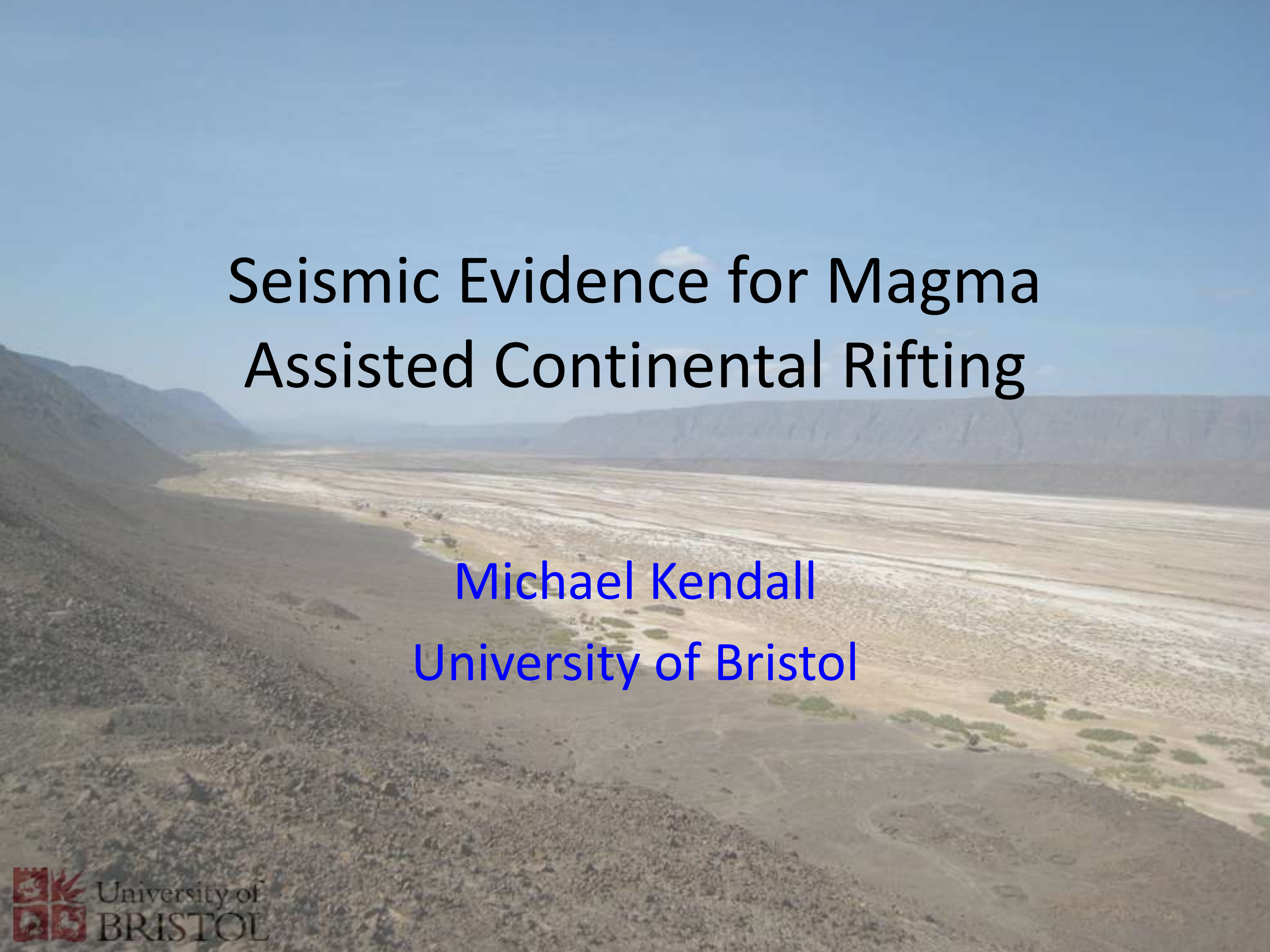


# Seismic Evidence for Magma Assisted Continental Rifting

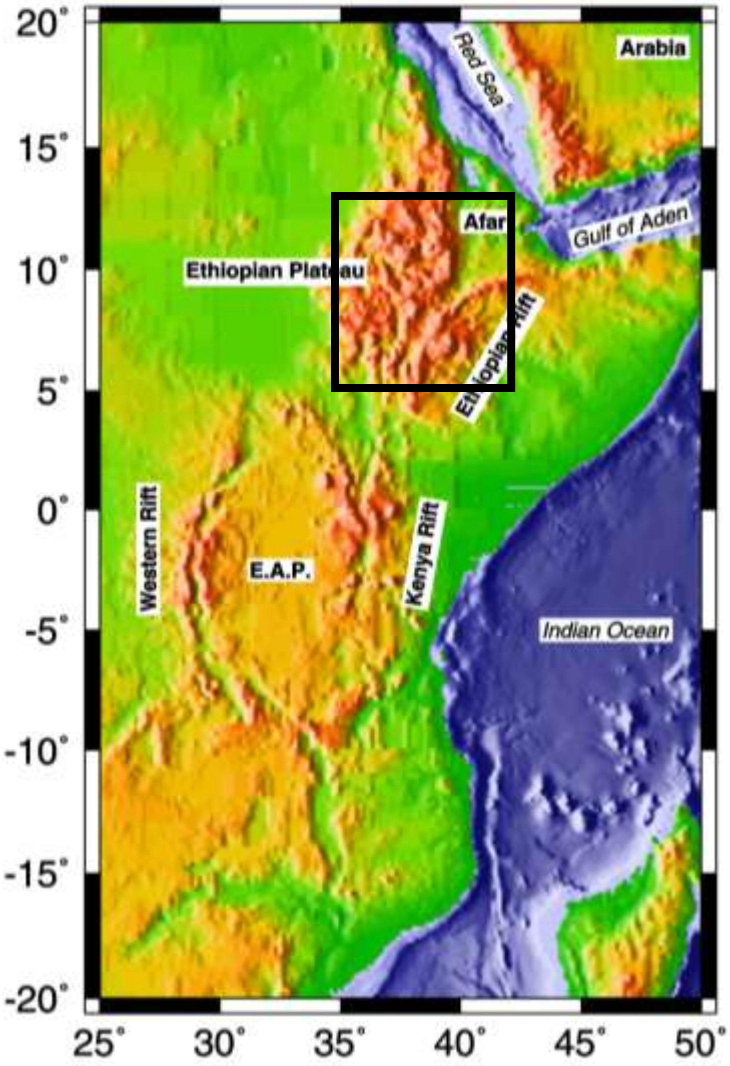
Michael Kendall

University of Bristol

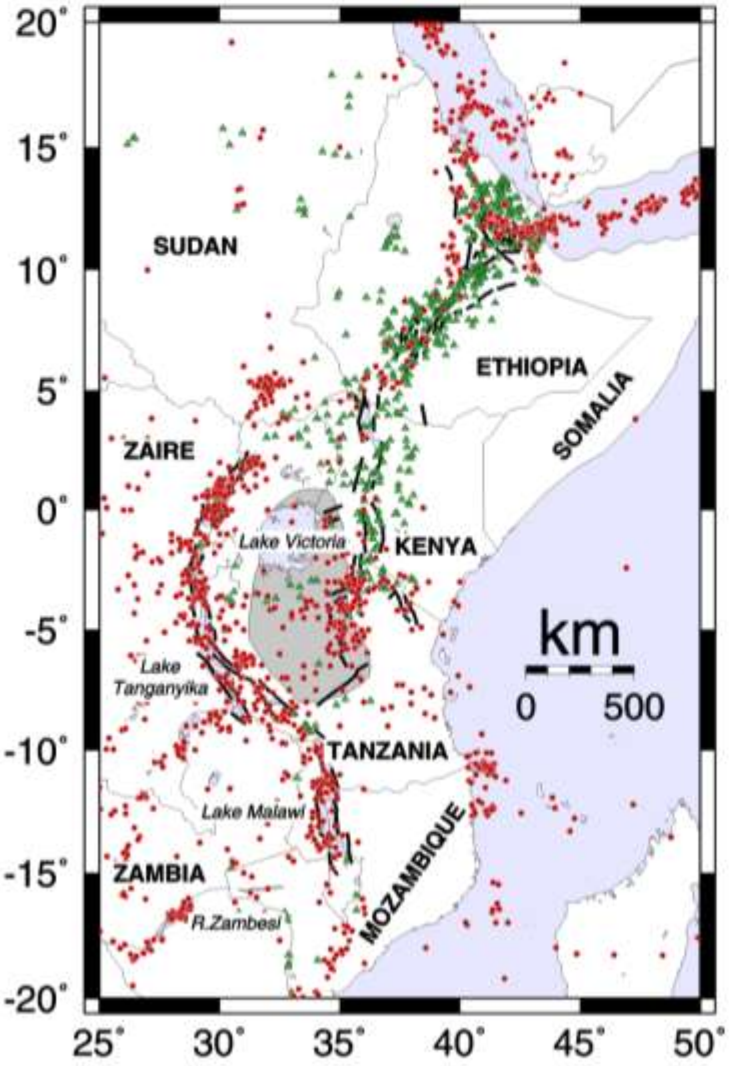
# or
# 10 years of fieldwork in Ethiopia

- Atalay Ayele, Elias Lewi – Addis Ababa University
- Mike Kendall, **Anna Stork**, James Wookey – Bristol
- Nick Johnson, Kathy Whaler – Edinburgh
- Ghebrebrhan Ogubazghi, Berhe Goitom – Eritrea Inst of Tech
- **James Hammond, Ian Bastow** – Imperial College
- Graham Stuart, **Dave Thompson**, Tim Wright – Leeds
- Cindy Ebinger, **Manahloh Belachew** – Rochester
- **Catherine Rychert, Derek Keir** – NOC Southampton

# East-Africa Rift System: juvenile continental rifting to oceanic spreading

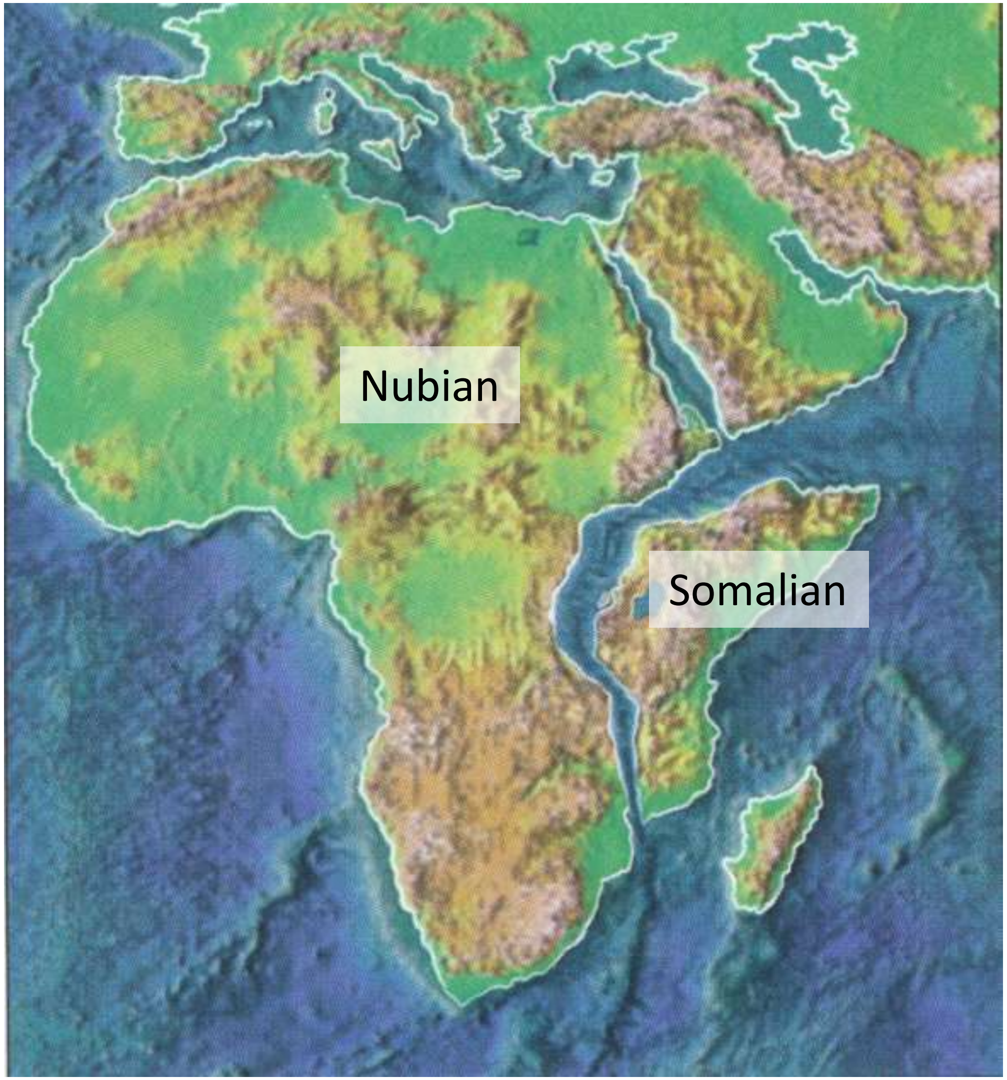


East Africa - Topography
(E.A.P. - East African Plateau)

