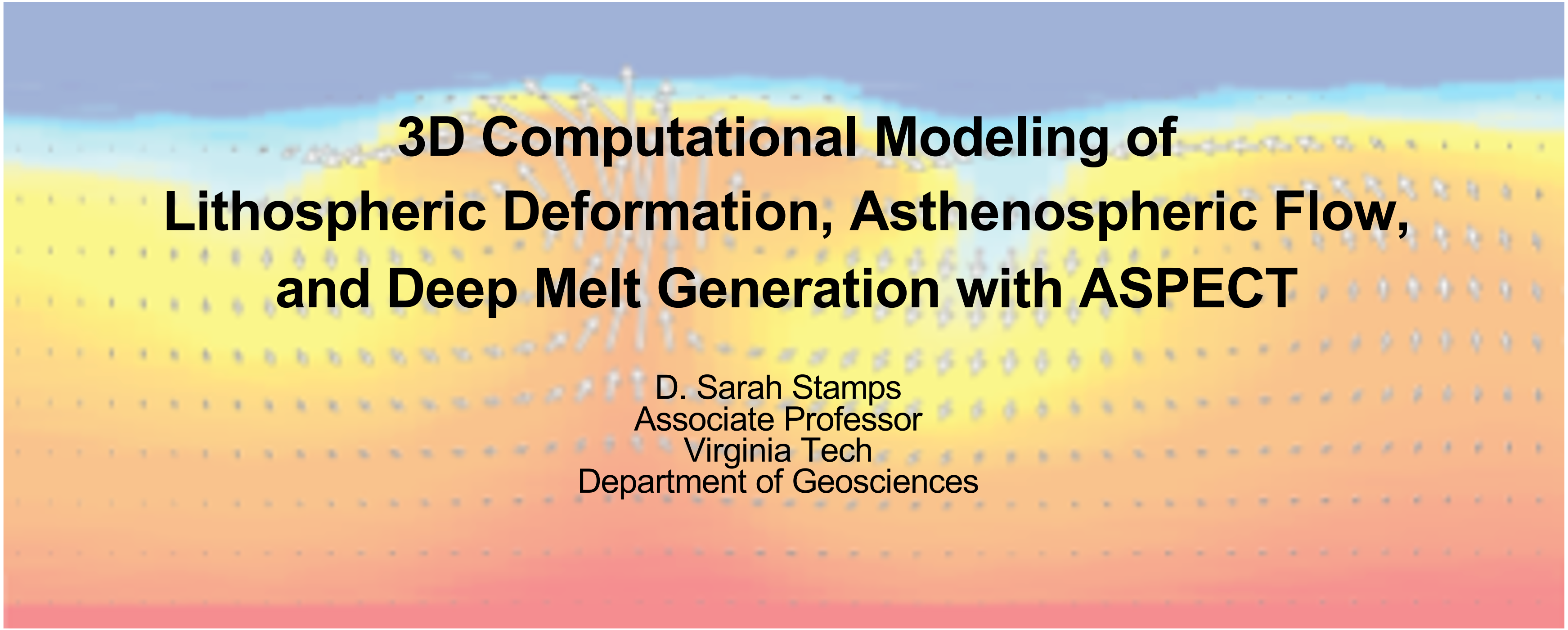

3D Computational Modeling of Lithospheric Deformation, Asthenospheric Flow, and Deep Melt Generation with ASPECT

D. Sarah Stamps
Associate Professor
Virginia Tech
Department of Geosciences

Contributions from:

Tahiry Rajaonarison, New Mexico Tech, USA
Emmanuel Njinju, Virginia Tech, USA
John Naliboff, New Mexico Tech, USA
Asenath Kwagalakwe, Virginia Tech, USA

EAR-1551864 GeoPRISMS Geodynamic Processes at Rifting and Subducting Margins
EAR-1740704 EarthCube BALTO Brokered Alignment of Long-tail Observations
NSF FRES 2021633
CIG COMPUTATIONAL INFRASTRUCTURE for GEODYNAMICS

Overview

Introduction

Lithospheric Deformation

Asthenospheric Flow

Deep Melt Generation

Summary & Conclusions

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Emmanuel Njinju, Virginia Tech, USA
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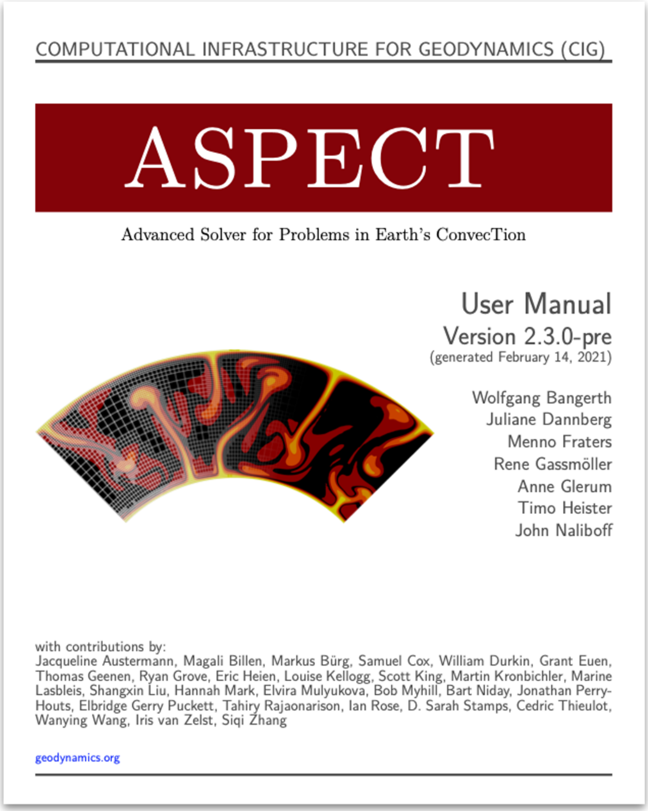
EAR-1551864
EAR-1740704
FRES 2021633

What is ASPECT?

- Advanced Solver for Problems in Earth's ConvecTion
- NSF Computational Infrastructure for Geodynamics finite element code (EAR-1550901)
- A community code that builds on the deal.II, Trilinos, and p4est libraries
- Applications in mantle convection on Earth and other planets, lithospheric deformation, melt generation


COMPUTATIONAL INFRASTRUCTURE FOR GEODYNAMICS (CIG)

ASPECT

Advanced Solver for Problems in Earth's ConvecTion

User Manual
Version 2.3.0-pre
(generated February 14, 2021)

Wolfgang Bangerth
Juliane Dannberg
Menno Fraters
Rene Gassmöller
Anne Glerum
Timo Heister
John Naliboff

with contributions by:
Jacqueline Austermann, Magali Billen, Markus Bürg, Samuel Cox, William Durkin, Grant Euen, Thomas Geenen, Ryan Grove, Eric Heien, Louise Kellogg, Scott King, Martin Kronbichler, Marine Lasbleis, Shangxin Liu, Hannah Mark, Elvira Mulyukova, Bob Myhill, Bart Niday, Jonathan Perry-Houts, Elbridge Gerry Puckett, Tahiry Rajaonarison, Ian Rose, D. Sarah Stamps, Cedric Thieulot, Wanying Wang, Iris van Zelst, Siqi Zhang

geodynamics.org

What is ASPECT?

ASPECT solves the Stokes equations for velocity and pressure

$$-\nabla \cdot \left[2\eta \left(\varepsilon(\mathbf{u}) - \frac{1}{3}(\nabla \cdot \mathbf{u})\mathbf{1}\right)\right] + \nabla p = \rho \mathbf{g}$$

Conservation of momentum

$$\nabla \cdot (\rho \mathbf{u}) = 0$$

Conservation of mass

η = viscosity

$\varepsilon(\mathbf{u})$ = strain rate

p = pressure

ρ = density

$\mathbf{g}$ = gravitational acceleration

What is ASPECT?

Coupled is the energy equation for solving for temperature

$$\left(\rho C_p - \rho T \Delta S \frac{\partial X}{\partial T}\right)\left(\frac{\partial T}{\partial t} + \mathbf{u}\cdot\nabla T\right) - \nabla\cdot k\nabla T = \rho H$$

Internal heat production

Viscous shear heating $+2\eta\left(\varepsilon(\mathbf{u}) - \frac{1}{3}(\nabla\cdot\mathbf{u})\mathbf{1}\right) : \left(\varepsilon(\mathbf{u}) - \frac{1}{3}(\nabla\cdot\mathbf{u})\mathbf{1}\right)$

Adiabatic compression of material $+\alpha T\left(\mathbf{u}\cdot\nabla p\right)$

Phase change (latent heat) $+\rho T \Delta S \frac{\partial X}{\partial p}\mathbf{u}\cdot\nabla p$

C_p = specific heat capacity

T = temperature

S = specific entropy

$\mathbf{u}$ = velocity

k = thermal conductivity

α = thermal expansion coefficient

Where can I find ASPECT?

- Current release version

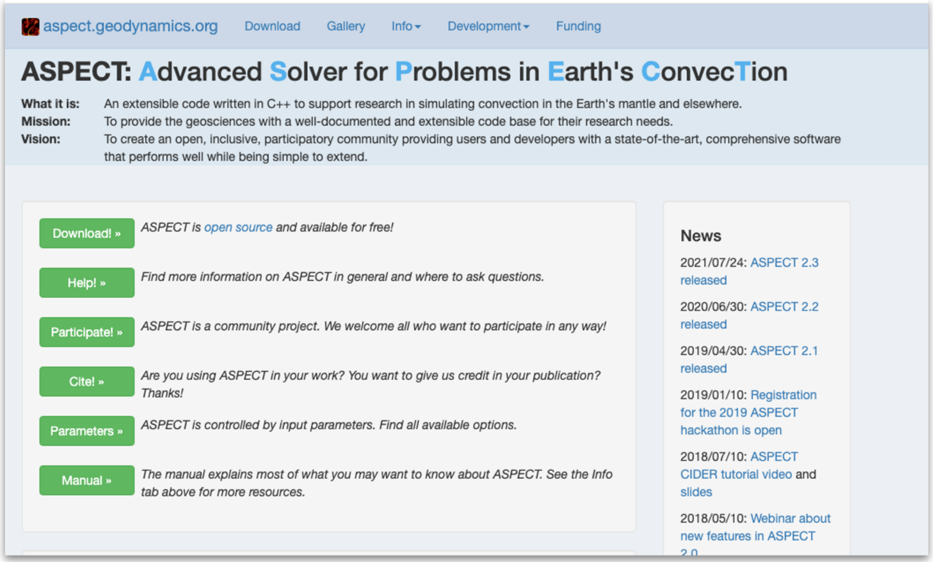
https://aspect.geodynamics.org/

- Current development version:

https://github.com/geodynamics/aspect.git

- Extensions to ASPECT from specific papers

Zenodo and/or GitHub usually



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EAR-1551864
EAR-1740704
FRES 2021633

