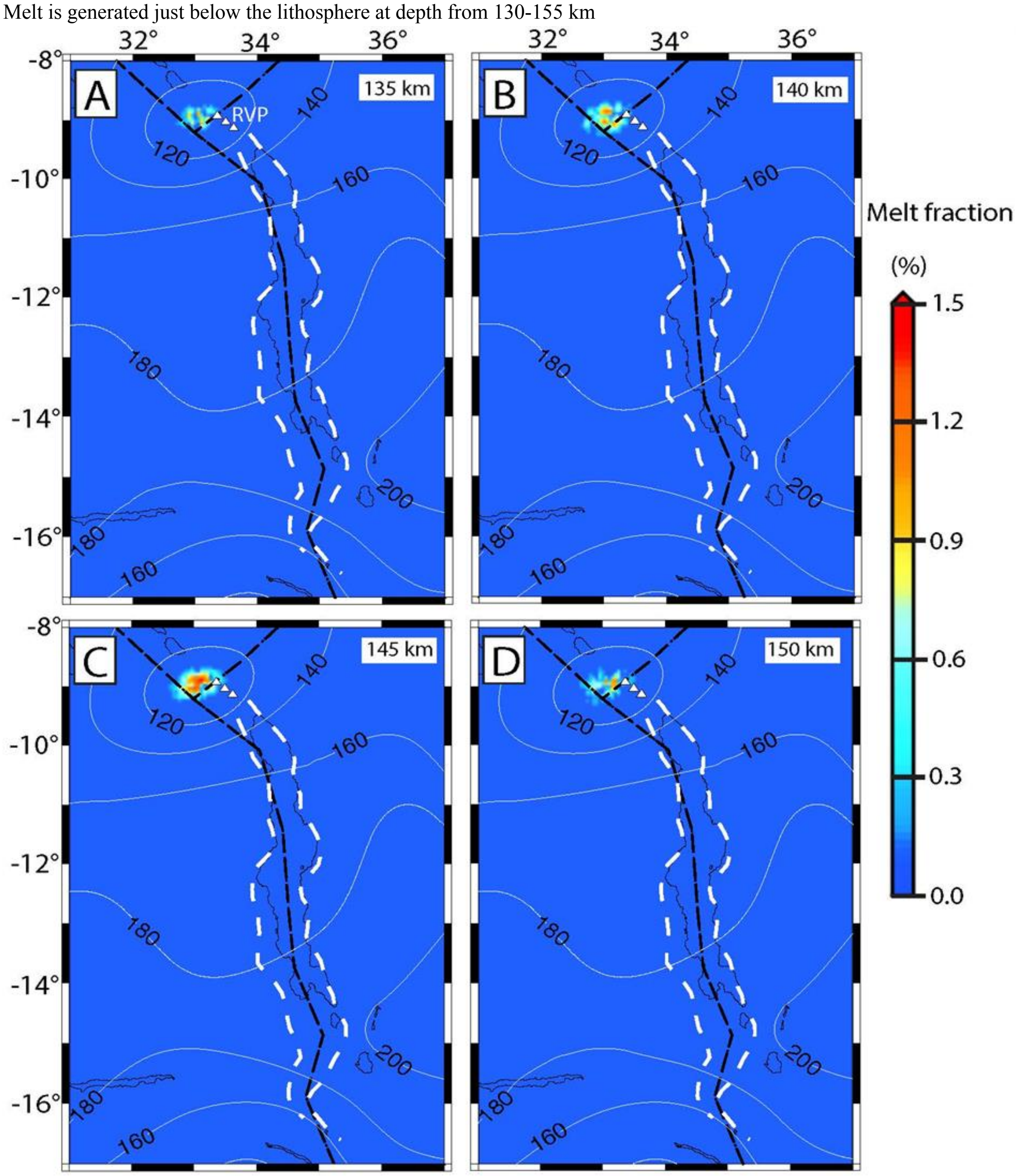

Figure 10: Depth slices showing melt fractions beneath the RVP and the Malawi Rift at (A) 135 km, (B) 140 km, (C) 145 km and (D) 150 km depth at 17 Ma.

DISCUSSION

1. **Sources of Melt Beneath the RVP**

LMC is a possible source for the melt beneath the RVP:

- LMC generates asthenospheric upwelling beneath the RVP that entrains deep-hot mantle materials to shallower sublithospheric depths to generate melt
- The LMC driven upwelling may entrain deeper plume materials