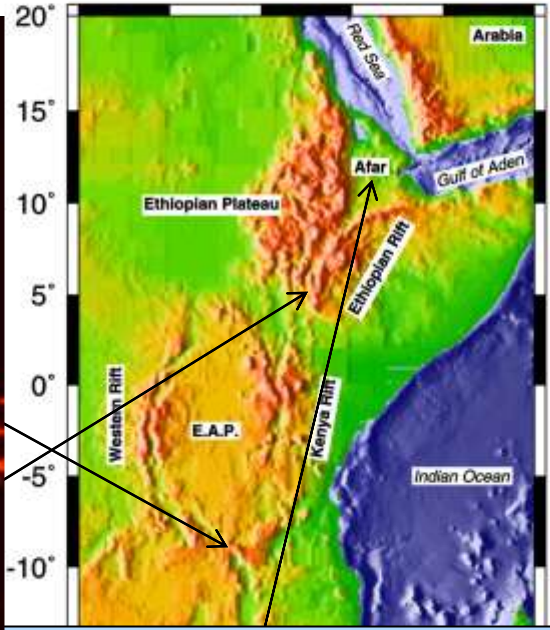


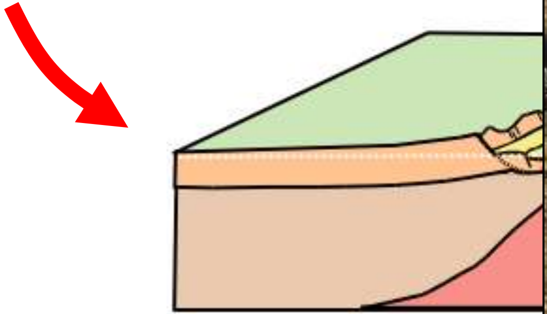
East Africa - Seismicity (Dots) and Volcanoes (Triangles).
(The Nyanza craton is shown by the shaded pattern)

# Birth of an Ocean



- Continental rifting - fundamental component of plate tectonics
- Rift valley has played a key role in the evolution of humans – climate, habitability
- How and why do continents break apart?





Fundamental process – but how does it work

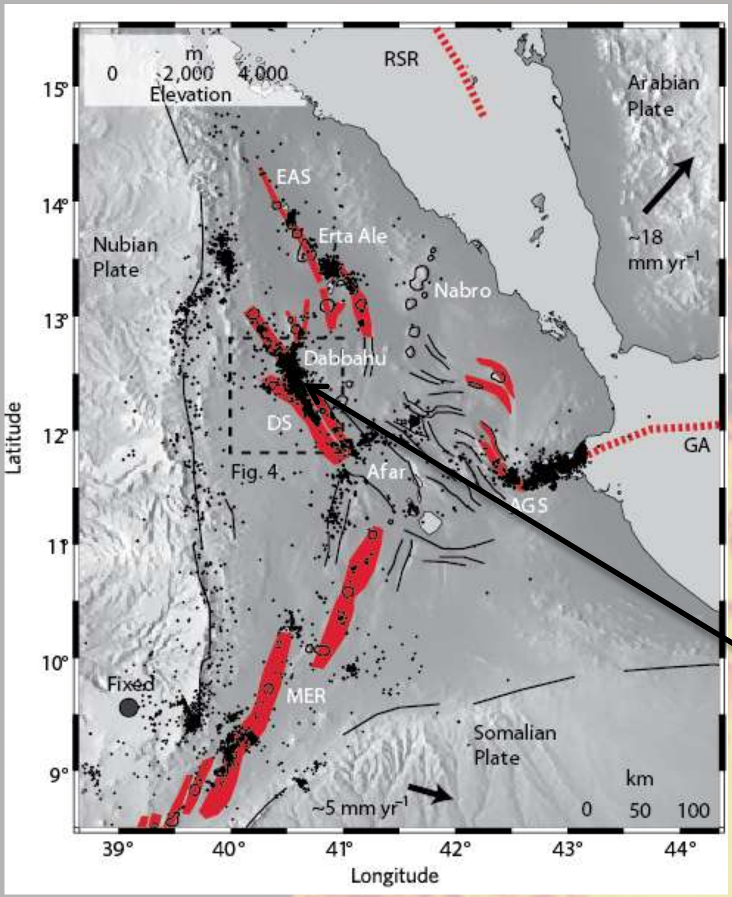
# The volcano-seismic crisis in Afar - Sept, 2005

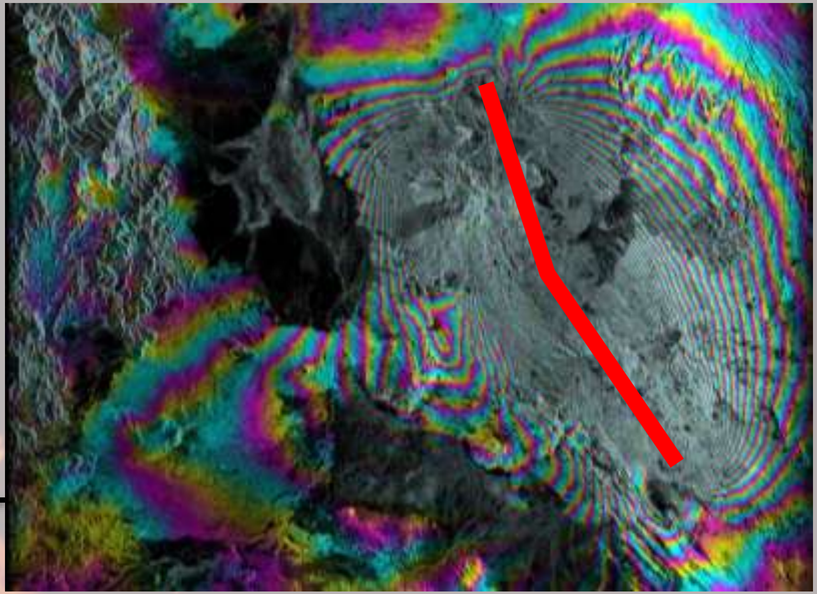
Anthony Philpotts, October 2005

## Afar (Sept 2005): a “once in a generation” event.

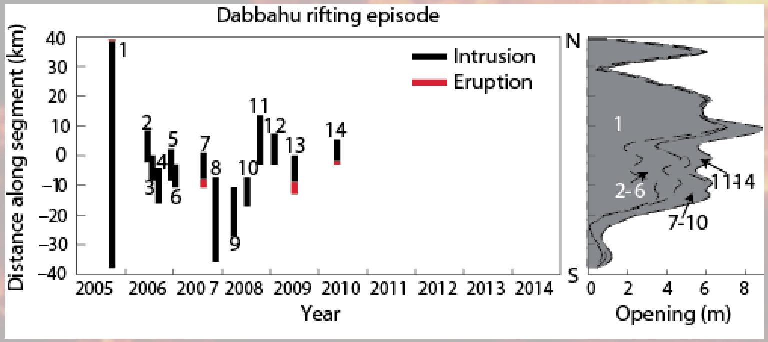
- 60 km of plate boundary opened by up to 8 metres.
- 2.5 km$^3$ of new crust created.
- First rifting event above sea level in the era of satellite geodesy.
- First eruption of rhyolite in Africa in over a century.
- UK/Ethiopian/US team first on the ground.

UBO université de bretagne occidentale
University of Rochester Earth Sciences
Addis Ababa University
University of Leeds
University of Oxford
The University of Edinburgh
University of Bristol
The University of Auckland New Zealand
Lamont-Doherty Earth Observatory
The Earth Institute at Columbia University
University of Cambridge
Royal Holloway University of London
Purdue