ASPECT can be used for modeling lithospheric deformation

Geophysical Research Letters

RESEARCH LETTER
10.1029/2020GL090483

Role of Lithospheric Buoyancy Forces in Driving Deformation in East Africa From 3D Geodynamic Modeling

Tahiry A. Rajaonarison[1], D. Sarah Stamps[1], and John Naliboff[2,3]

[1]Department of Geosciences, Virginia Tech, Blacksburg, VA, USA, [2]Dep… New Mexico Tech, Socorro, NM, USA, [3]Department of Earth and Planet… CA, USA

Key Points:

- 3D geodynamic models reveal that lithospheric buoyancy forces primarily drive ~E-W extension across East Africa
- Lithospheric buoyancy forces generate rigid plate motions aligned with kinematic predictions derived from GPS data
- Additional forces arising from horizontal mantle tractions may be required to explain along-rift surface motions in deforming zones

Abstract Despite decades of investigation, the origin of for… highly debated. Deciphering their relative contributions is chall… dependent nature of lithospheric rheology. Recent geodynamic…

Rajaonarison, T. A., Stamps, D. S., & Naliboff, J. (2020b). *Trajaona/aspect: Rifting model of the East African Rift (version v1.0)*. Zenodo. https://doi.org/10.5281/zenodo.4005094

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August 28, 2020 | Software | Open Access

trajaona/aspect: Rifting Model of the East African Rift

Tahiry Rajaonarison; D. Sarah Stamps; John Nalibof

This software package is a modified version of ASPECT v.2.2.0, which allows to reproduce model results of Rajaonarison et al. (submitted to GRL). The model setup is as follow:

1) In this model, the lithospheric deformation is driven by lithospheric buoyancy forces which are imposed by implementing the CRUST1.0 (density and thicknesses for lower, middle, and upper crust) and ETOPO1 data sets into the 3D model.

2) The lithospheric temperature structure is a steady-state conductive geothermal gradient characteristic of the continental lithosphere, which is constrained using estimates of regional lithospheric thickness and surface heat flow of the key tectonic regions (cratons, mobile belts, and rifts).

3) Isostatic compensation is enforced through adjustments to the mantle density (i.e. Pratt isostasy) down to 100 km, with a constant value of 3300 kg/m**3 assigned from the compensation depth to 660 km.

4) The rheological model combines non-linear viscous flow: dislocation creep of dry quartzite with plastic failure in the crust, dislocation creep of olivine in the mantle lithosphere, and composite rheology of dry olivine in the sublithospheric mantle. In the deforming regions, a plastic strain weakening factor for cohesion and friction is applied to the lithospheric viscosity to promote strain localization.

The model can be run using the parameter file (EAR_rifting.prm) that is attached with this description. We refer the reader to the ASPECT user manual for information about how to run model in ASPECT.

This work was funded by the National Science Foundation (NSF) GeoPRISMS grant EAR-1551864.

Available in GitHub

Indexed in OpenAIRE

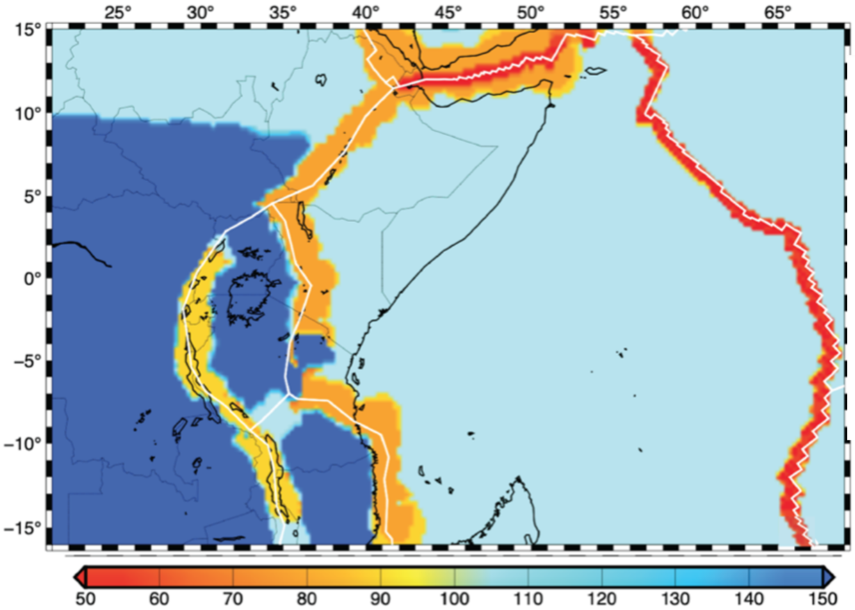
Publication date:
August 28, 2020
DOI:
DOI 10.5281/zenodo.4005094

Rajaonarison, T. A., Stamps, D. S., & Naliboff, J. (2021). Role of lithospheric buoyancy forces in driving deformation in East Africa from 3D geodynamic modeling. Geophysical Research Letters, 48, e2020GL090483. https://doi. org/10.1029/2020GL090483

EAR-1551864

Geo PRISMS Geodynamic Processes at Rifting and Subducting Margins

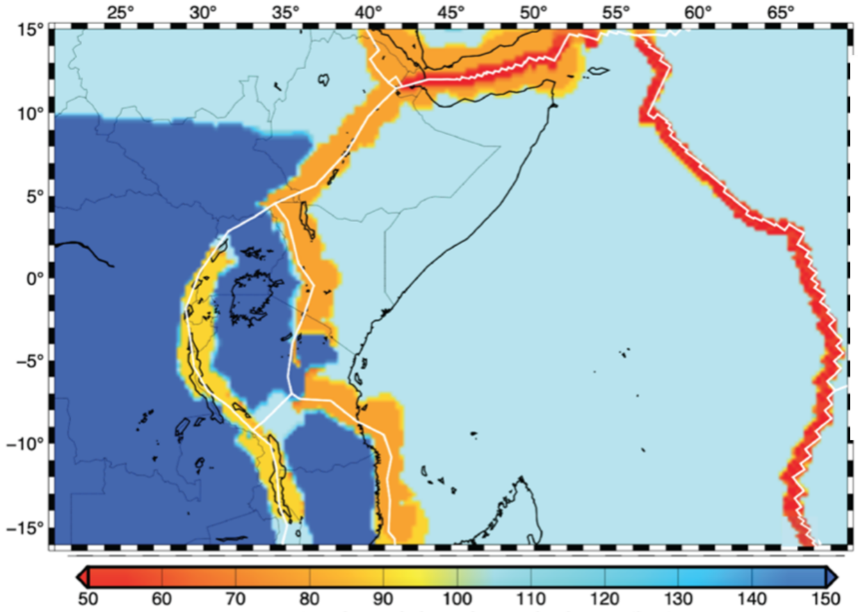
Model Set-up: Lithospheric and Crustal Thickness



Synthetic Lithospheric Thickness (km)
Averaged from 3 seismically constrained models

Continental rift areas = 90 km, 70 km
Cratons = 150 km
Oceanic Ridges = 50 km
Mobile Belts+ = 100 km

Model Set-up: Lithospheric and Crustal Thickness



Synthetic Lithospheric Thickness (km)
Averaged from 3 seismically constrained models

Continental rift areas = 90 km, 70 km
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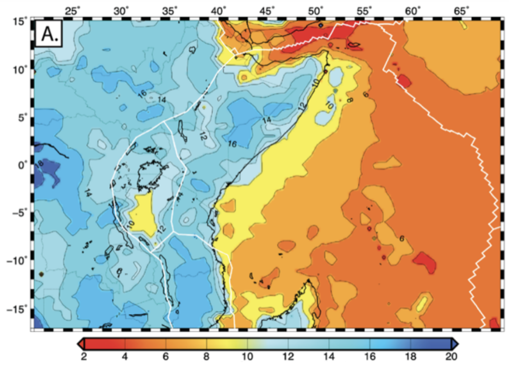
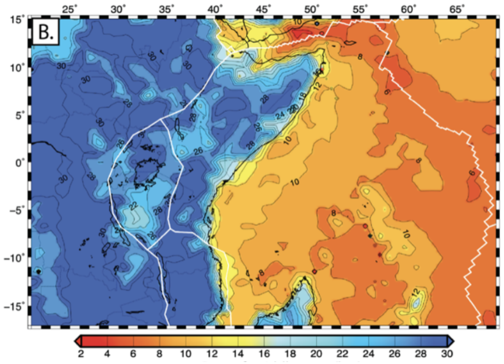
Mobile Belts+ = 100 km

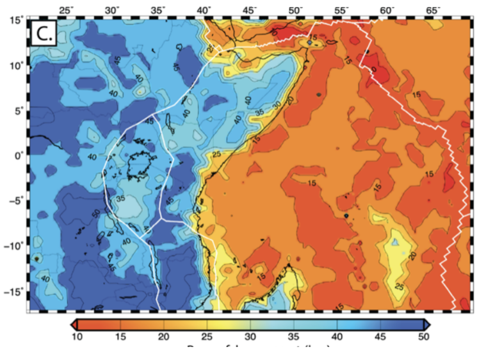
CRUST1.0 (Laske et al., 2012)



Base of Upper Crust (km)

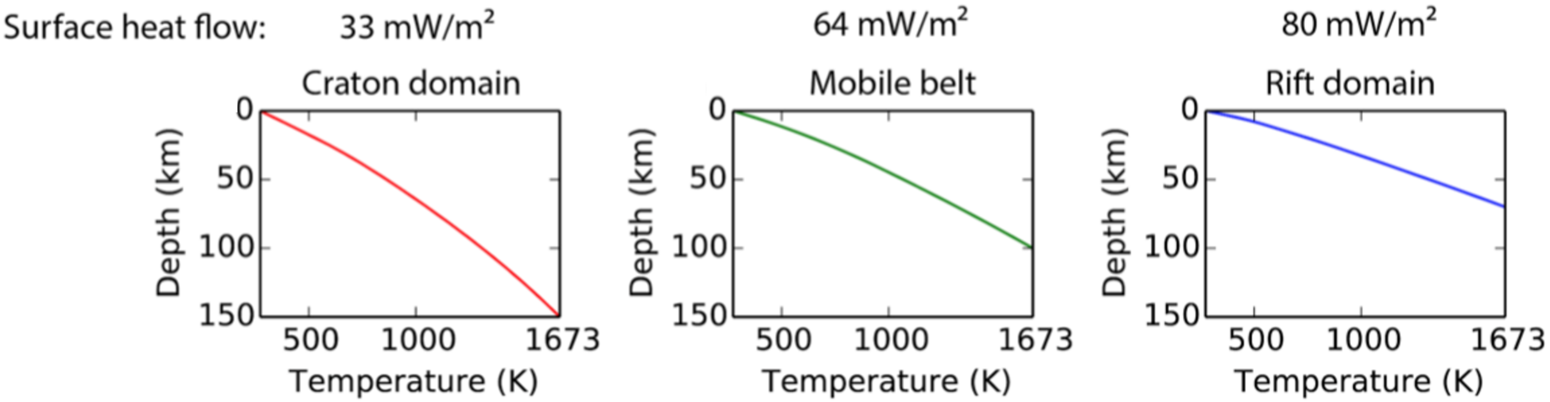


Base of Middle Crust (km)