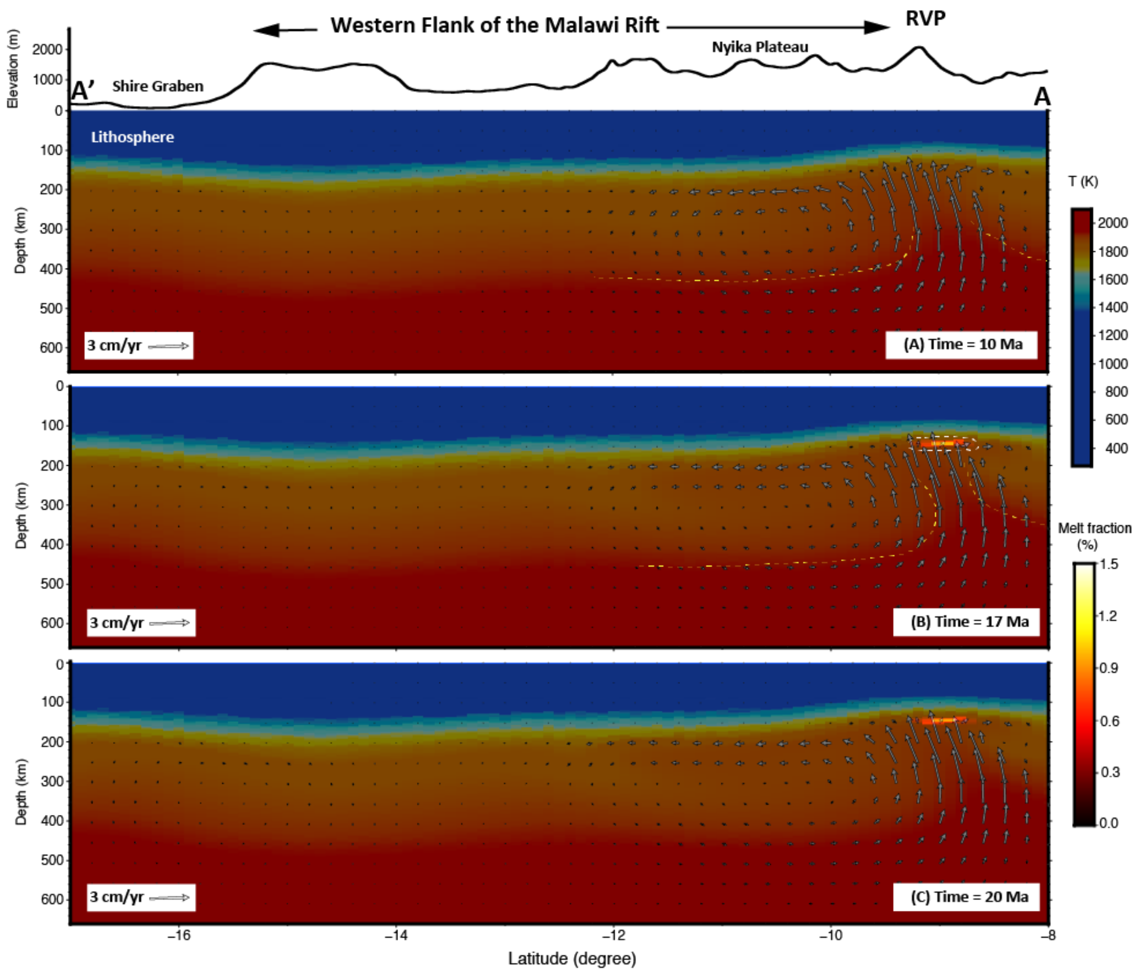

Figure 11: Profile showing time-dependent lithospheric modulated convection (LMC) across the Rungwe Volcanic Province (RVP) and the Malawi Rift (profile AA'; Figures 5 and 8). (A) Time = 10 Ma. (B) Time = 17 Ma. (C) Time = 20 Ma. Note the similarity in the structure of the mantle flow indicating relatively stable LMC. Yellow dotted lines indicates the upper boundary of deep hot asthenospheric mantle rising to shallower depths beneath the lithosphere. RVP = Rungwe Volcanic Province (RVP).

Other possible sources for the melt beneath the RVP:

- Plume sources evident from highe $^{3}He/^{4}He$ ratios (Hilton et al., 2011) and high mantle potential temperatures (Rooney et al., 2012)
- Lithospheric sources: Melting of metasomatized lithospheric mantle (Rooney, 2020)

2. **LMC and rifting in Malawi**

- LMC generates asthenospheric upwelling and melt beneath the RVP
- Southward mantle flow from the RVP towards the Malawi Rift might enhance rifting in Malawi either by:
  - thermal erosion of the base of the lithosphere or,
  - by contributing melts/fluids for metasomatic weakening of the lithosphere (Njinju et al., 2019)

CONCLUSIONS

- LMC is a possible source for the melt beneath the RVP and might be responsible for the shallow low velocity zone imaged beneath the RVP
- Given that there is evidence of possible plume sources of melt and melt from metasomatized lithospheric mantle, we conclude that the melt beneath the RVP is a mixture of melt formed by different processes and sourced from different depths
- Our BALTO-ASPECT plug-in provides the capability of a user to rapidly model melt generation from LMC 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 the lithosphere-asthenosphere system in the Malawi Rift

Sorry for the inconvenience!

ABSTRACT

The EarthCube BALTO (Brokered Alignment of Long-Tail Observations) project is aimed at developing new cyberinfrastructures that enables brokered access to diverse geoscience datasets. Towards achieving this BALTO objective, we developed a plug-in for the community extensible NSF open-source code ASPECT (Advanced Solver for Problems in Earth's Convection) that permits ASPECT to read data from the BALTO server (OPeNDAP's Hyrax open-source data server) over the web. We present a use-case of the BALTO-ASPECT client, which accesses lithospheric structures from the BALTO server to constrain a 3-D lithospheric modulated convection (LMC) modeling and melt generation beneath the Rungwe Volcanic Province (RVP) and the Malawi Rift. We test the hypothesis that at least part of the melt feeding the RVP is generated from LMC. In the model, we assume a rigid lithosphere, while for the asthenosphere we use non-Newtonian, temperature-, pressure- and porosity-dependent creep laws of peridotite. We find that a significant percentage of decompression melt from LMC occurs at a maximum depth of ~200 km beneath the axis of the Malawi Rift, consistent with the location and maximum depth of imaged low velocity zones. At shallower depths (~100 km), the melting region is focused beneath the RVP where there is rapid (~3 cm/yr) upwelling. Our results suggest that asthenospheric upwelling due to LMC is the main source of melt beneath the RVP and might also entrain the plume head materials with reported high 3He/4He values. We, therefore, propose that part of the melt beneath the northern Malawi Rift feeding the RVP can be generated by LMC without necessitating plumes impinging the base of the lithosphere at present. This use-case demonstrates the capability of the BALTO-ASPECT client to accelerate research by brokering input data from the BALTO server for modeling LMC and melt generation.

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