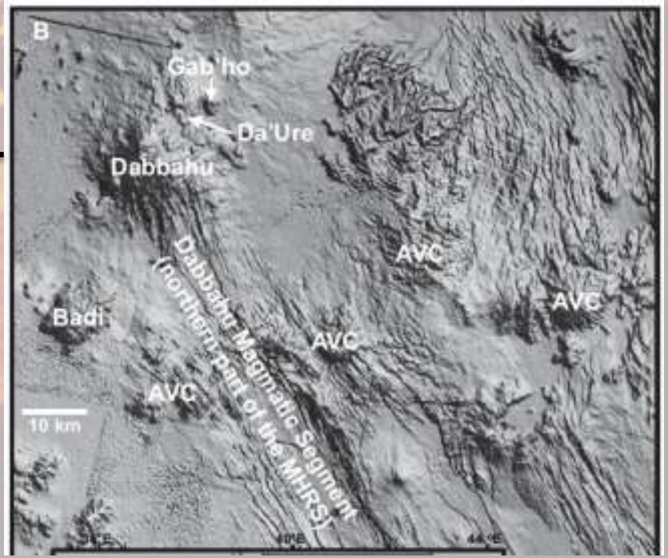




Wright et al., 2006

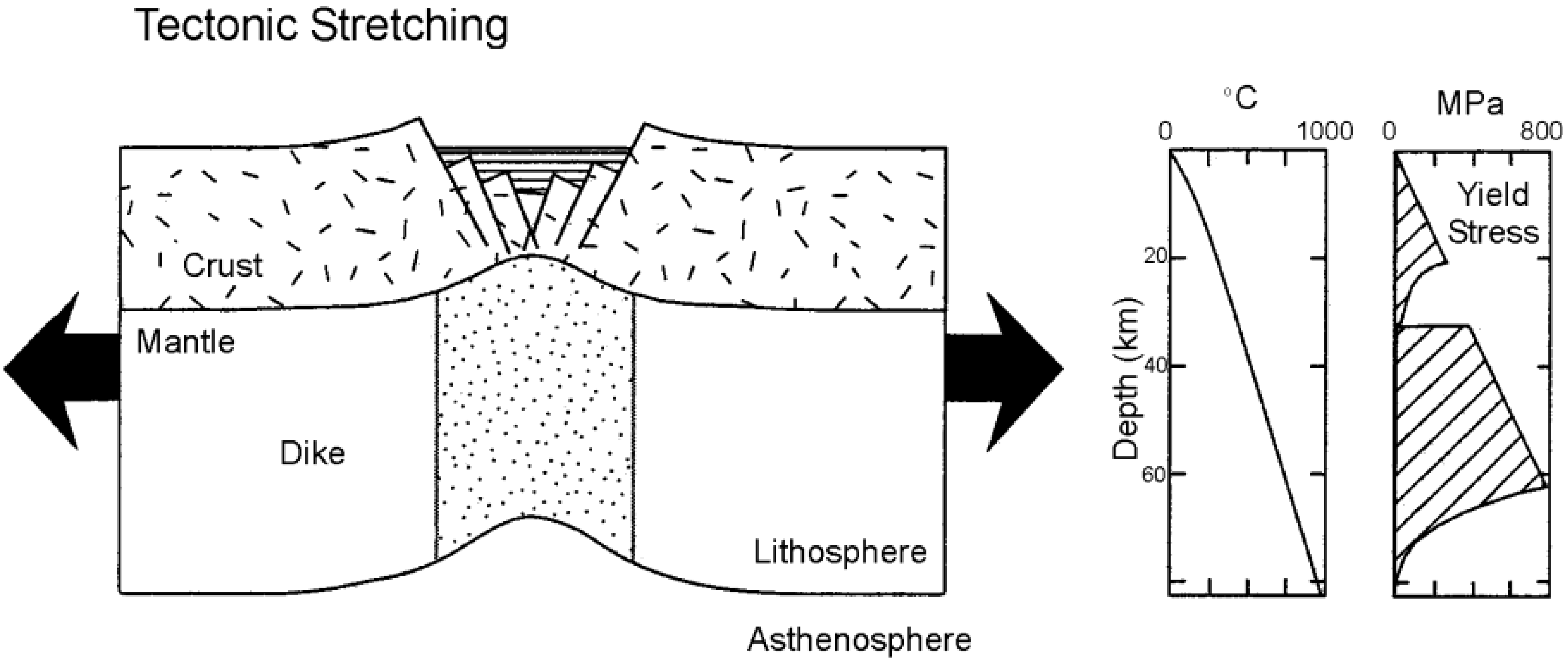


Wright et al., 2012



Field et al., 2013

# Breaking a plate.



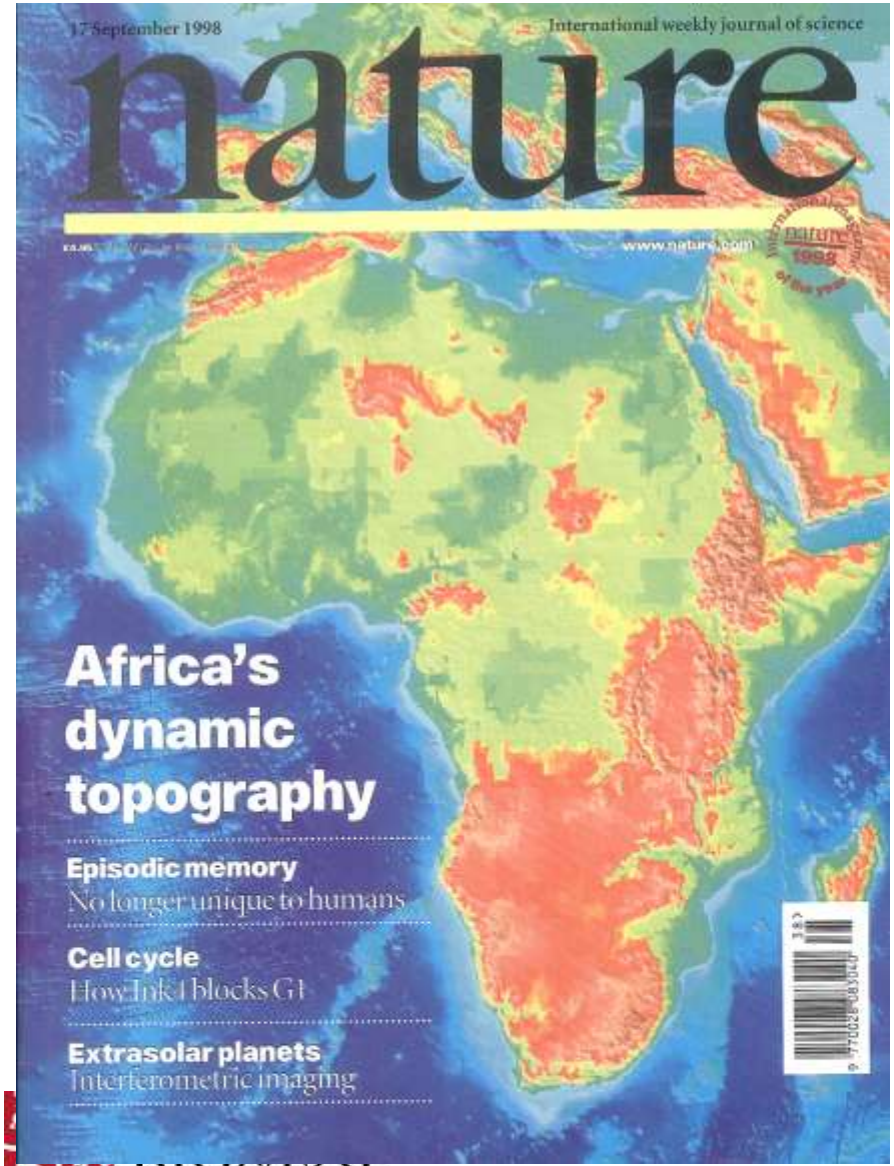
Broad zone of stretching

Buck, 2004

# So why is Africa rifting?

- Forces available for rifting
  - Distant subduction
  - Gravitational potential energy
  - Basal traction – compression vs extension
  - Preexisting weaknesses and lithospheric thin spots