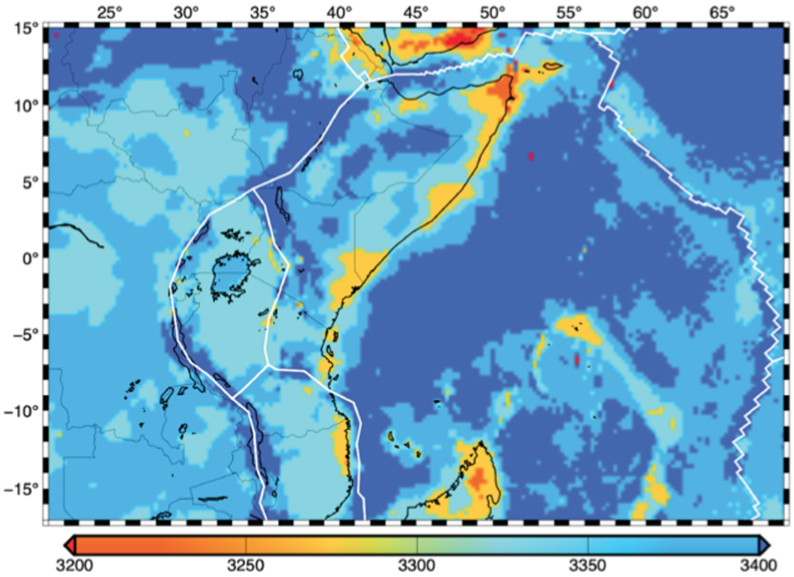
Base of Lower Crust (km)

Model Set-up: Temperature



- A steady-state conductive geothermal gradient (Chapman, 1986).
- Constrained by lithospheric thickness and surface heat flow of the key tectonic regions.
- Below the lithosphere, the temperature increases approximately adiabatically.

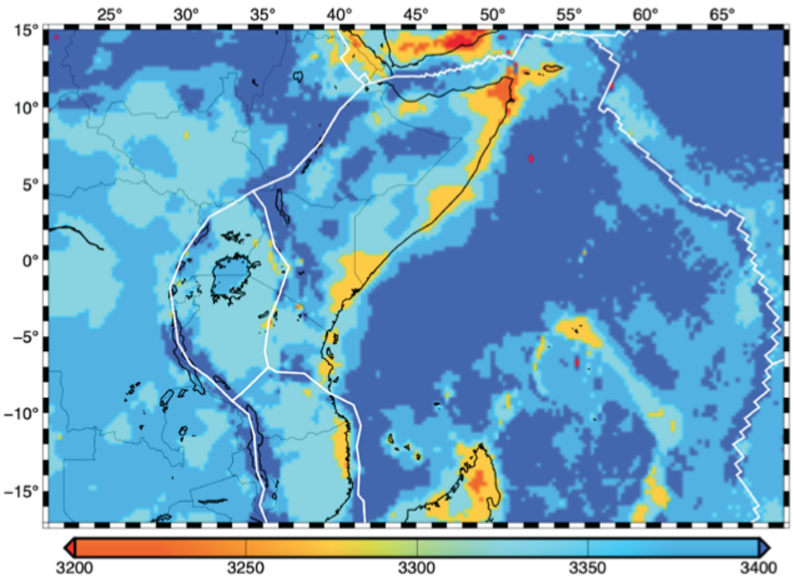
Model Set-up: Density



Vertically Averaged Mantle Lithosphere Density (kg/m3)

- 100 km compensation depth
- Laterally varying density in lithospheric mantle for isostatic compensation

Model Set-up: Density



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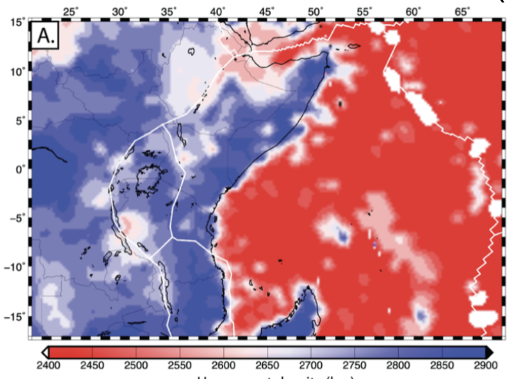
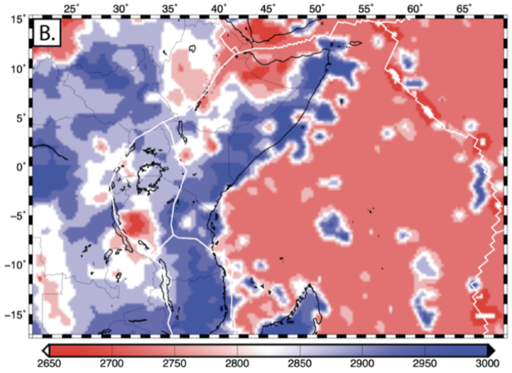
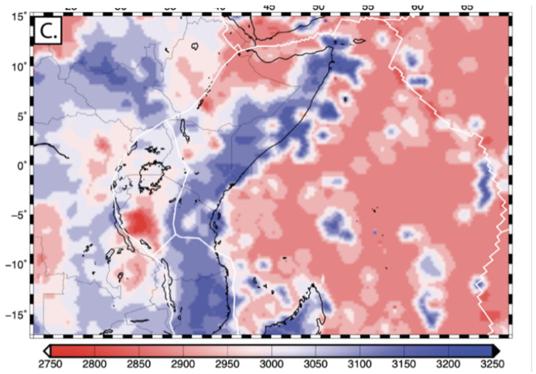
CRUST1.0 (Laske et al., 2012)



Density of Upper Crust (km)



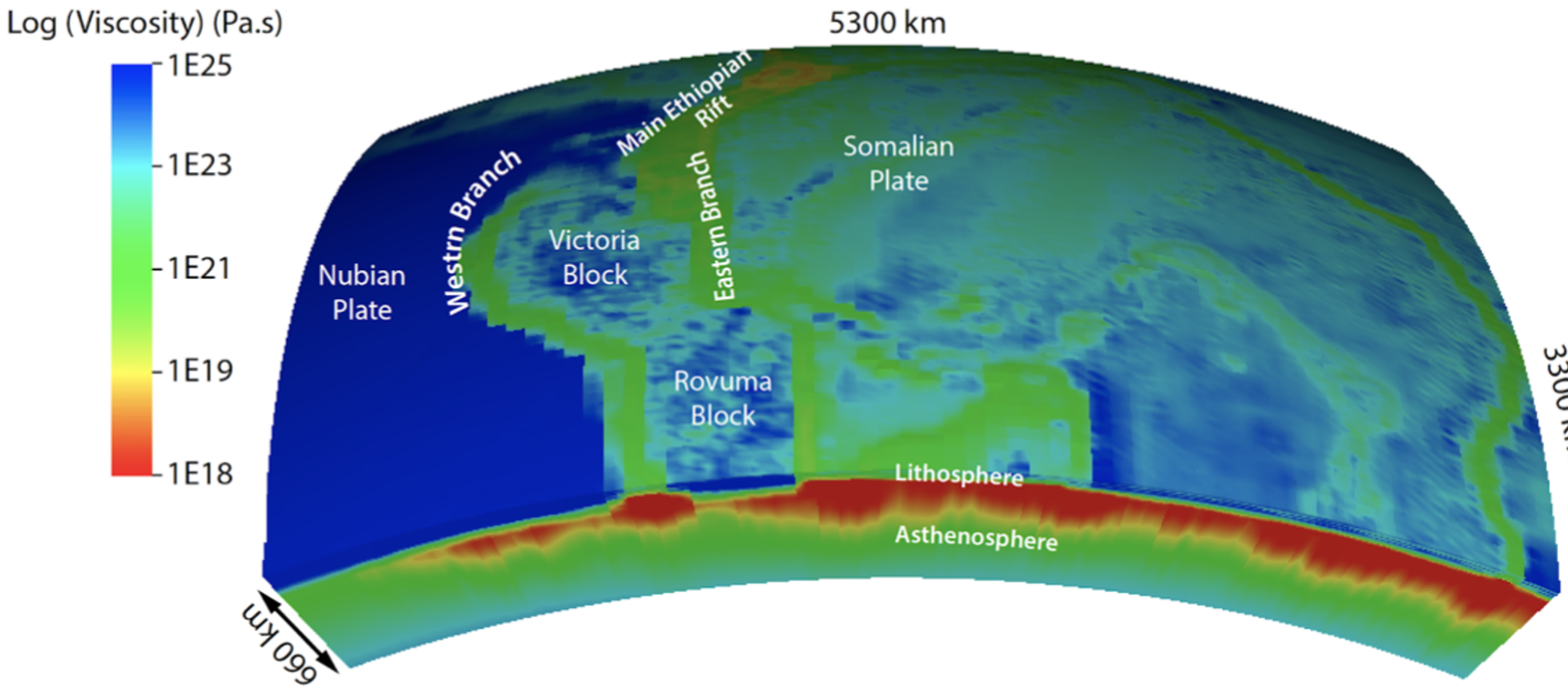
Density of Middle Crust (km)



Density of Lower Crust (km)

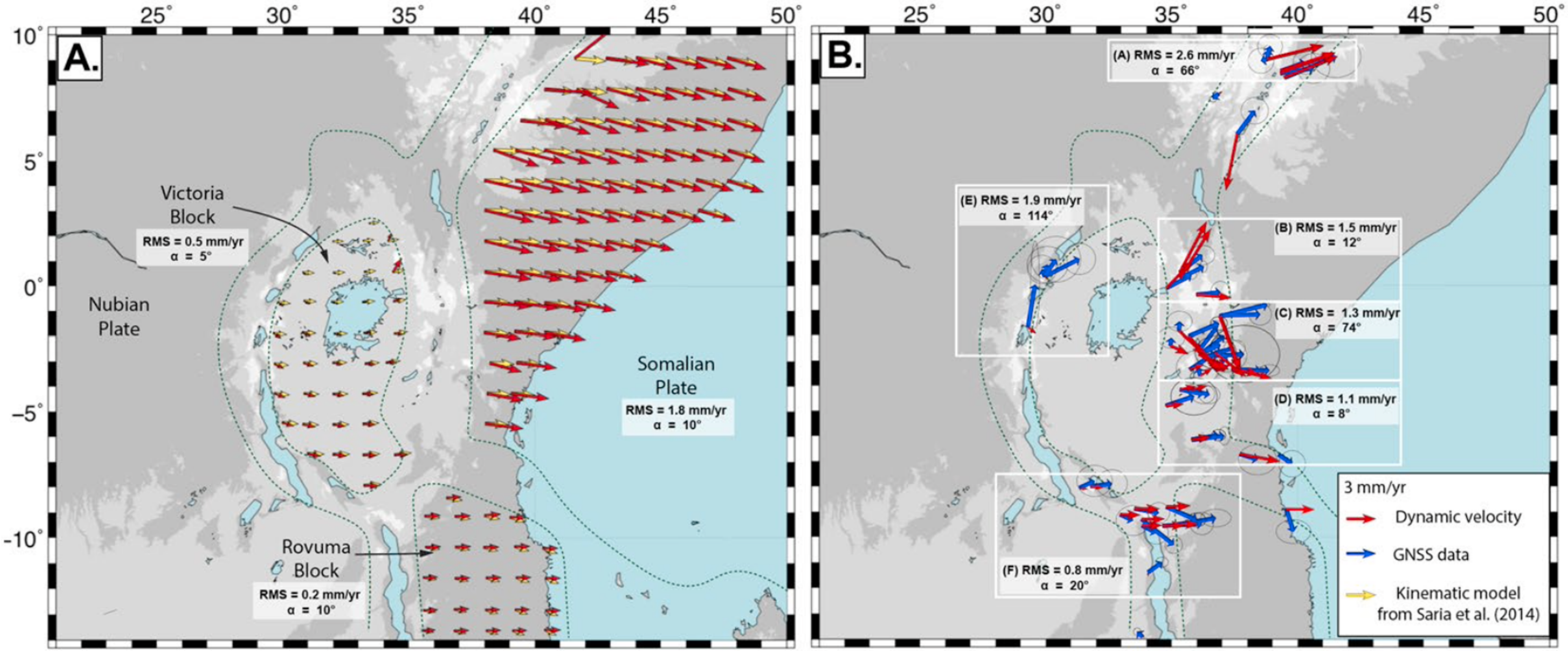
Model Set-up: Viscosity

- Crust: Combines nonlinear quartzite dislocation creep with plastic failure (Gleason et al., 1995)
- Mantle lithosphere: Combines olivine dislocation creep (Hirth & Kolhstedt, 2003) with plastic failure
- Sublithospheric mantle: Composite dry olivine diffusion and dislocation creep (Hirth & Kolhstedt, 2003)



Case Study Results: East African Rift

- Lithospheric buoyancy forces primarily drive ~E-W extension across East Africa
- Lithospheric buoyancy forces generate rigid plate motions aligned with kinematic predictions derived from GPS data
- Additional forces arising from horizontal mantle tractions may be required to explain along-rift surface motions in deforming zones



Overview

Contributions from:
Tahiry Rajaonarison, New Mexico Tech, USA
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FRES 2021633
EAR-1551864
EAR-1740704

ASPECT can be used for modeling asthenospheric flow

JGR Solid Earth

RESEARCH ARTICLE

10.1029/2019JB018560

Key Points:

- Asthenospheric flow patterns beneath Madagascar are predicted from edge-driven convection and mantle wind modeling
- Comparison of predicted shear wave splitting parameters with seismic anisotropy suggests a predominantly asthenospheric source
- Dislocation creep rheology extends into the asthenosphere beneath some continental regions

Numerical Modeling of Mantle Flow Beneath Madagascar to Constrain Upper Mantle Rheology Beneath Continental Regions

T. A. Rajaonarison[1], D. S. Stamps[1], S. Fishwick[2], S. Brune[3,4], A. Glerum[3], and J. Hu[5]

[1]Department of Geosciences, Virginia Polytechnic Institute and State University, Blacksburg, VA, USA, [2]Department of Geology, University of Leicester, Leicester, UK, [3]GFZ German Research Center of Geosciences, Potsdam, Germany, [4]Institute of Earth and Environmental Sciences, University of Potsdam, Potsdam, Germany, [5]Division of Geological and Planetary Sciences, California Institute of Technology, Pasadena, CA, USA

Abstract Over the past few decades, azimuthal seismic anisotropy measurements have been widely

Rajaonarison, T. A., Stamps, D. S., Fishwick, S., Brune, S., Glerum, A., & Hu, J. (2020). Numerical modeling of mantle flow beneath Madagascar to constrain upper mantle rheology beneath continental regions. Journal of Geophysical Research: Solid Earth, 125, e2019JB018560. https://doi.org/ 10.1029/2019JB018560

Built into the ASPECT release code

A.74 Parameters in section `Initial temperature model/Adiabatic boundary`

- *Parameter name:* `Adiabatic temperature gradient`

  Value: 0.0005

  Default: 0.0005

  Description: The value of the adiabatic temperature gradient. Units: $\mathrm{K\,m^{-1}}$.

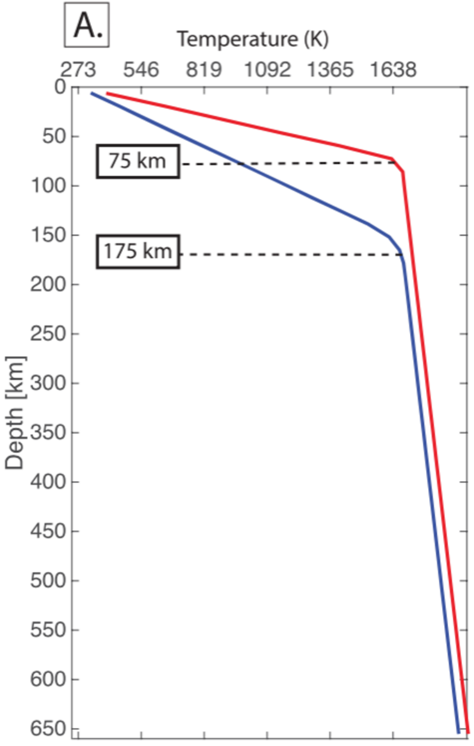
  Possible values: A floating point number v such that $0 \leq v \leq \text{MAX\_DOUBLE}$

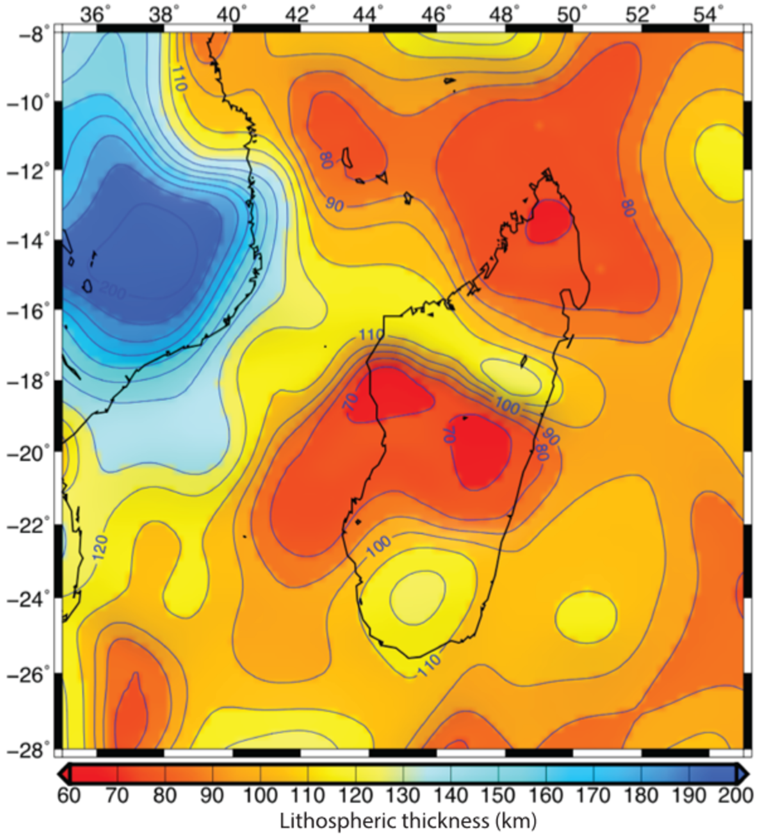
EAR-1551864

Geo PRISMS Geodynamic Processes at Rifting and Subducting Margins

Model Setup: Initial Temperature Conditions

- Lithospheric thickness input with isotherm at lithosphere-asthenosphere boundary (LAB, i.e. Fishwick 2010, updated)
- Approximate conductive geotherm in lithosphere: linear gradient from surface to LAB isotherm (1673 K)
- Approximately adiabatic geotherm below lithosphere (i.e. 0.5 K/km)