# Africa: superplume … superswell



17 September 1998

International weekly journal of science

nature

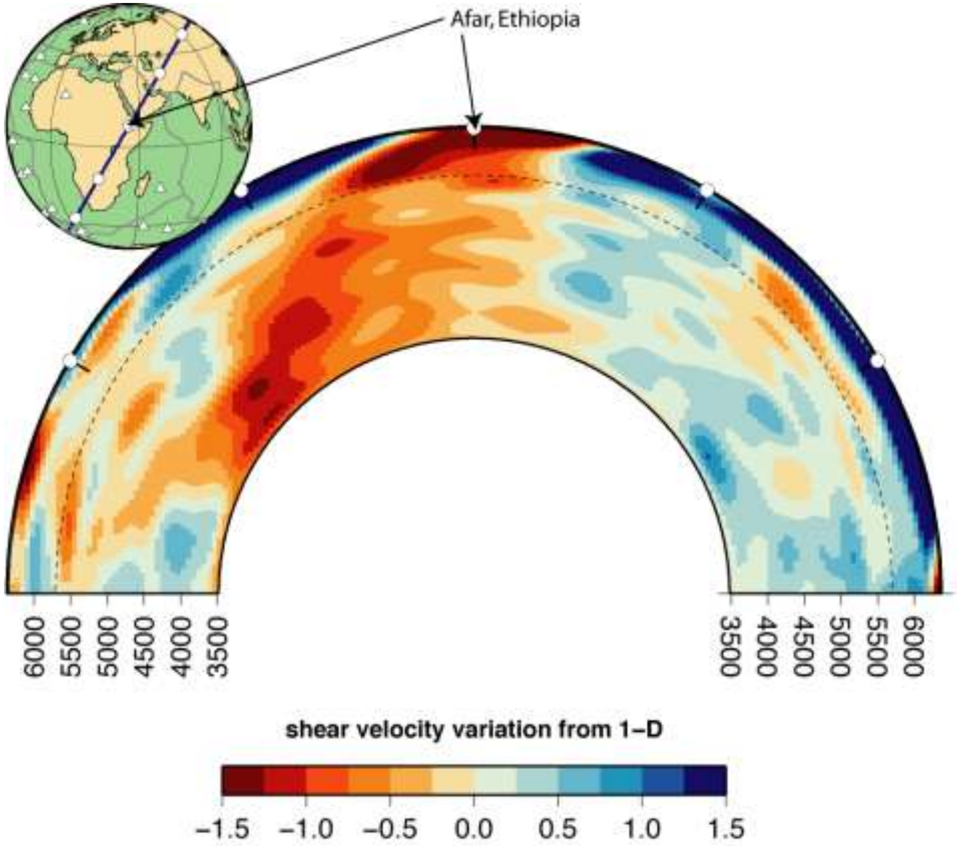
www.nature.com

Africa's dynamic topography

**Episodic memory**
No longer unique to humans

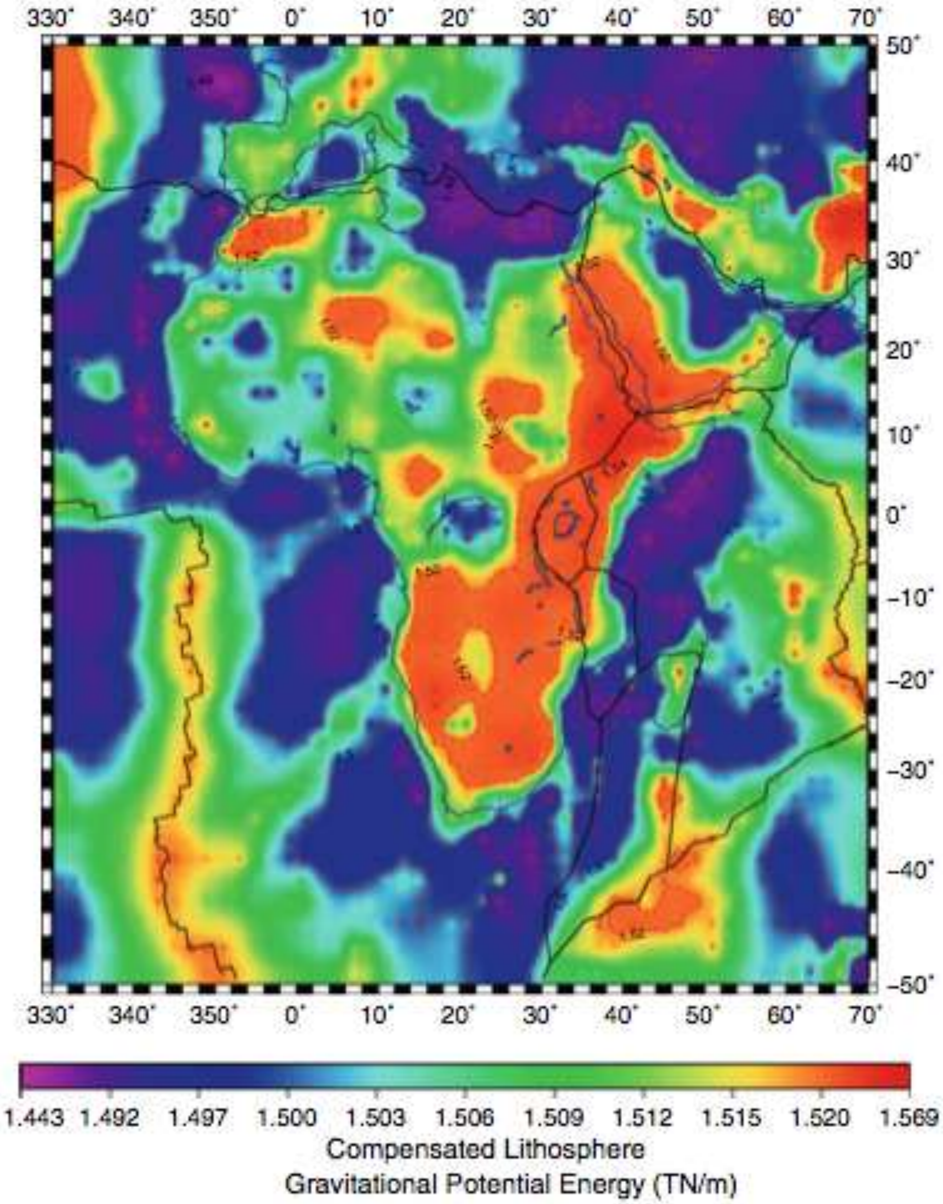
**Cell cycle**
How Ink4 blocks G1

**Extrasolar planets**
Interferometric imaging



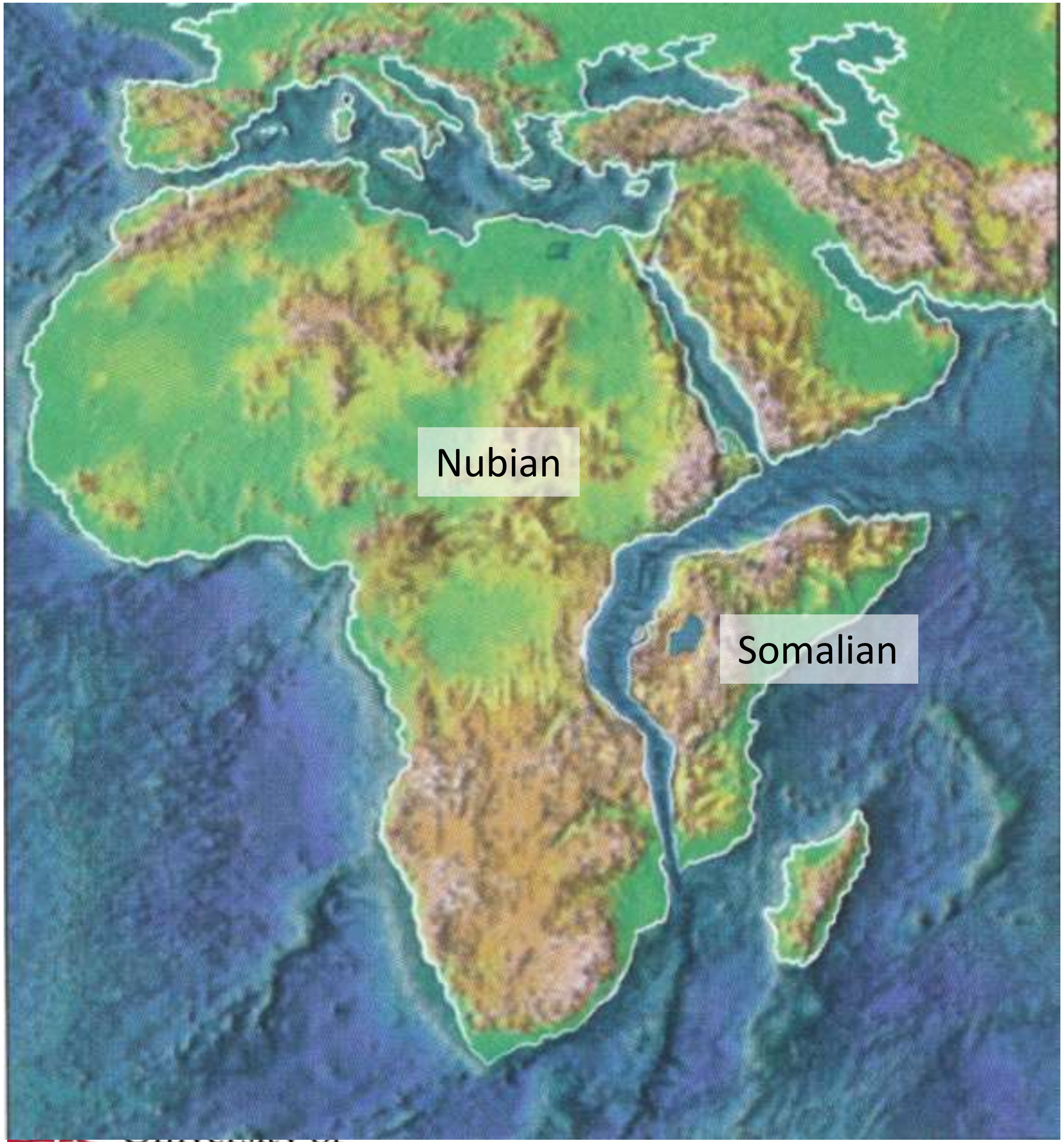
Ritsema and Allen 2003
Lithgow-Bertelloni and Silver 1998

# Gravitational potential energy



" Once quantified, it appears that deviatoric stresses alone are not sufficient to overcome the strength of the continental lithosphere in the Eastern rift."

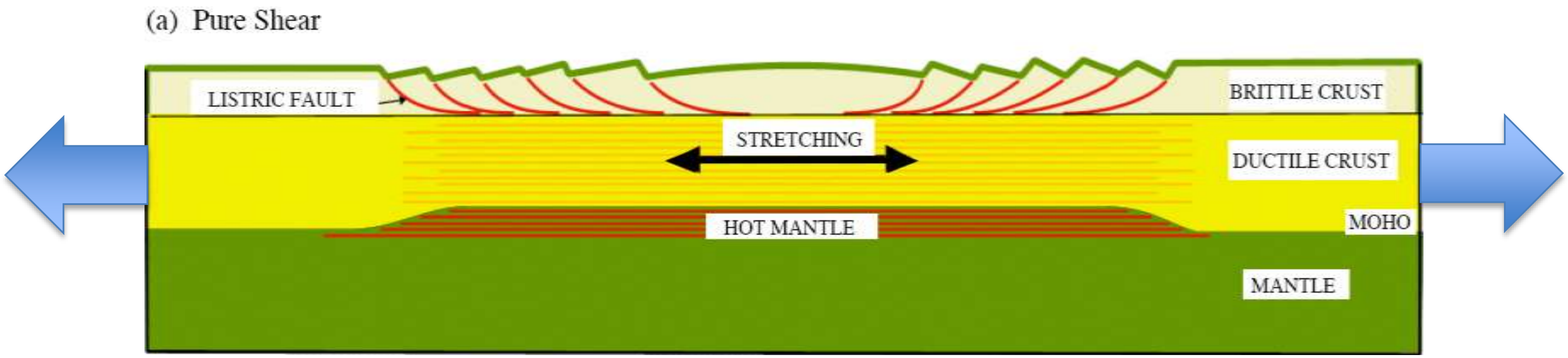
Stamps et al., 2010



## Plate Force Paradox:

Plate forces are up to an order of magnitude too small to break thick cold continental lithosphere (Buck 2004).

- Continental rifting - fundamental component of plate tectonics
- How and why do continents break apart?

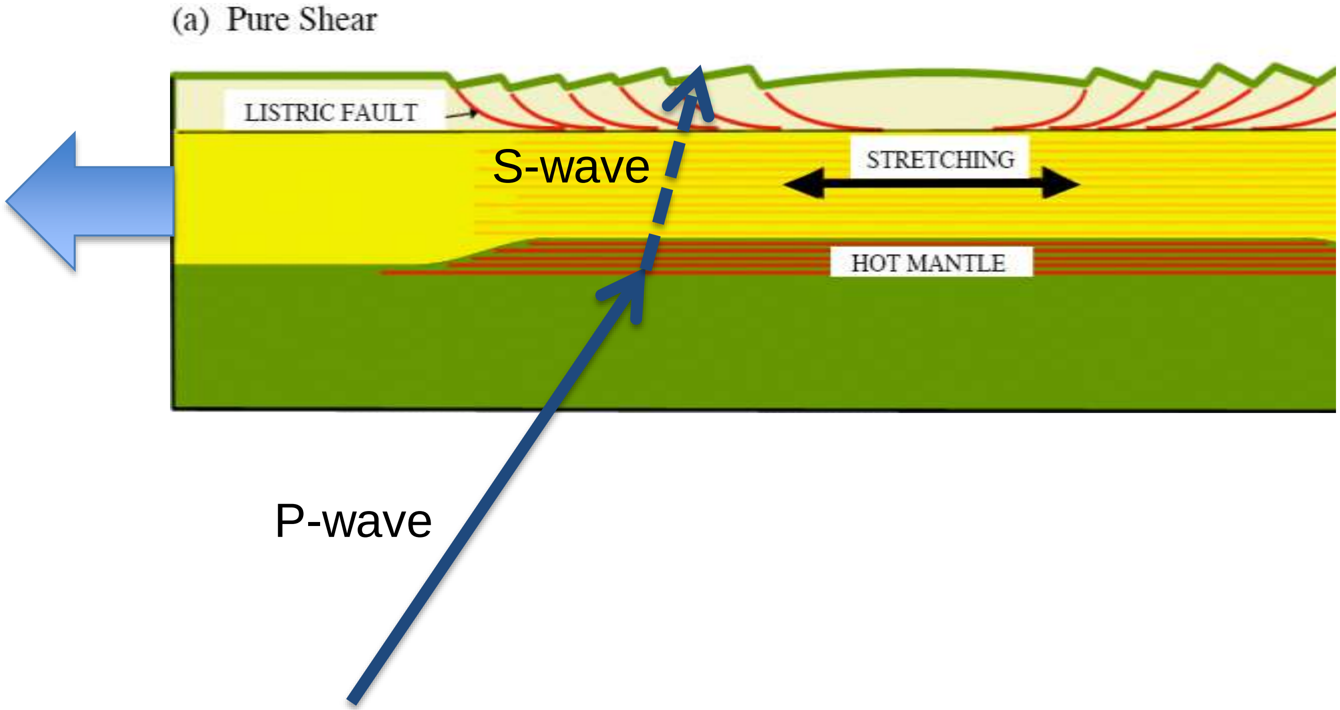


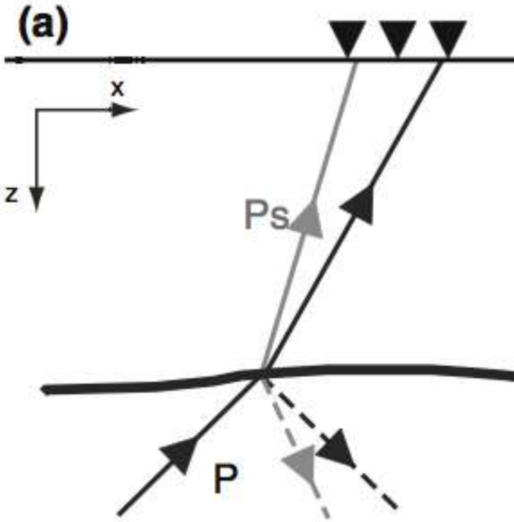
**McKenzie 1978**

Which seismic methods can be used to address this question?

# Seismic methods for imaging

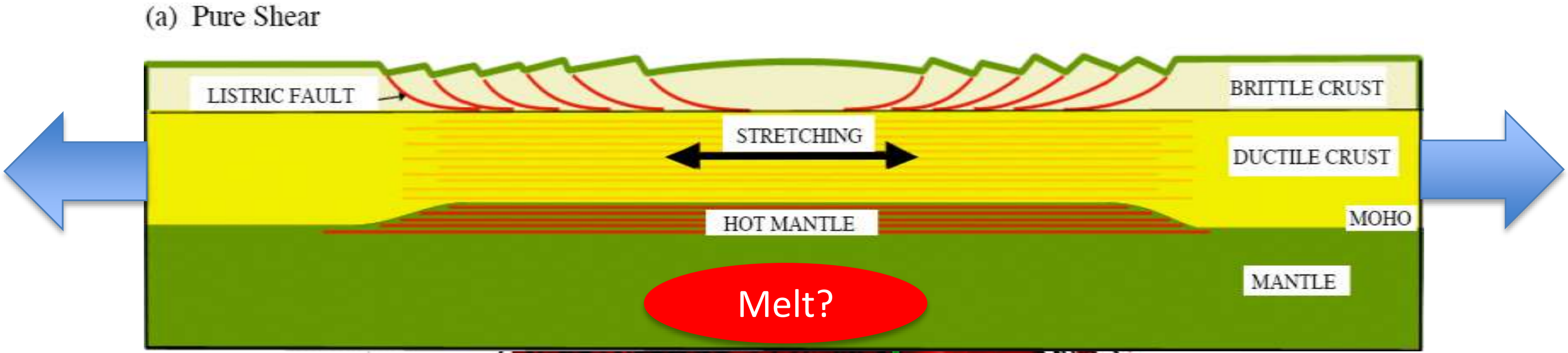
- Receiver functions – discontinuity structure; Vp/Vs ratios