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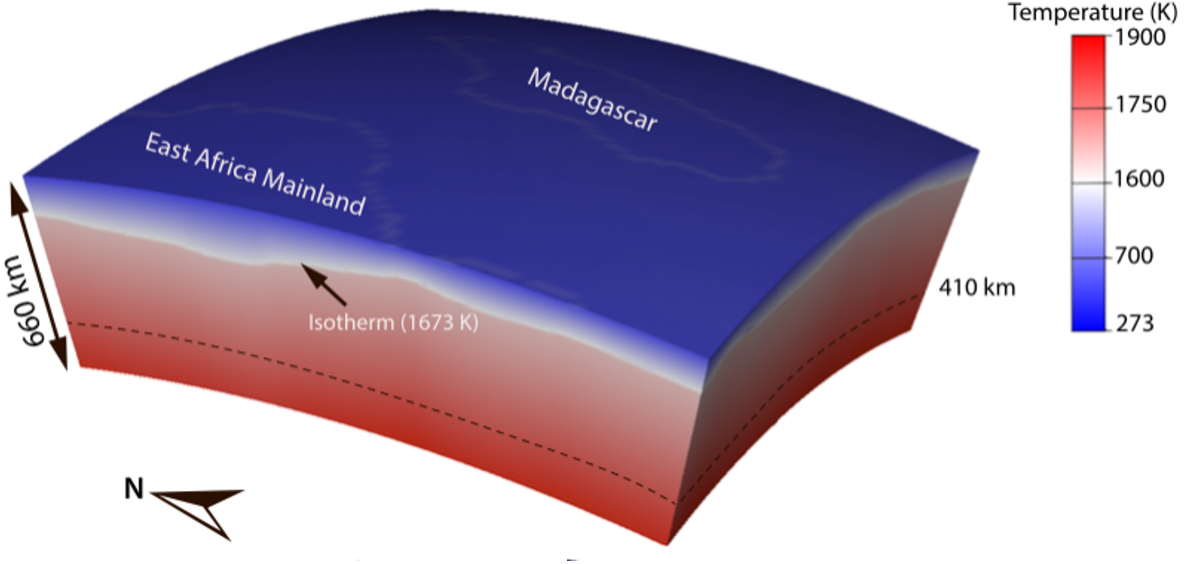
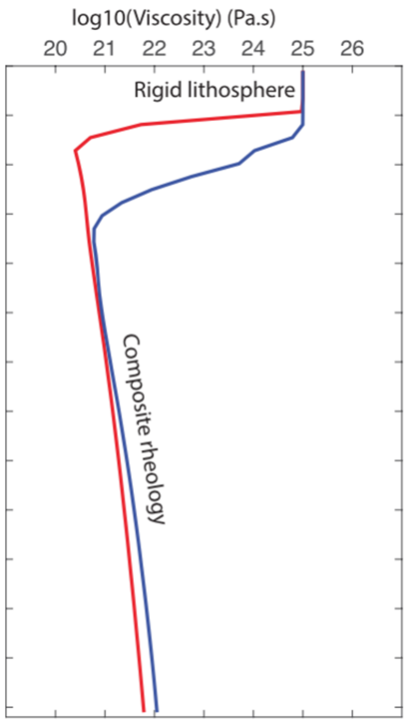
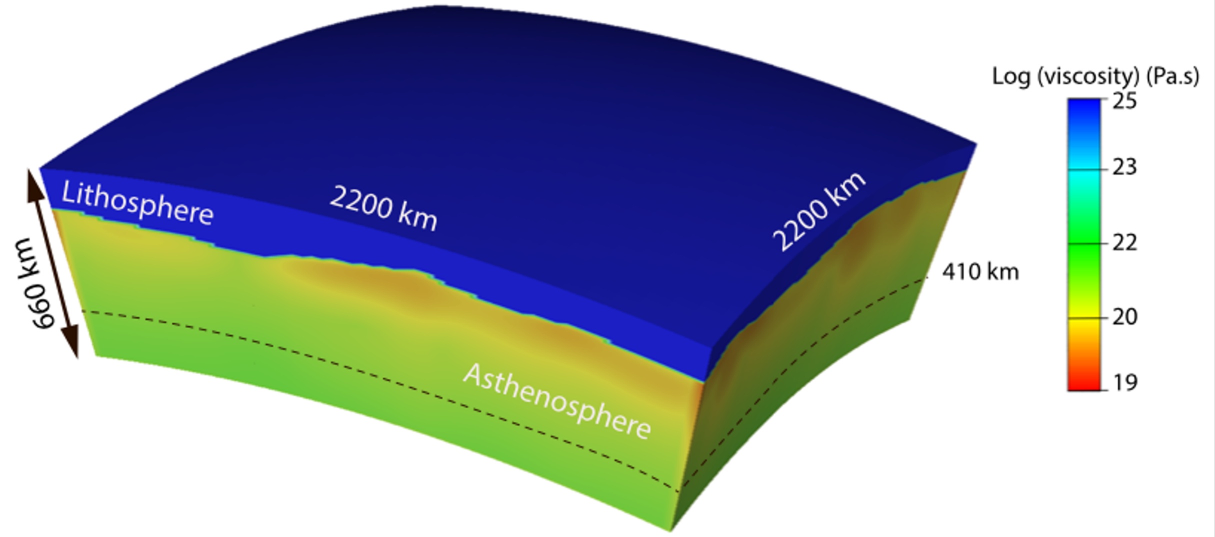


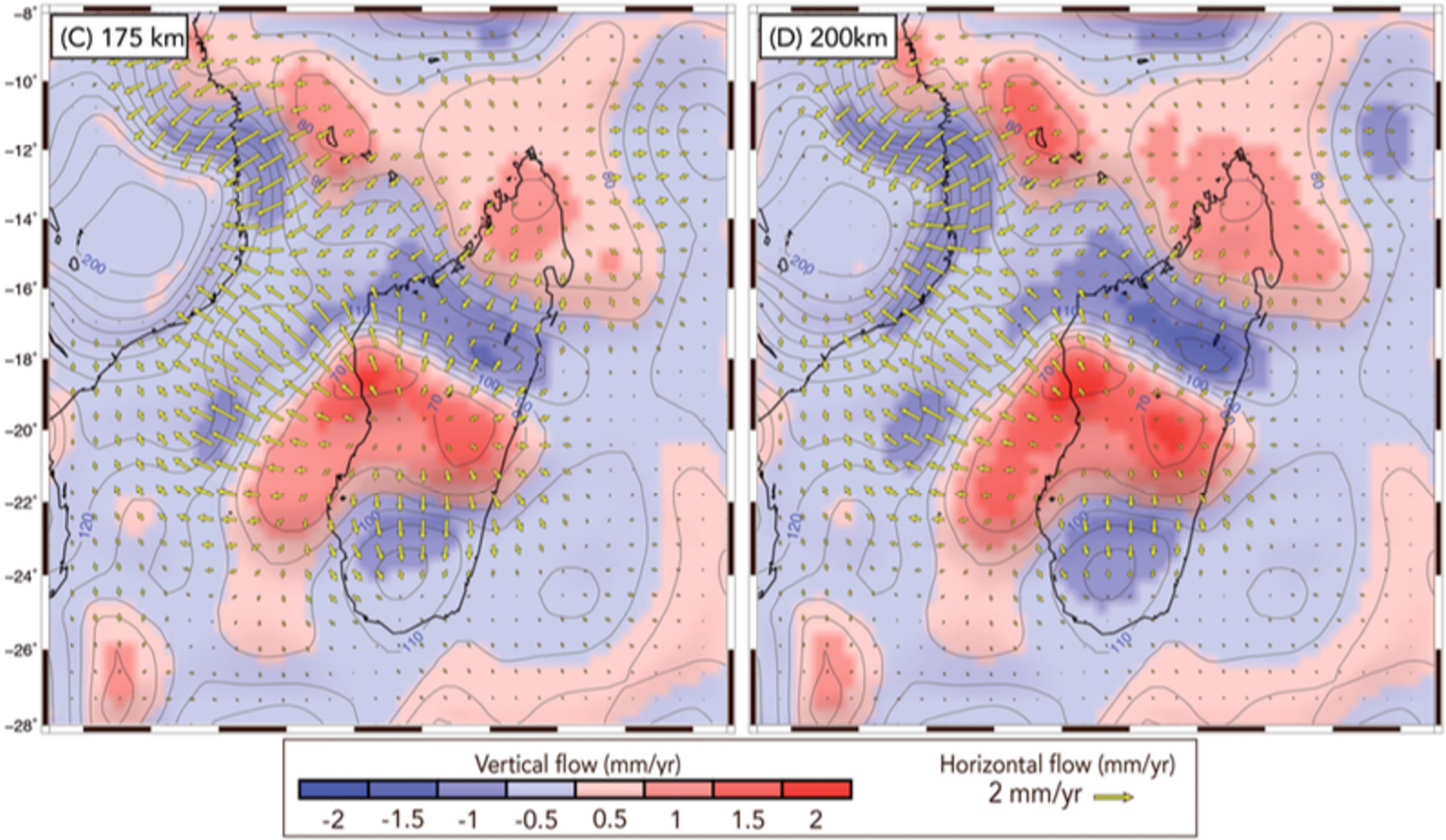
Model Setup: Viscosity and Density

- High viscosity lithosphere (1E25 Pa.s)
- Composite rheology for sublithospheric mantle (Jadamec & Billen, 2010)
- Temperature dependent density below the lithosphere





Case Study: Madagascar



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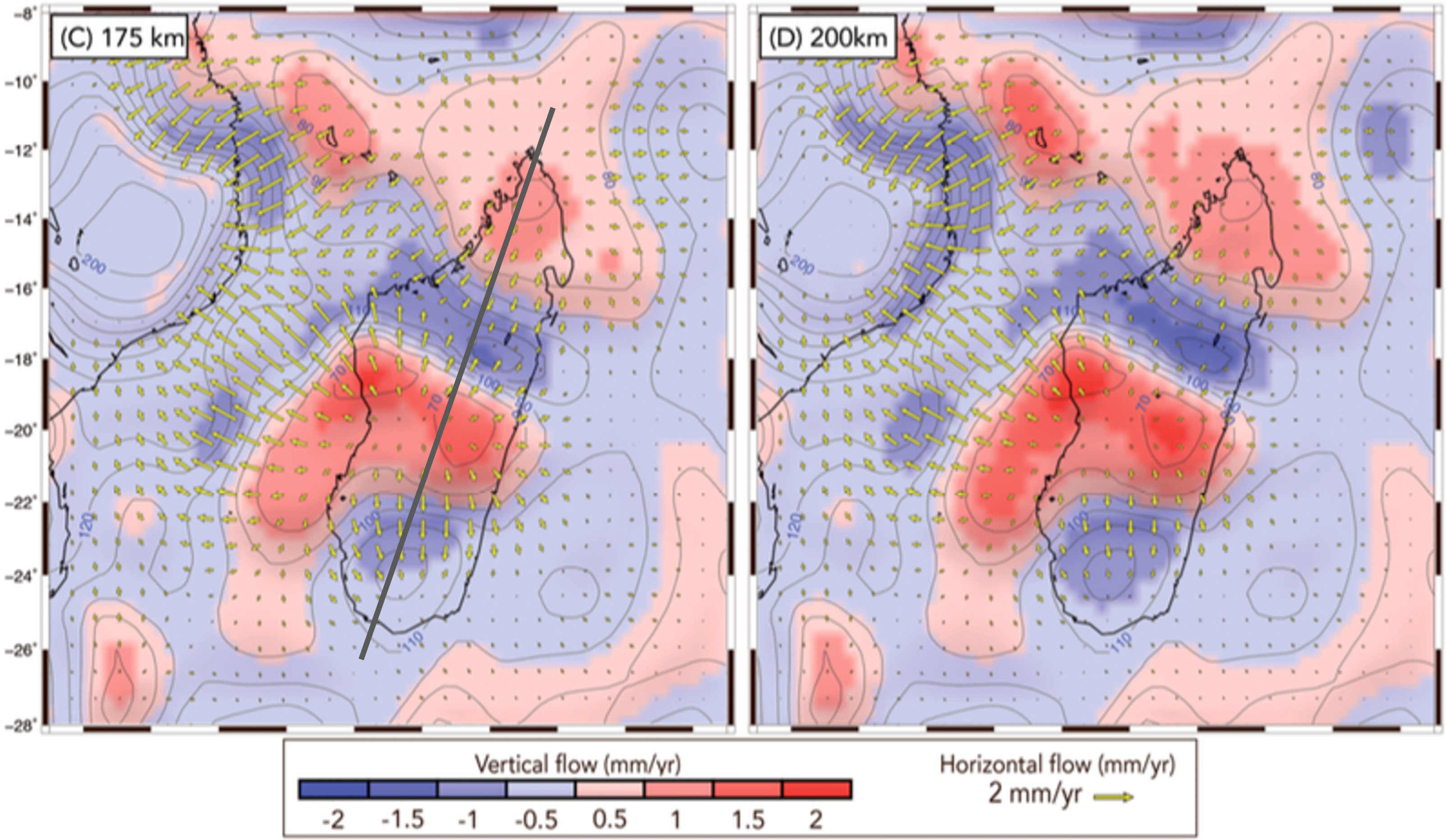

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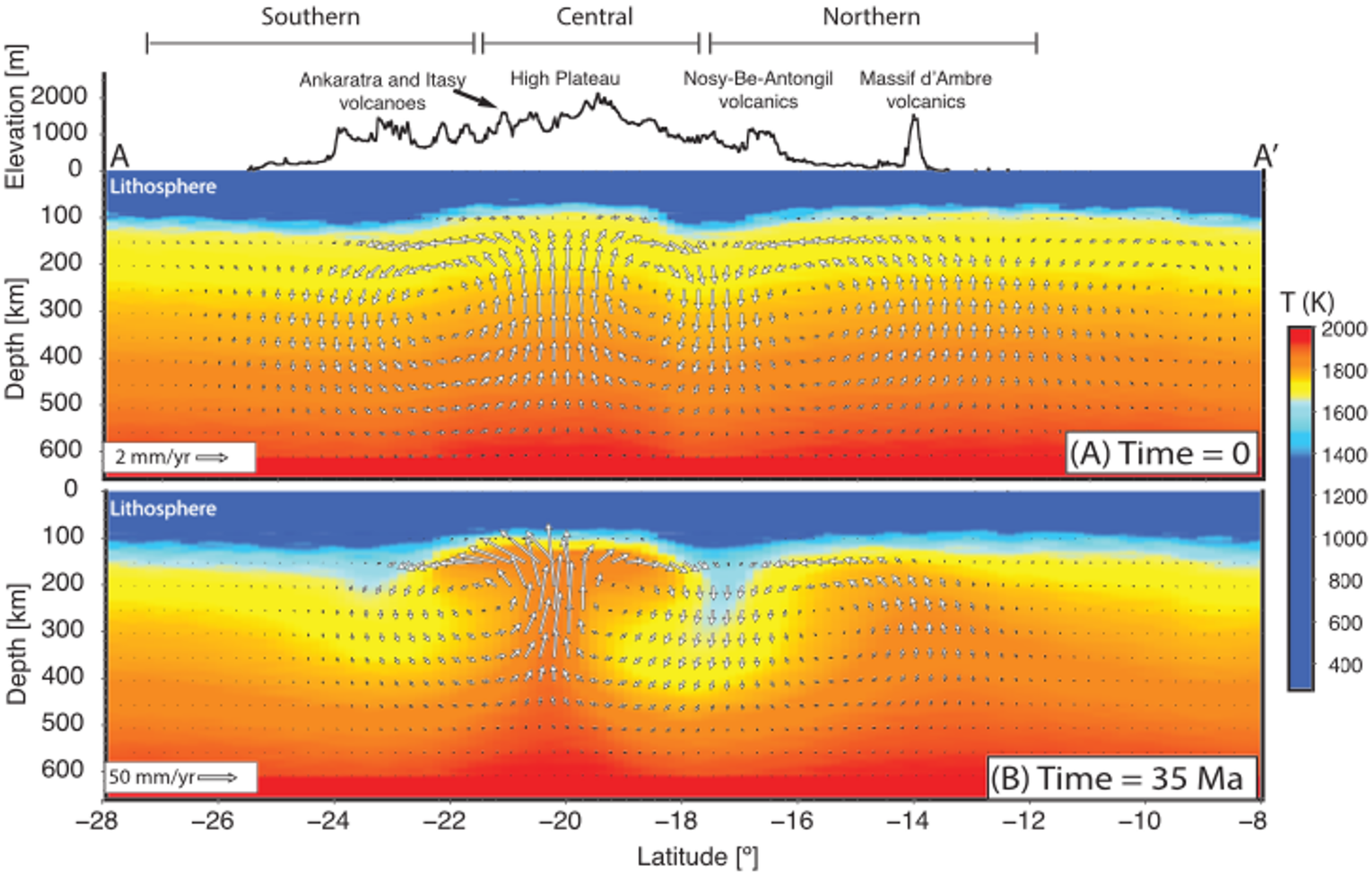

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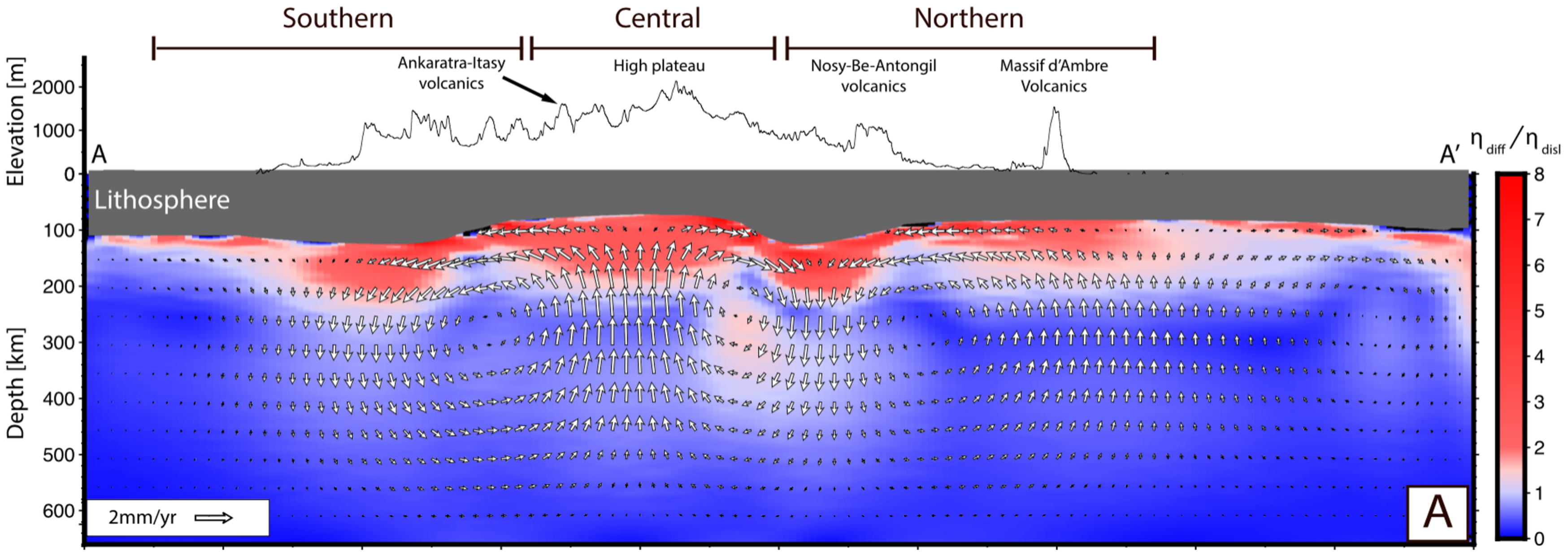

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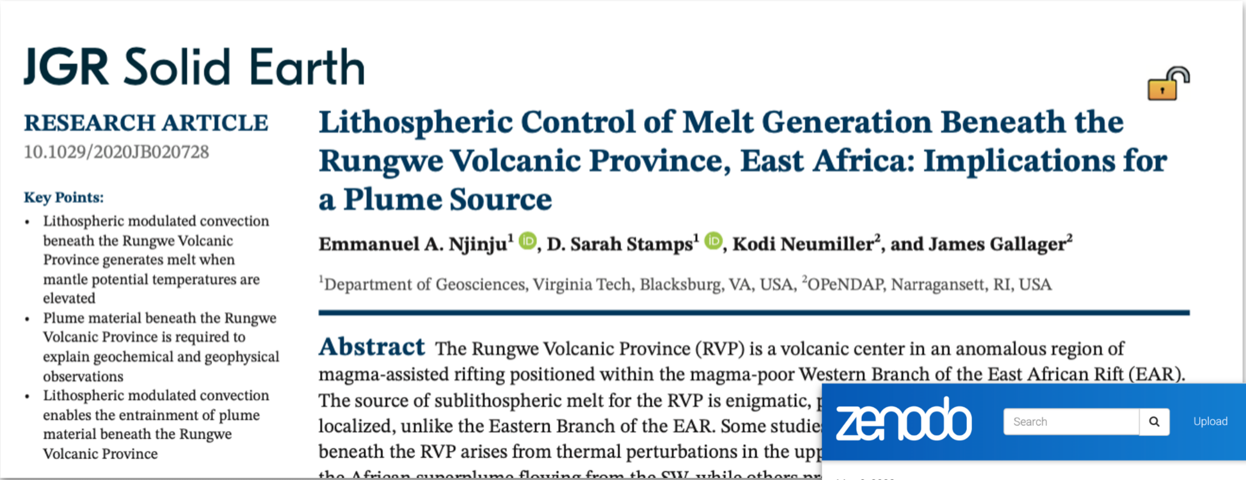
ASPECT can be used for modeling deep melt generation


JGR Solid Earth

RESEARCH ARTICLE
10.1029/2020JB020728

Key Points:

- Lithospheric modulated convection beneath the Rungwe Volcanic Province generates melt when mantle potential temperatures are elevated
- Plume material beneath the Rungwe Volcanic Province is required to explain geochemical and geophysical observations
- Lithospheric modulated convection enables the entrainment of plume material beneath the Rungwe Volcanic Province

Lithospheric Control of Melt Generation Beneath the Rungwe Volcanic Province, East Africa: Implications for a Plume Source

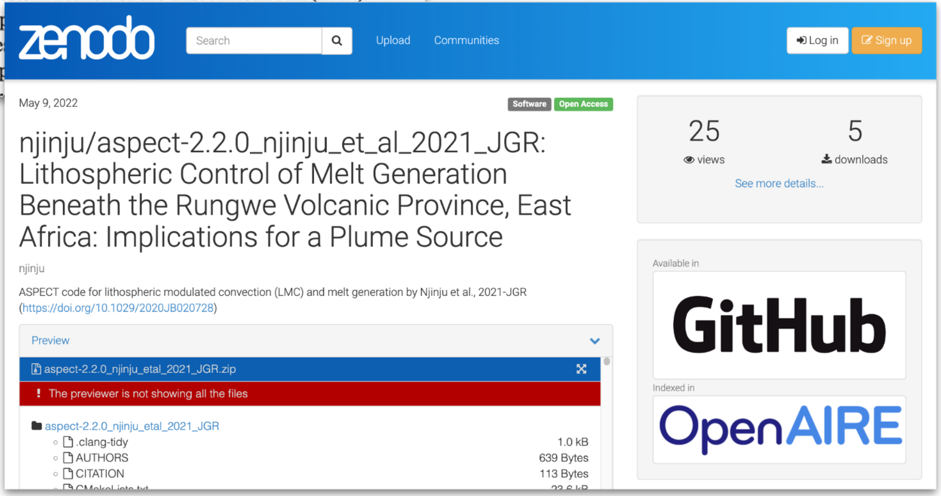
Emmanuel A. Njinju[1], D. Sarah Stamps[1], Kodi Neumiller[2], and James Gallager[2]

[1]Department of Geosciences, Virginia Tech, Blacksburg, VA, USA, [2]OPeNDAP, Narragansett, RI, USA