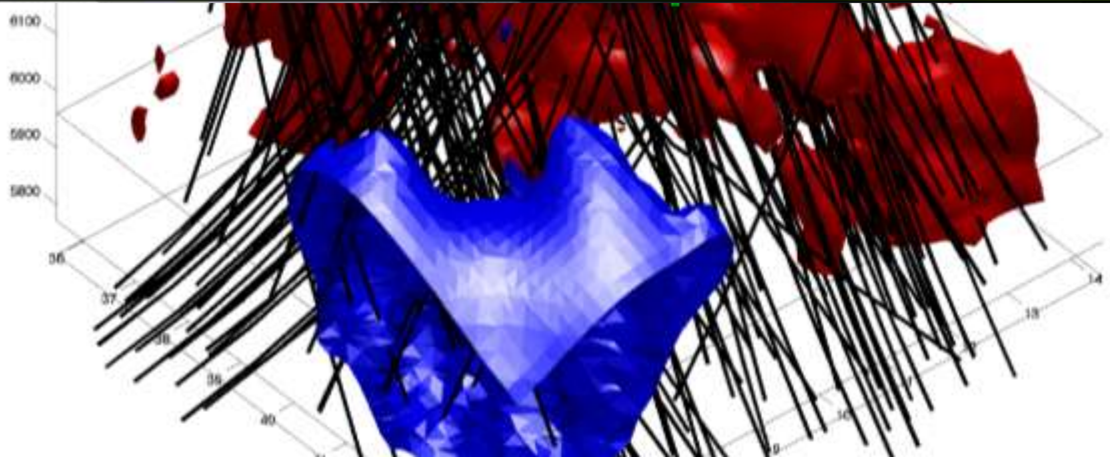




# Seismic methods for imaging

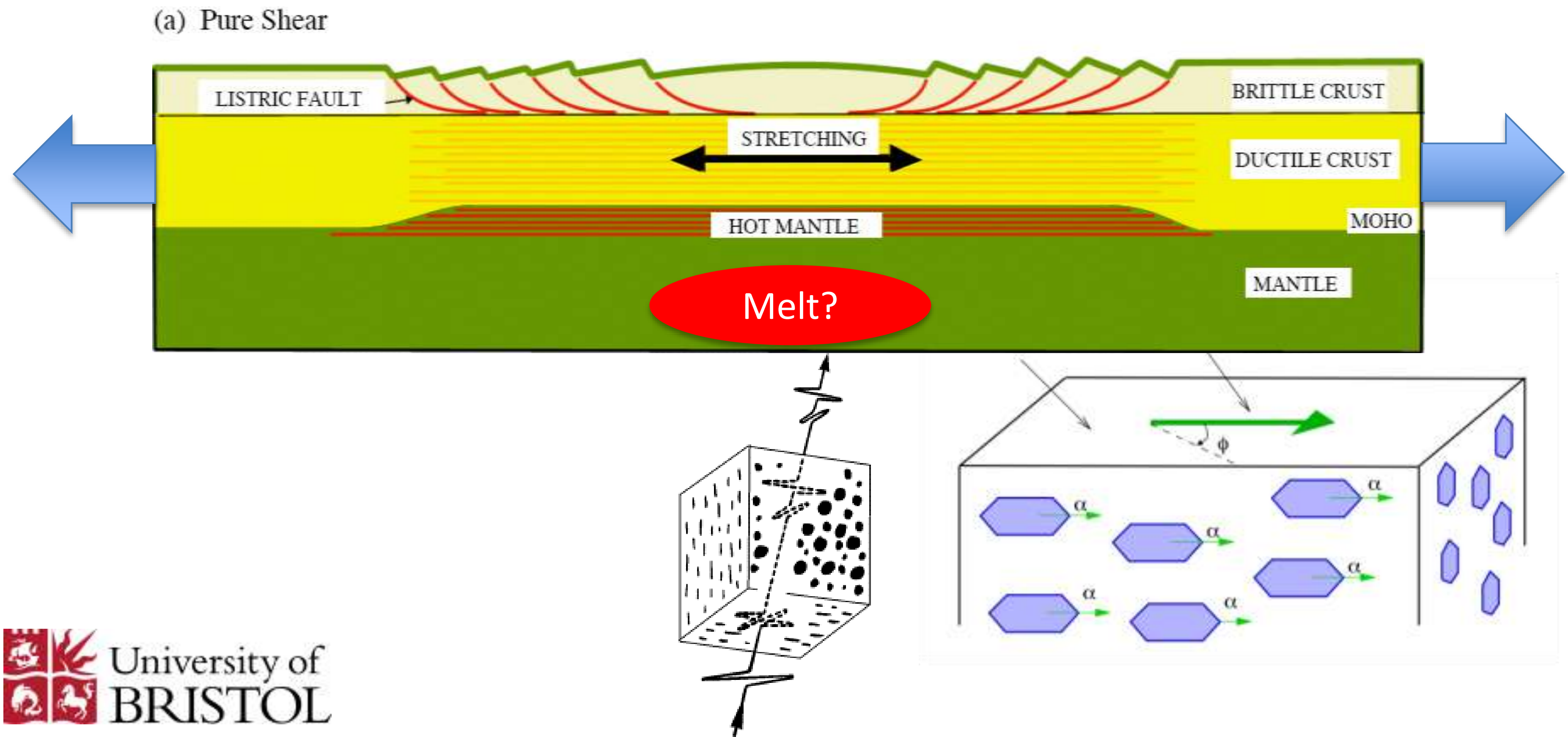
- Tomography – velocity structure; thermal anomalies; partial melt