Abstract The Rungwe Volcanic Province (RVP) is a volcanic center in an anomalous region of magma-assisted rifting positioned within the magma-poor Western Branch of the East African Rift (EAR). The source of sublithospheric melt for the RVP is enigmatic, p localized, unlike the Eastern Branch of the EAR. Some studie beneath the RVP arises from thermal perturbations in the upp

njinju. (2022). njinju/aspect-2.2.0_njinju_et_al_2021_JGR: Lithospheric Control of Melt Generation Beneath the Rungwe Volcanic Province, East Africa: Implications for a Plume Source (v2.2.0). Zenodo. https://doi.org/10.5281/zenodo.6533974

Njinju, E. A., Stamps, D. S., Neumiller, K., & Gallager, J. (2021). Lithospheric control of melt generation beneath the Rungwe Volcanic Province, East Africa: Implications for a plume source. Journal of Geophysical Research: Solid Earth, 126, e2020JB020728. https://doi. org/10.1029/2020JB020728

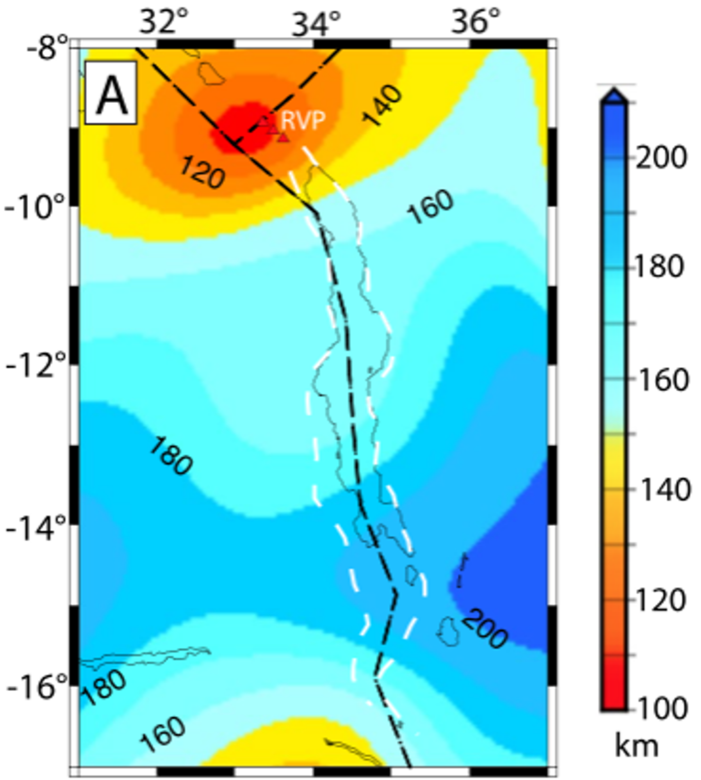


EAR-1740704

EarthCube BALTO
Brokered Alignment of Long-tail Observations

Model Setup: Initial Temperature Conditions

- Lithospheric thickness input with isotherm at lithosphere-asthenosphere boundary (LAB, i.e. Fishwick 2010, updated)
- Approximate conductive geotherm in lithosphere: linear gradient from surface to LAB isotherm (1673 K)
- Approximately adiabatic geotherm below lithosphere (i.e. 0.4 K/km)



Lithospheric Thickness

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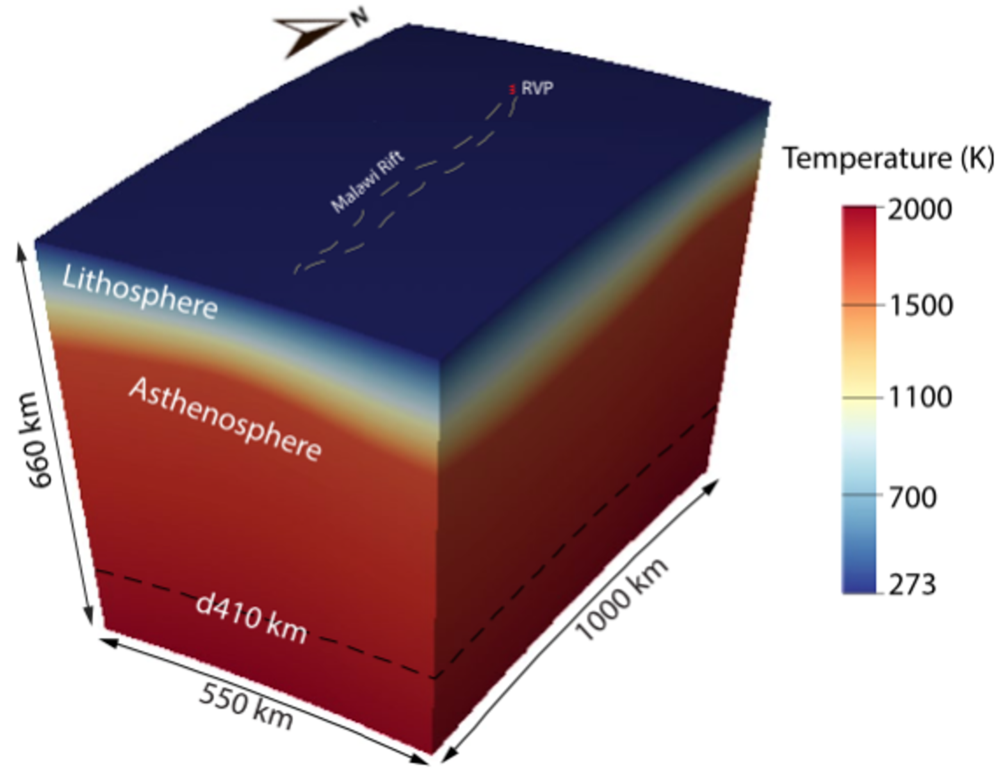


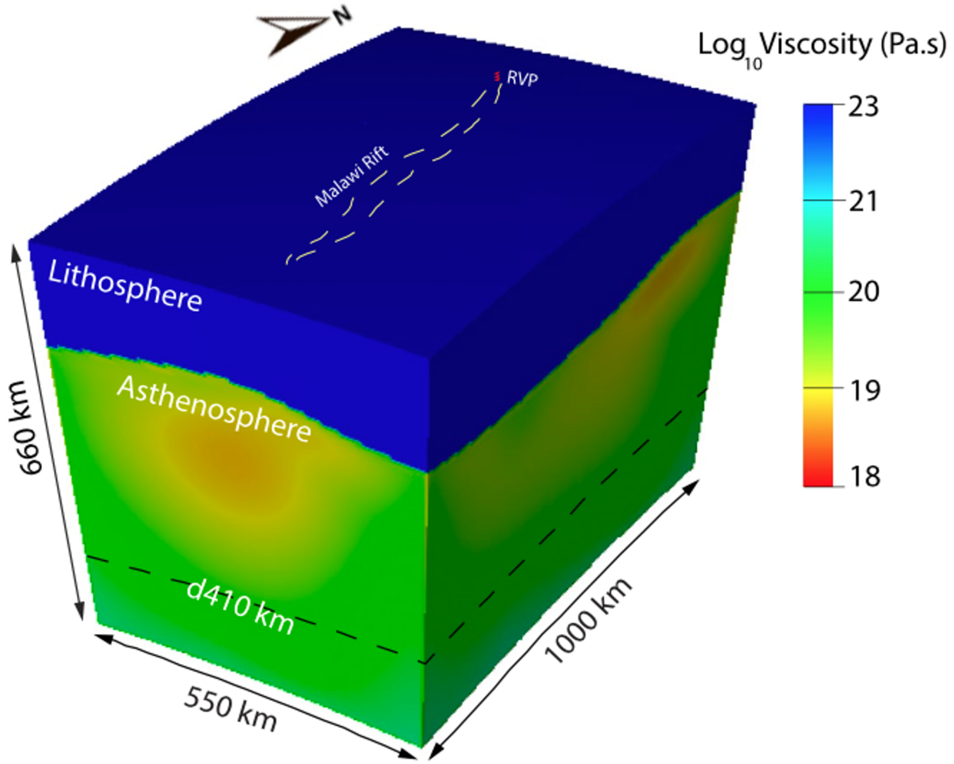
Model Setup: Viscosity

- Rigid lid lithospheric viscosity
- Composite rheology below the LAB (Jadamec & Billen, 2010)

$$\eta_{comp} = \frac{\eta_{diff} \times \eta_{disl}}{\eta_{diff} + \eta_{disl}}$$

η_{diff} = viscosity for diffusion creep

η_{disl} = viscosity for dislocation creep



Model Setup: Density and Melt Generation

- Crust = 2700 kg/m^3, Mantle_ref = 3300 kg/m^3

- Density of solid rock solid and the density of melt melt vary with both temperature and pressure below the LAB as follows:

$$\rho_{solid,melt} = \rho(T,p) = \rho_0\left[1-\alpha\left(T-T_0\right)\right]e^{\left[\beta\left(p-p_0\right)\right]}$$