(a) Pure Shear

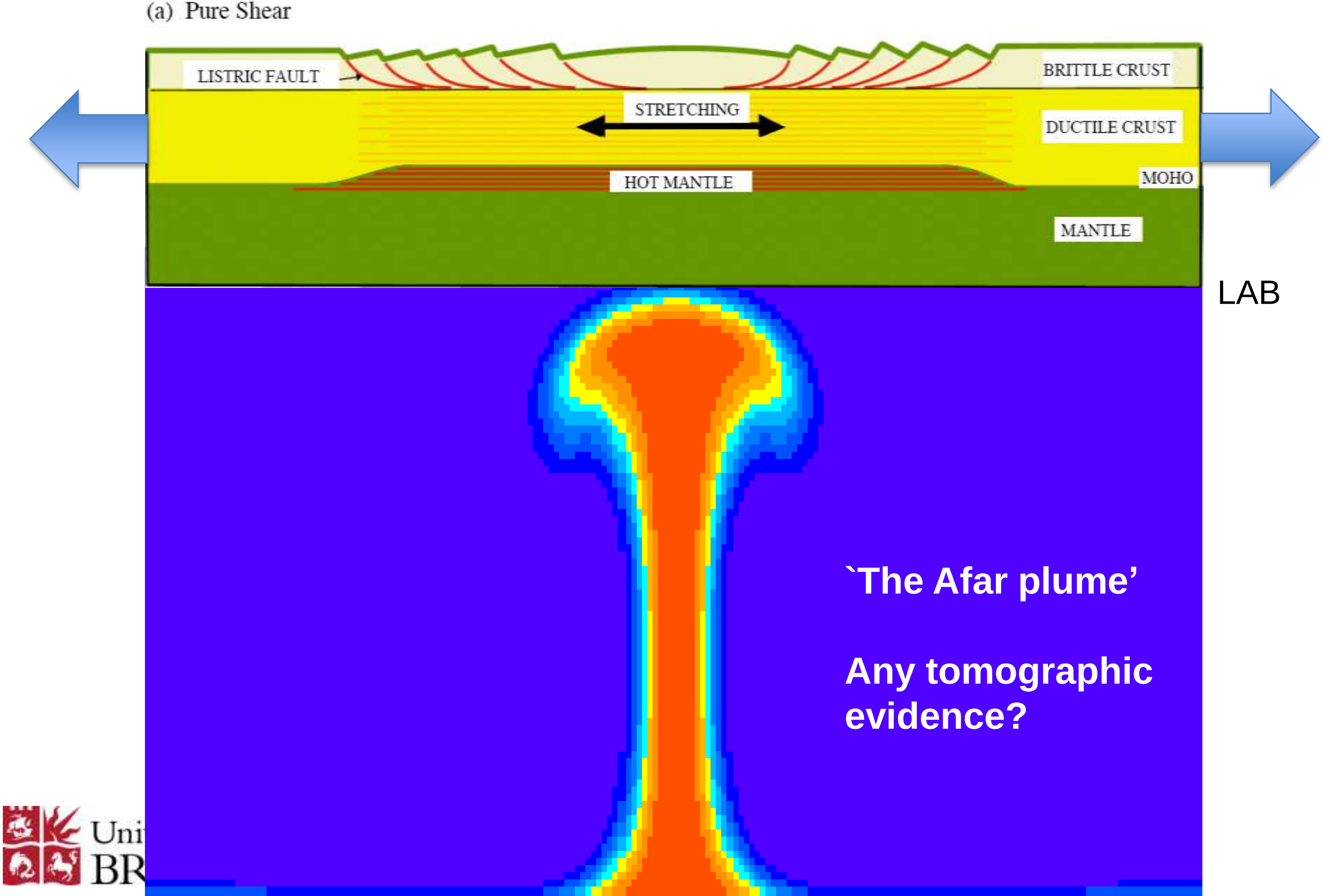


# Seismic methods for imaging

- Seismic anisotropy = mantle flow; aligned melt



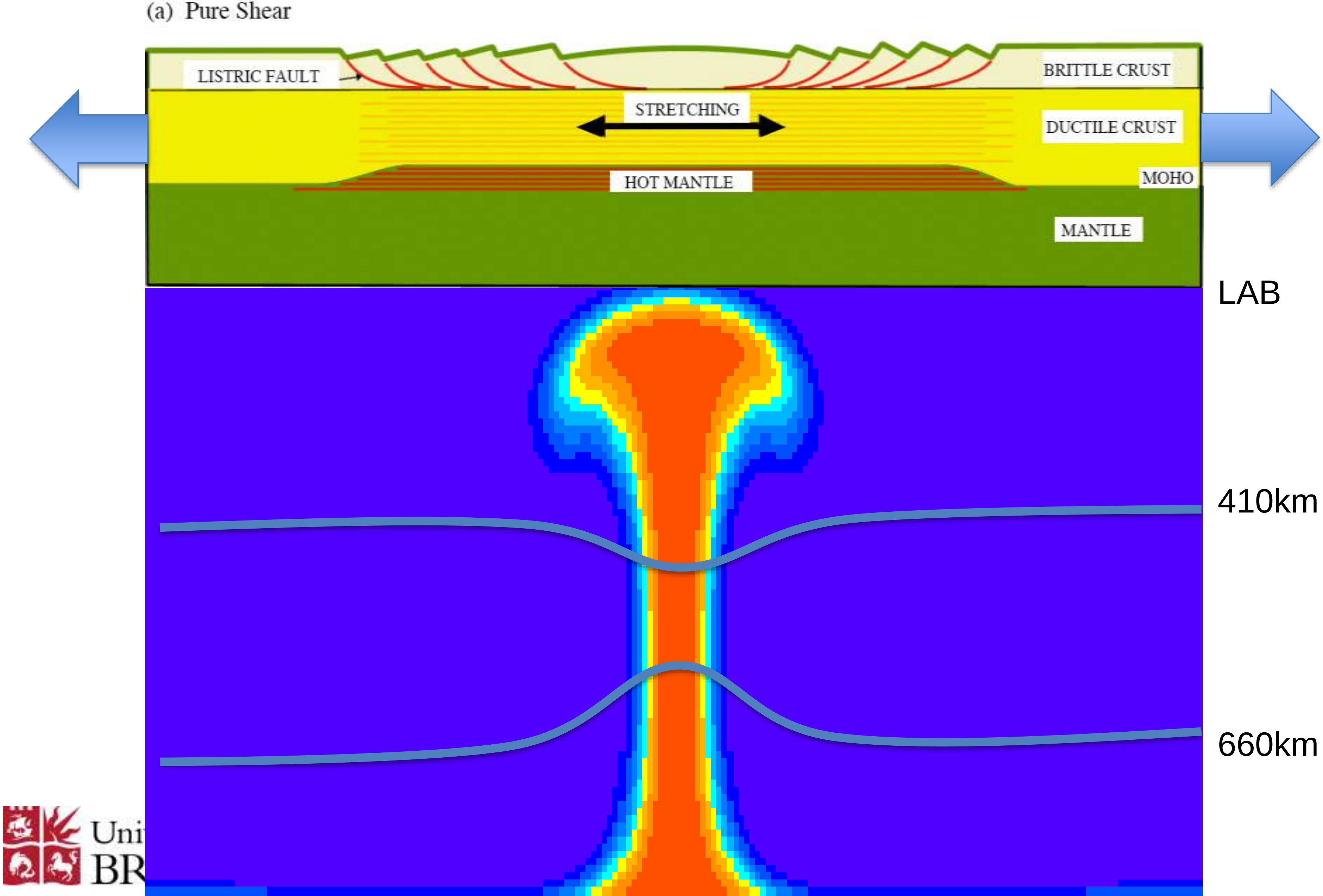
# Mantle plume



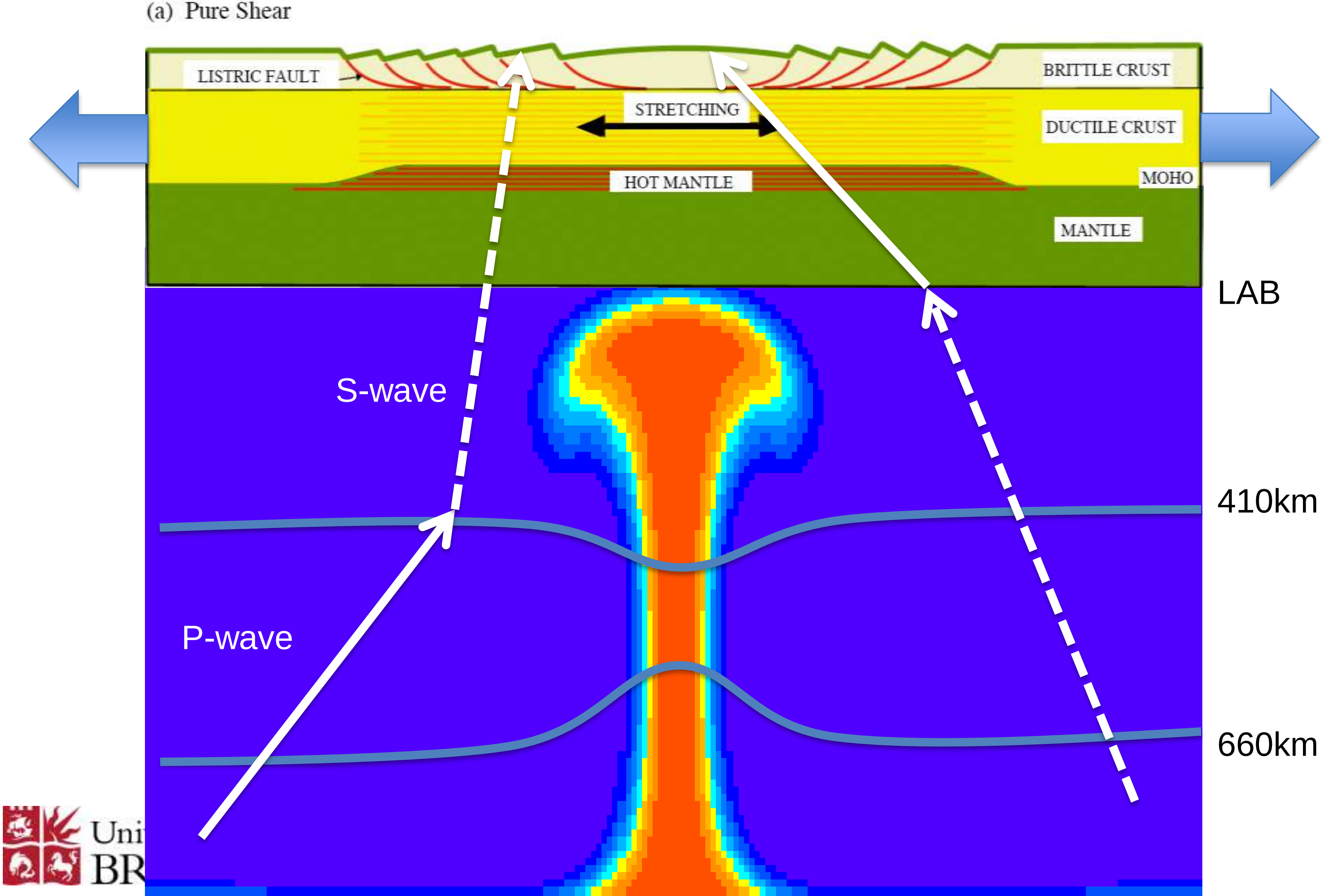
`The Afar plume’

Any tomographic evidence?

# Mantle plume



# Mantle plume



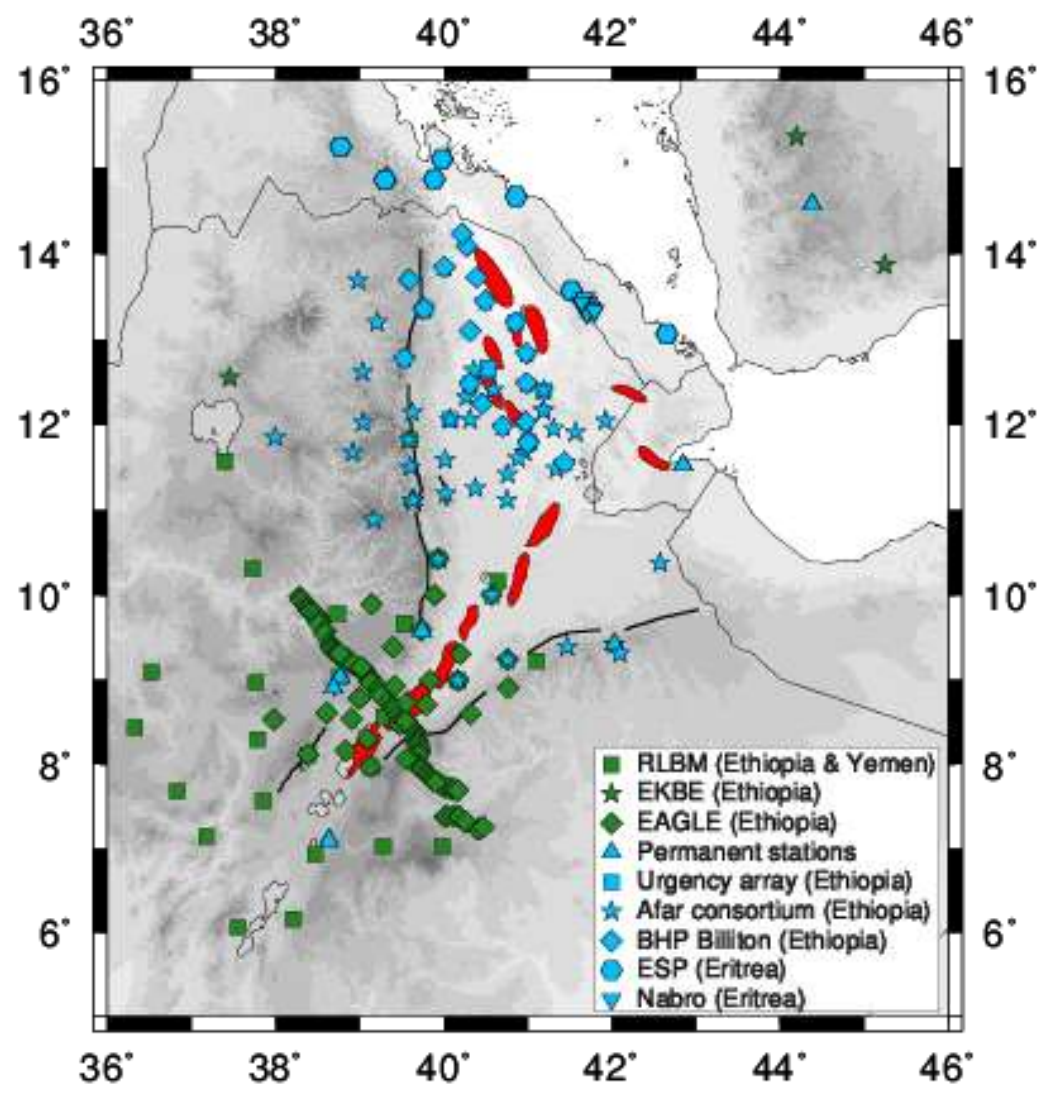
# Fieldwork

EAGLE

Ethiopia Afar Geoscientific
Lithospheric Experiment
2001 - 2003

Afar Rift
Consortium

- RLBM (Horn of Africa)
  - 5 stations: Jun 1999 - Dec 2002
- EKBE (MER)
  - 35 stations: Feb 2000 - Dec 2002
- EAGLE (MER)
  - 55 stations: Oct 2001 - Feb 2003
- Permanent stations (IRIS, GEOSCOPE)
  - 7 stations: Jul 1993 - Present
- **Urgency array (Afar)**
  - **9 stations: Oct 2005 - Ma, 2007**
- **Afar consortium (NERC & NSF)**
  - **51 stations: Mar 2007 – Oct 2009**
- **Danakil Seismic Project**
  - **12 stations: Oct 2009 – Feb 2013**
- **Eritrea Seismic Project**
  - **6 stations: Jun 2011 – Oct 2012**
- **Nabro Urgency Project**
  - **8 stations: Aug 2011 – Oct 2012**