ρ_0 = reference density

α = thermal expansivity

T_0 = reference temperature

T = temperature

β = compressibility coefficient

p = pressure

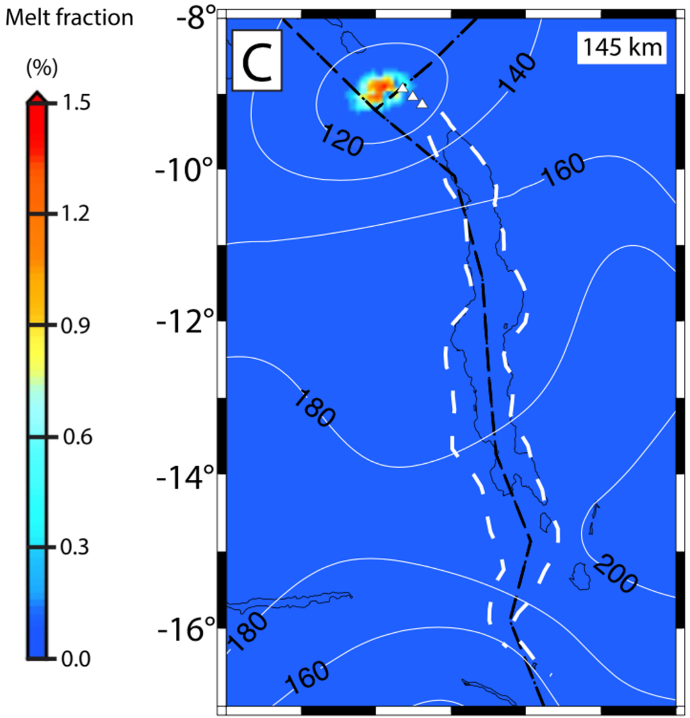
p_0 = reference pressure

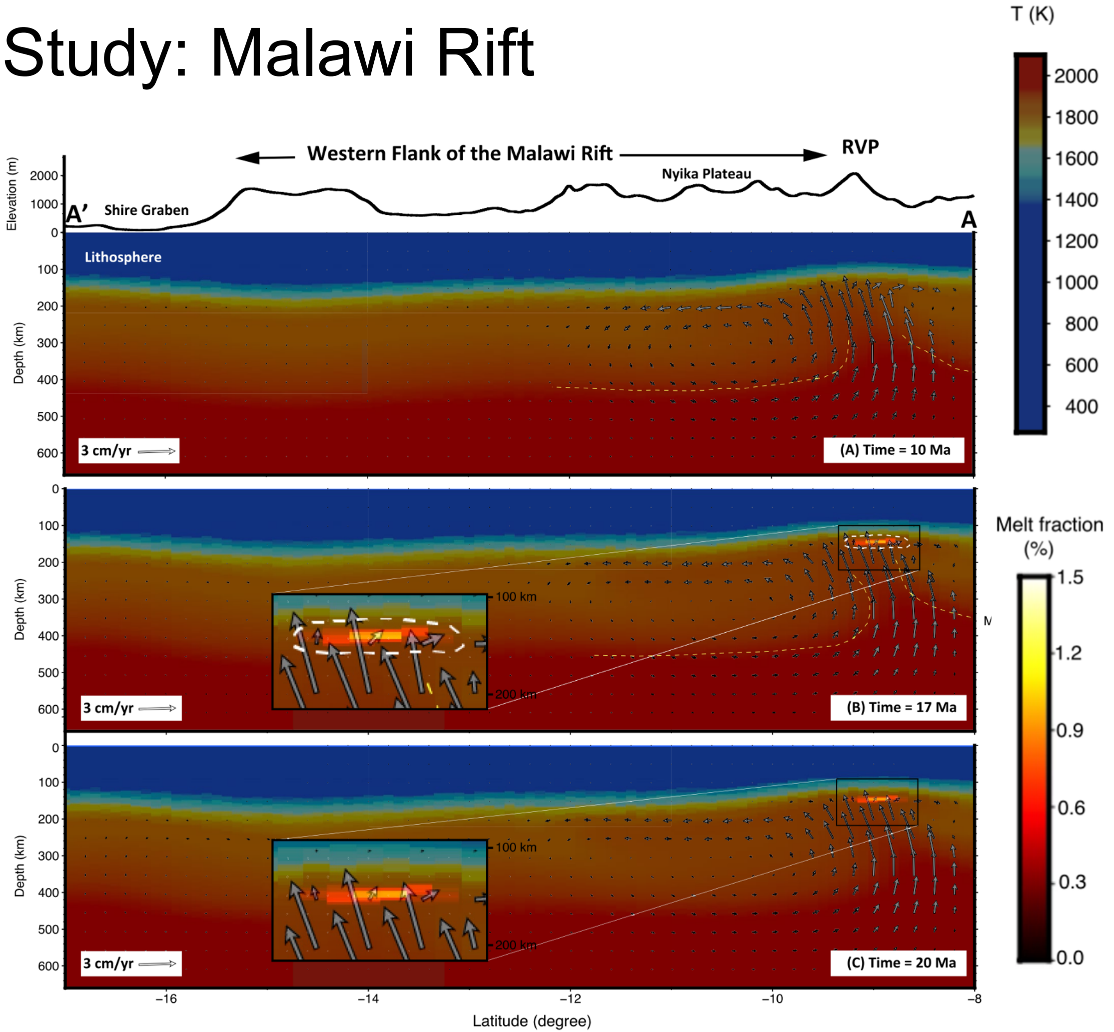
- Melt fraction:

$$F\left(p,T\right) = \left(\frac{T - T_{solidus}}{T_{liquidus} - T_{solidus}}\right)^{1.5}$$

$$for \quad T_{solidus} \le T \le T_{liquidus}$$

Case Study: Malawi Rift



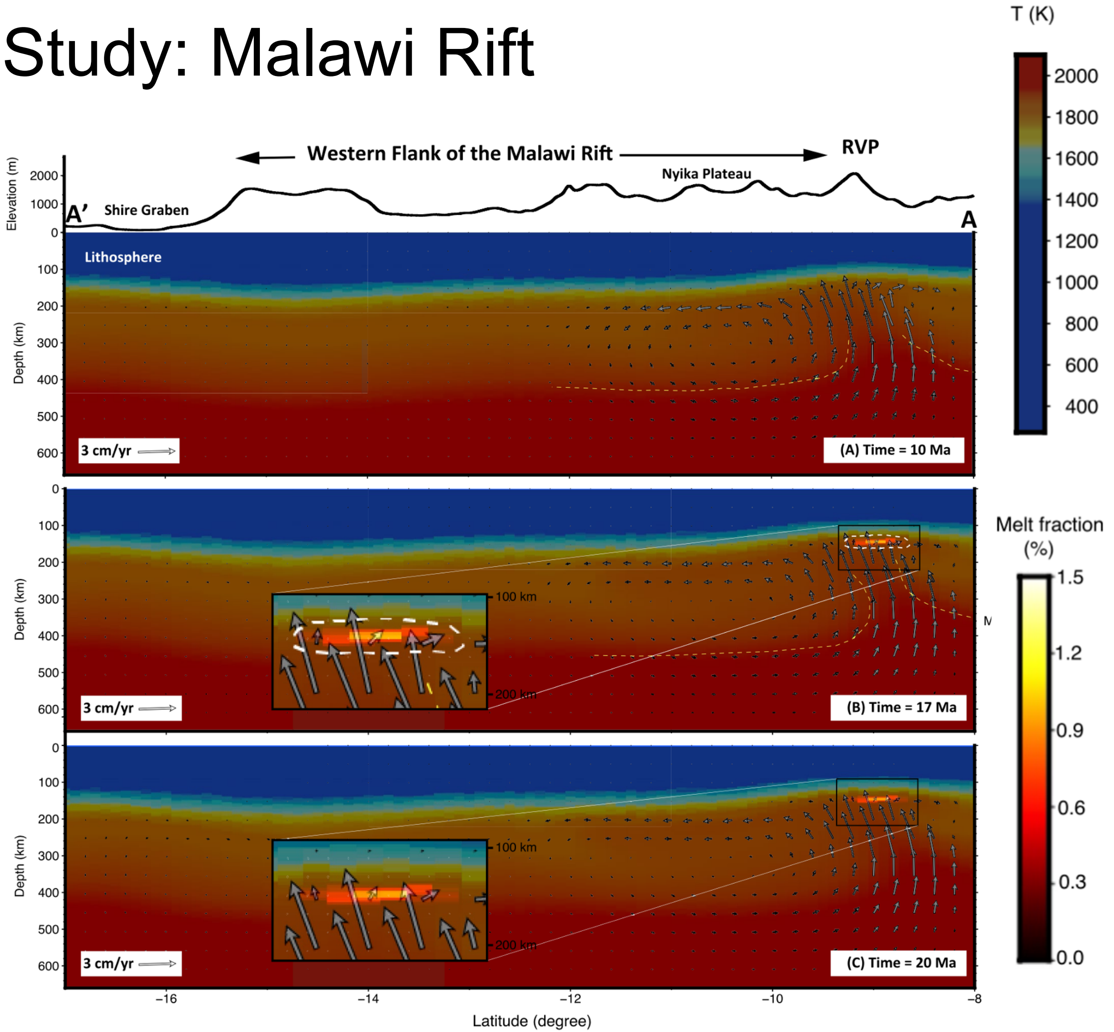


Case Study: Malawi Rift

- Lithospheric modulated convection beneath the Rungwe Volcanic Province generates melt when mantle potential temperatures are elevated

- Plume material beneath the Rungwe Volcanic Province is required to explain geochemical and geophysical observations

- Lithospheric modulated convection enables the entrainment of plume material beneath the Rungwe Volcanic Province



Overview

Introduction

Lithospheric Deformation

Asthenospheric Flow

Deep Melt Generation

Summary & Conclusions

Contributions from:
Tahiry Rajaonarison, New Mexico Tech, USA
Emmanuel Njinju, Virginia Tech, USA
John Naliboff, New Mexico Tech, USA
Asenath Kwagalakwe, Virginia Tech, USA

EAR-1551864
Geodynamic Processes at Rifting and Subducting Margins
EAR-1740704
BALTO
Brokered Alignment of Long-tail Observations
FRES 2021633
COMPUTATIONAL INFRASTRUCTURE for GEODYNAMICS

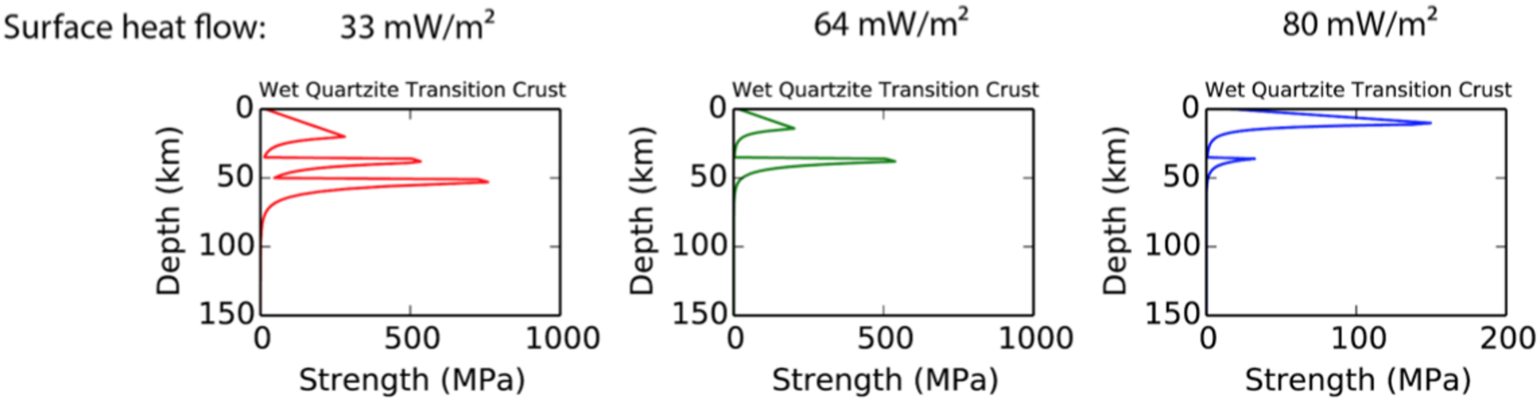
Summary and Conclusions

- ASPECT can be used for:
    - Lithospheric deformation
    - Asthenospheric flow
    - Deep melt generation

- Applications to:
    - East African Rift
        - Rigid plate motions explained by lithospheric buoyancy forces
    - Madagascar
        - Dislocation creep extends into the upper asthenosphere
    - Malawi Rift
        - Lithospheric control on the location of melt generation

- All developments are open access and available via Zenodo or the ASPECT release code

Model Set-up: Rheology



- Crust: combines nonlinear dislocation creep (dry quartzite) with plastic failure
- Mantle lithosphere: combines olivine dislocation creep with plastic failure
- Sublithospheric mantle: composite rheology