Seismic station on Nabro Volcano – Ethiopia/Eritrea Border

Seismic station – Biye Kabobe – Ethiopia/Somalia Border

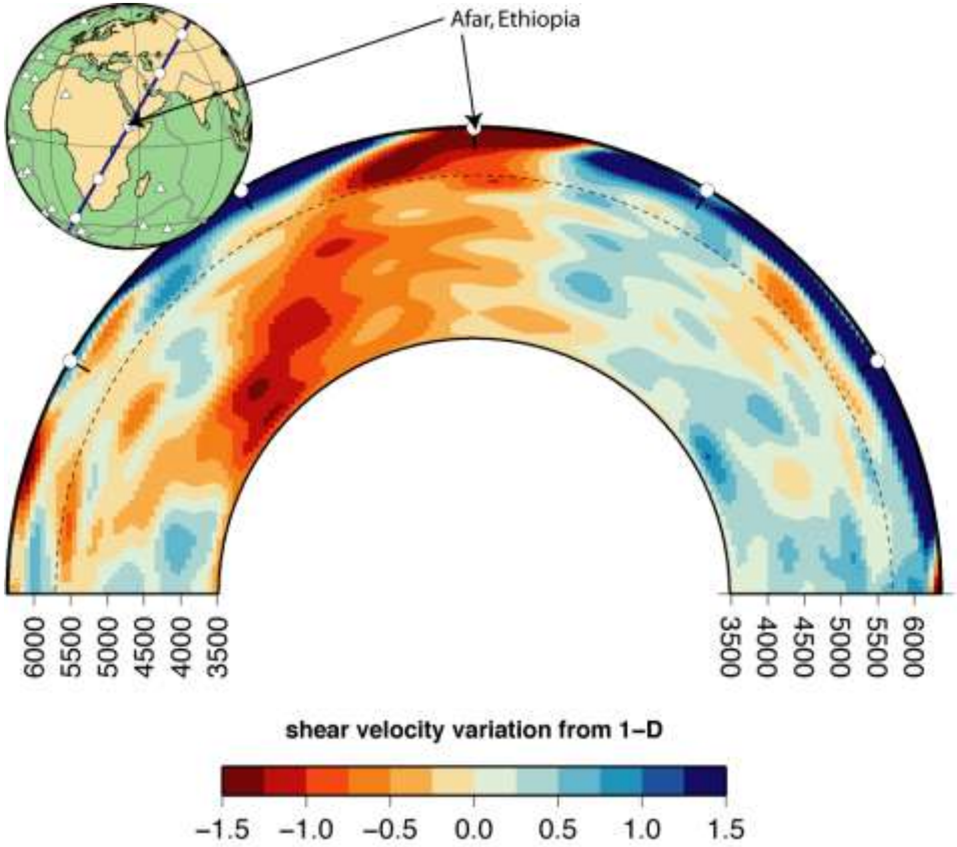
Dust storm in the Danakil Depression

# Results

- Tomography
- Receiver Functions
- Seismic anisotropy

# Architecture of a superplume

## Chemical versus thermal?

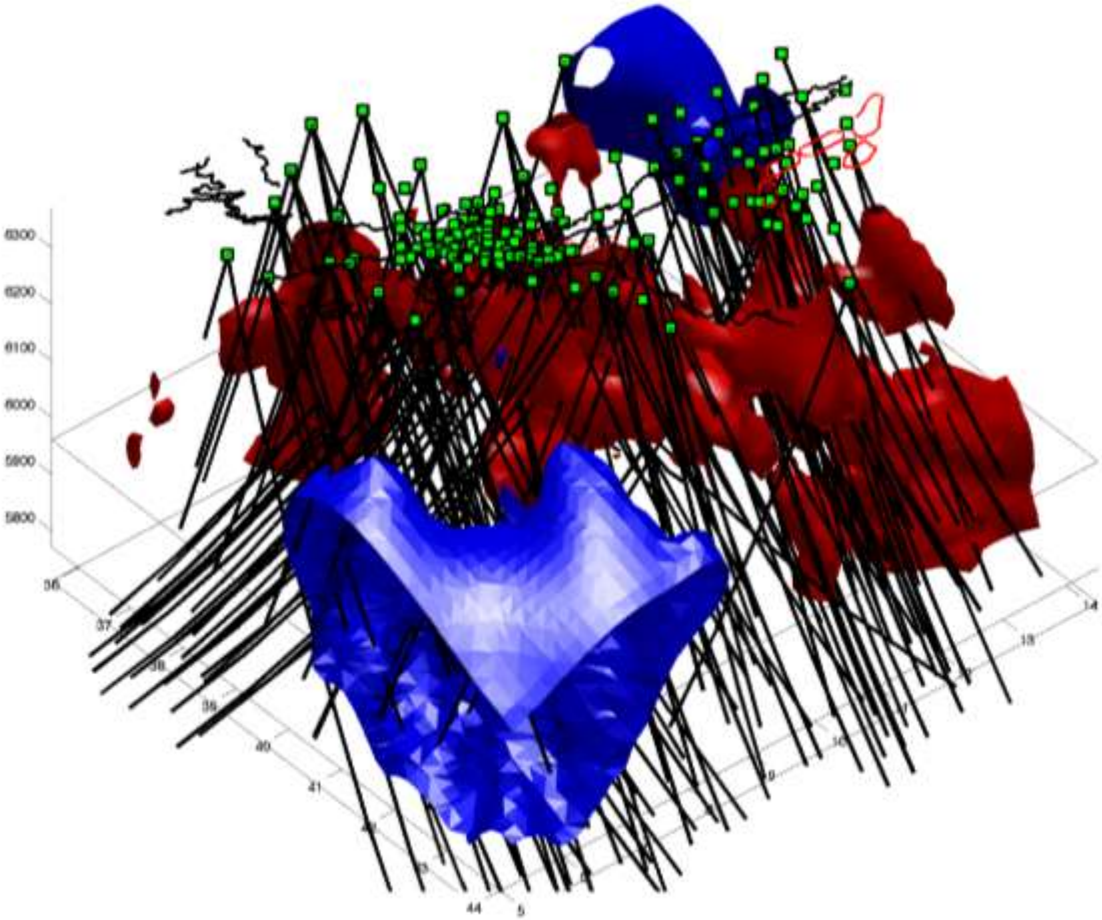


Ritsema and Allen 2003

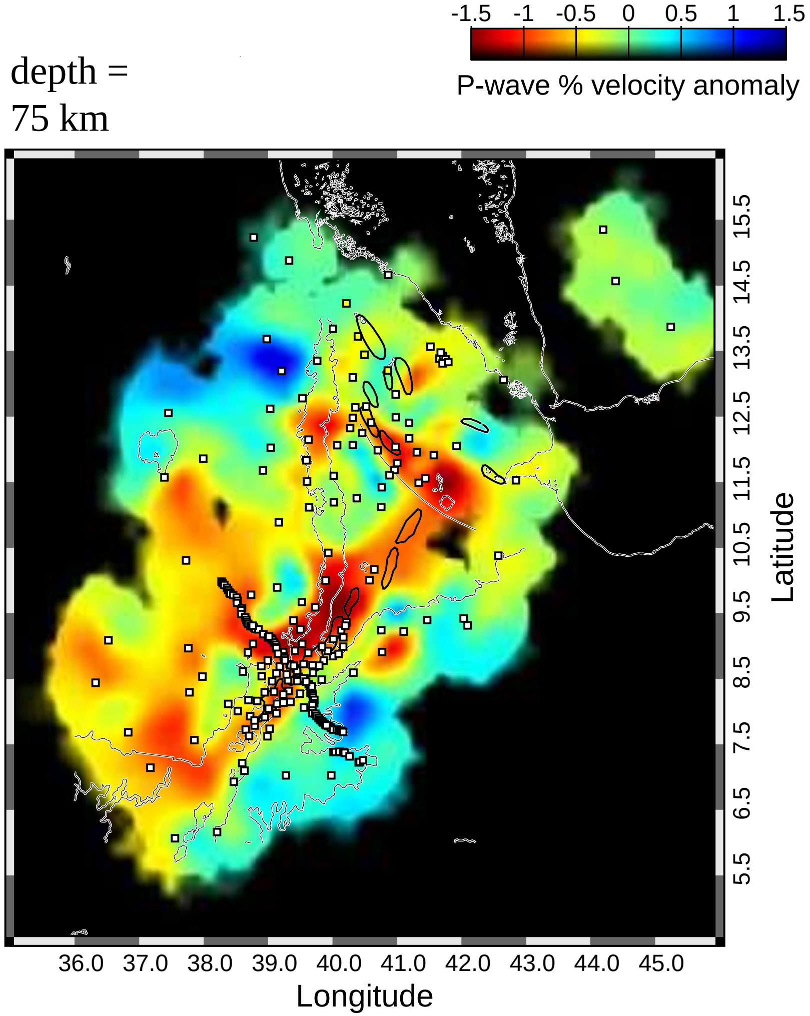
# P- and S-wave travel-time tomography

## Main Ethiopian Rift

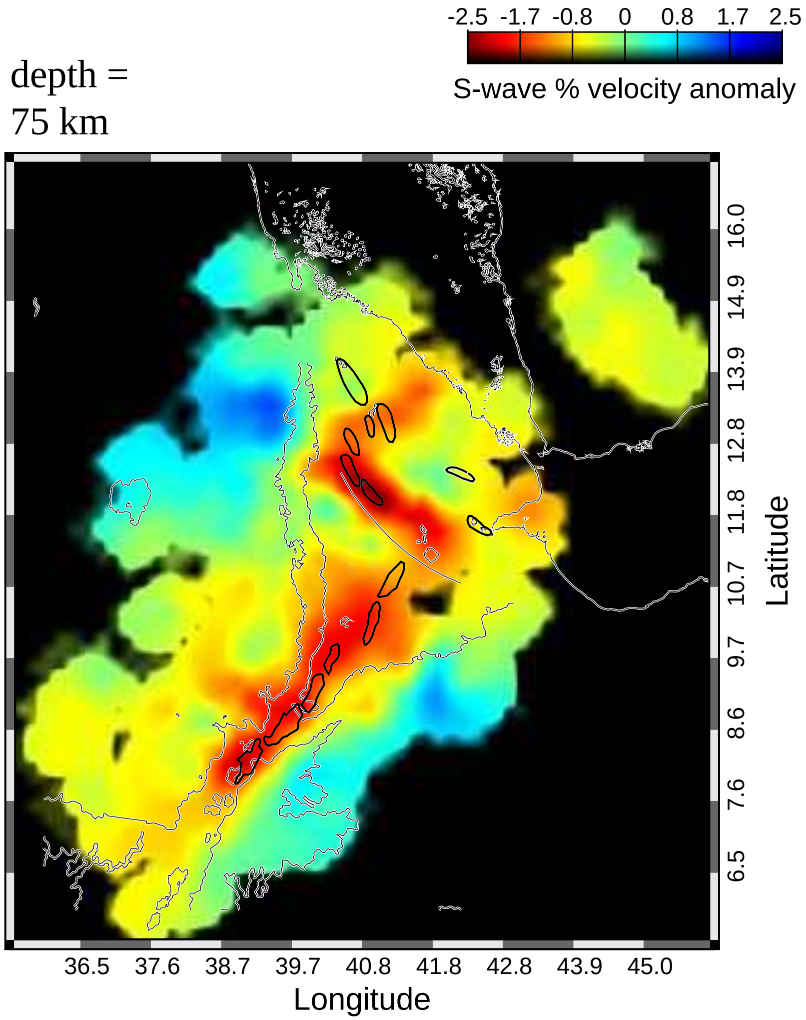
- Bastow et al. (GJI, 2005; 2008); Hammond et al. (2013)
- Broad low velocity sheet-like anomaly that cuts through the pan-African fabric; not a conventional plume-like upwelling.



# 50 – 150 km



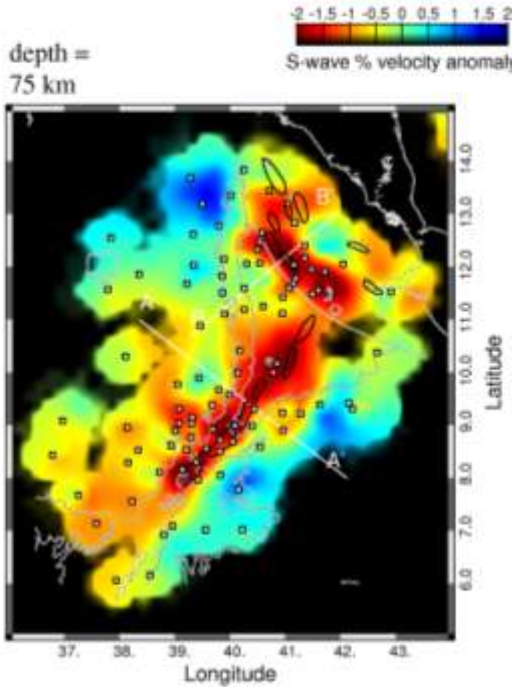
P-wave model – 10132 arrivals



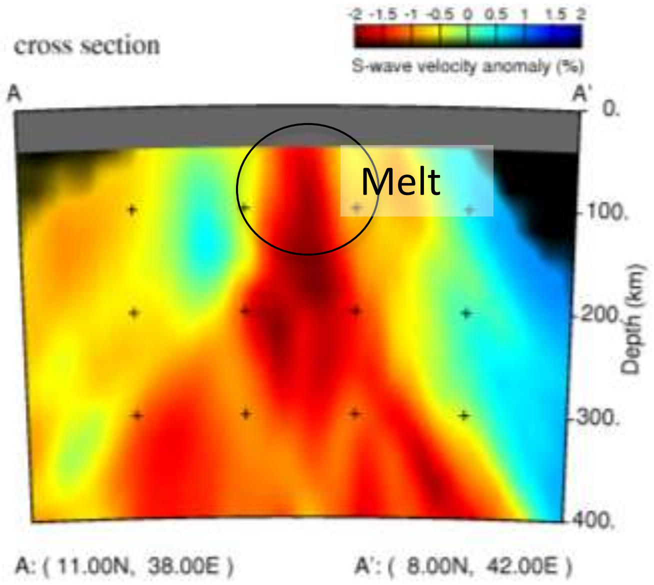
S-wave model – 10811 arrivals

Hammond et al., Geology, 2013

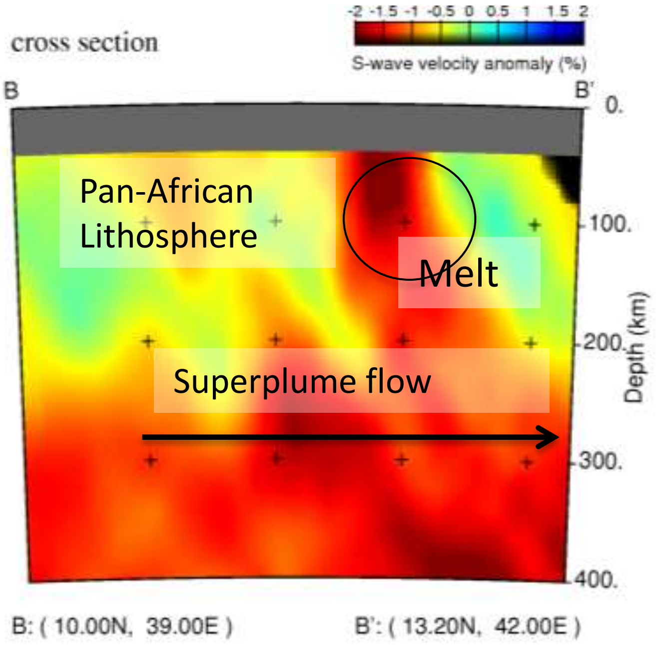
# Seismic tomography



- Focused low seismic velocity anomalies in top 150km – Melt
- Broad tabular low seismic velocity anomaly to depths of at least 400 km
- Seismically fast Pan-African lithosphere
- Seismic velocities are best explained by high temperatures and melt in elongate inclusions. **Huge absolute delay time and R values (Vp/Vs) -> melt**
- Latest absolute delay times of anywhere in the world.



Melt



Pan-African Lithosphere

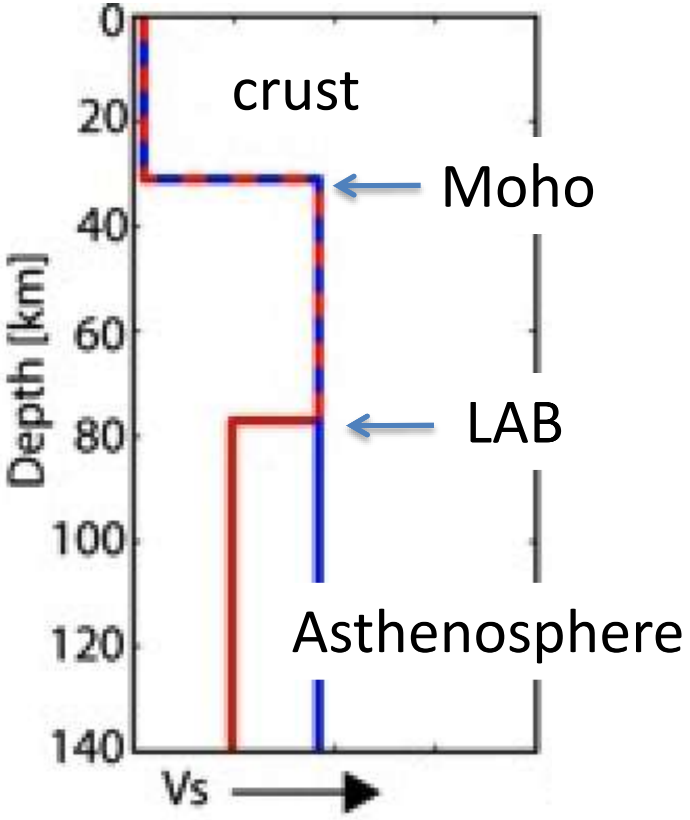
Melt

Superplume flow

# The Stratigraphy of the Lithosphere

Use receiver functions

- Image variations in crust:
  - Moho depth
  - Vp/Vs ratios
- Image variations in the lithosphere (tectonic plate)
  - lithosphere-asthenosphere boundary (LAB)



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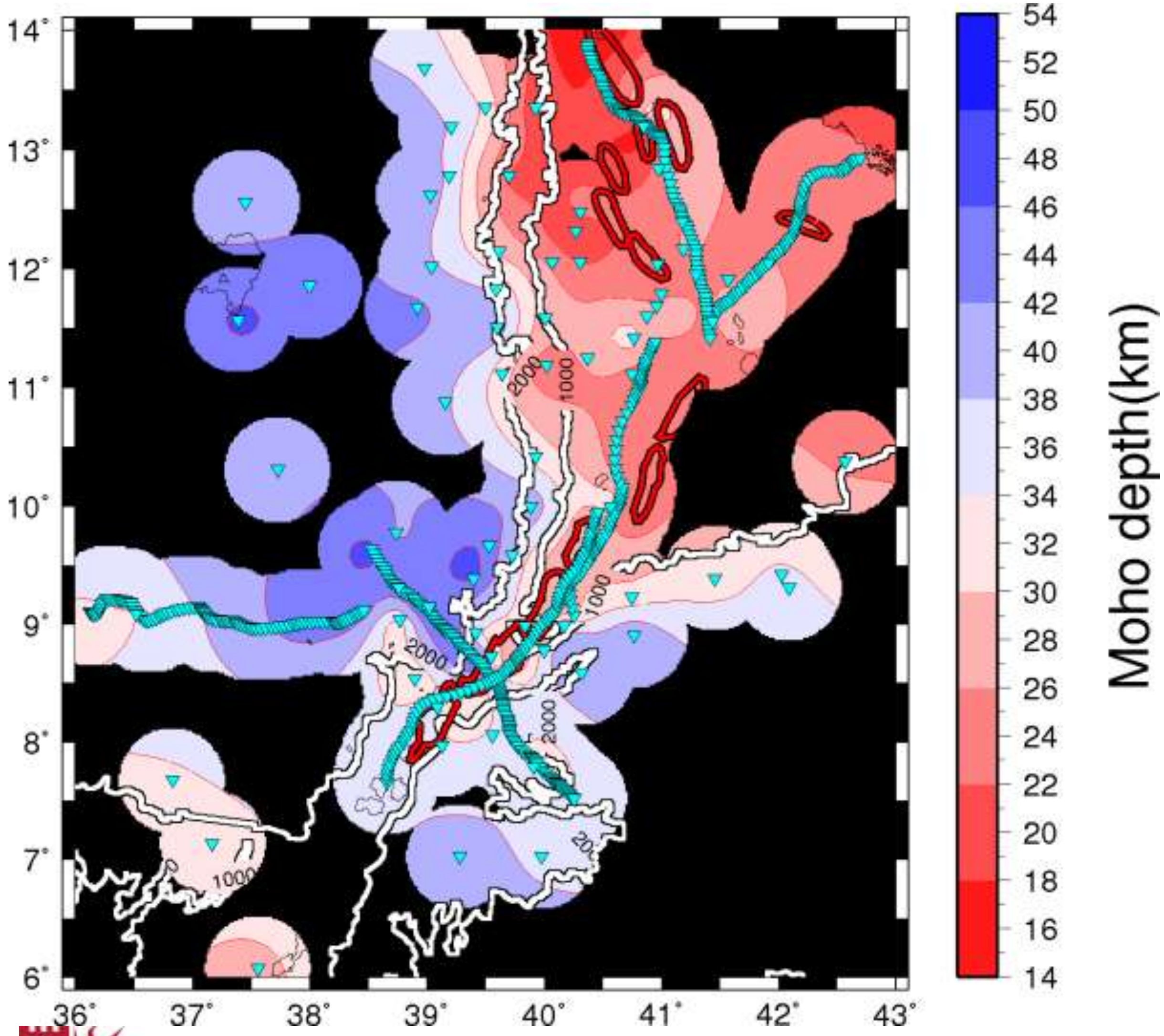
# Receiver Functions: Crustal thickness



- Dramatic variations across Ethiopia: 10-50km
- Thinnest crust in northern Afar
- Thickest beneath northern plateau
- Sharp variations at rift flanks

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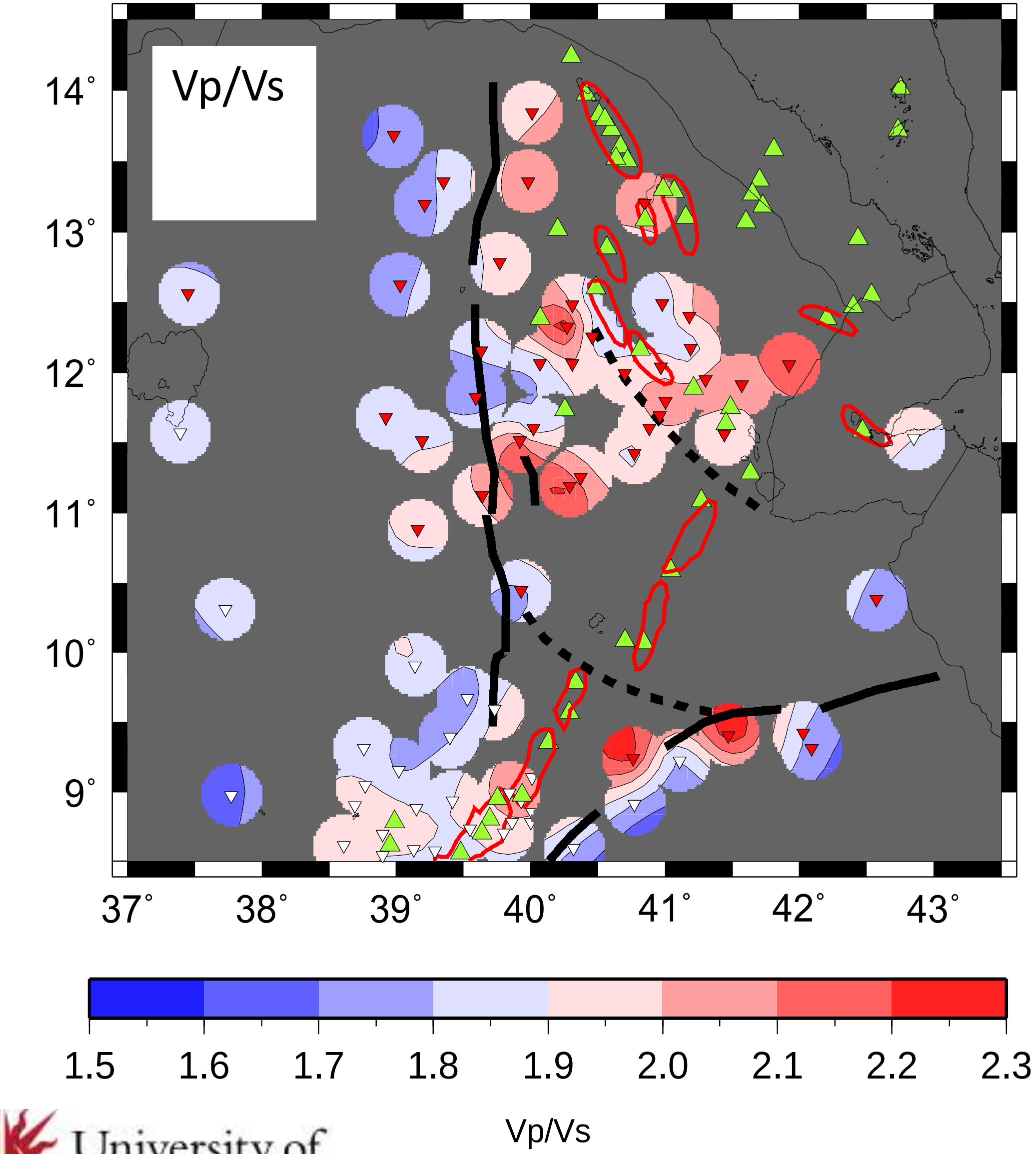
Hammond et al. 2011

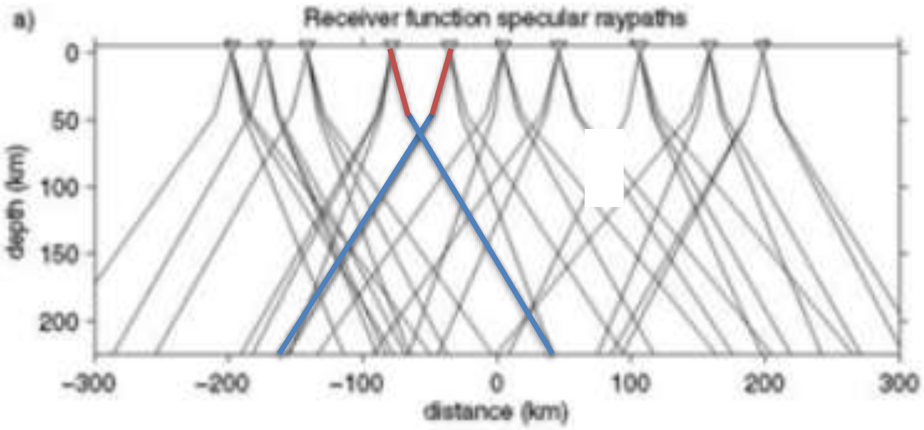
# Receiver Functions: Vp/Vs ratios

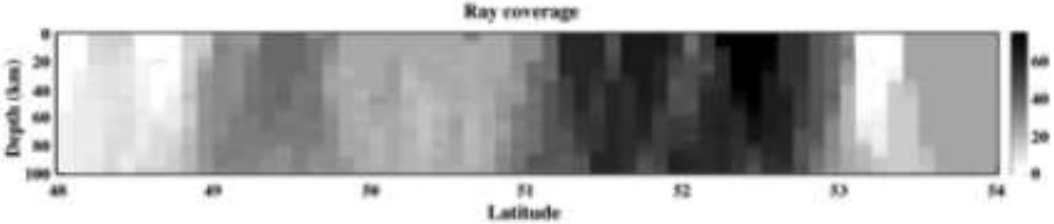


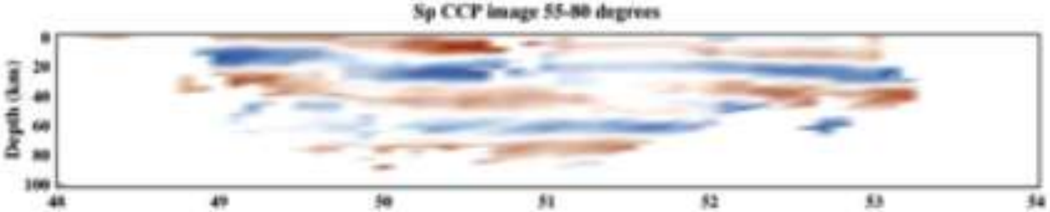
Hammond et al. 2011

- Vary from 1.6 beneath the plateaus
- Up to 2.3 in parts of Afar
- Vp/Vs > 2.0 means melt
- Sharp variations at rift flanks

# Crustal Structure: CCP migration

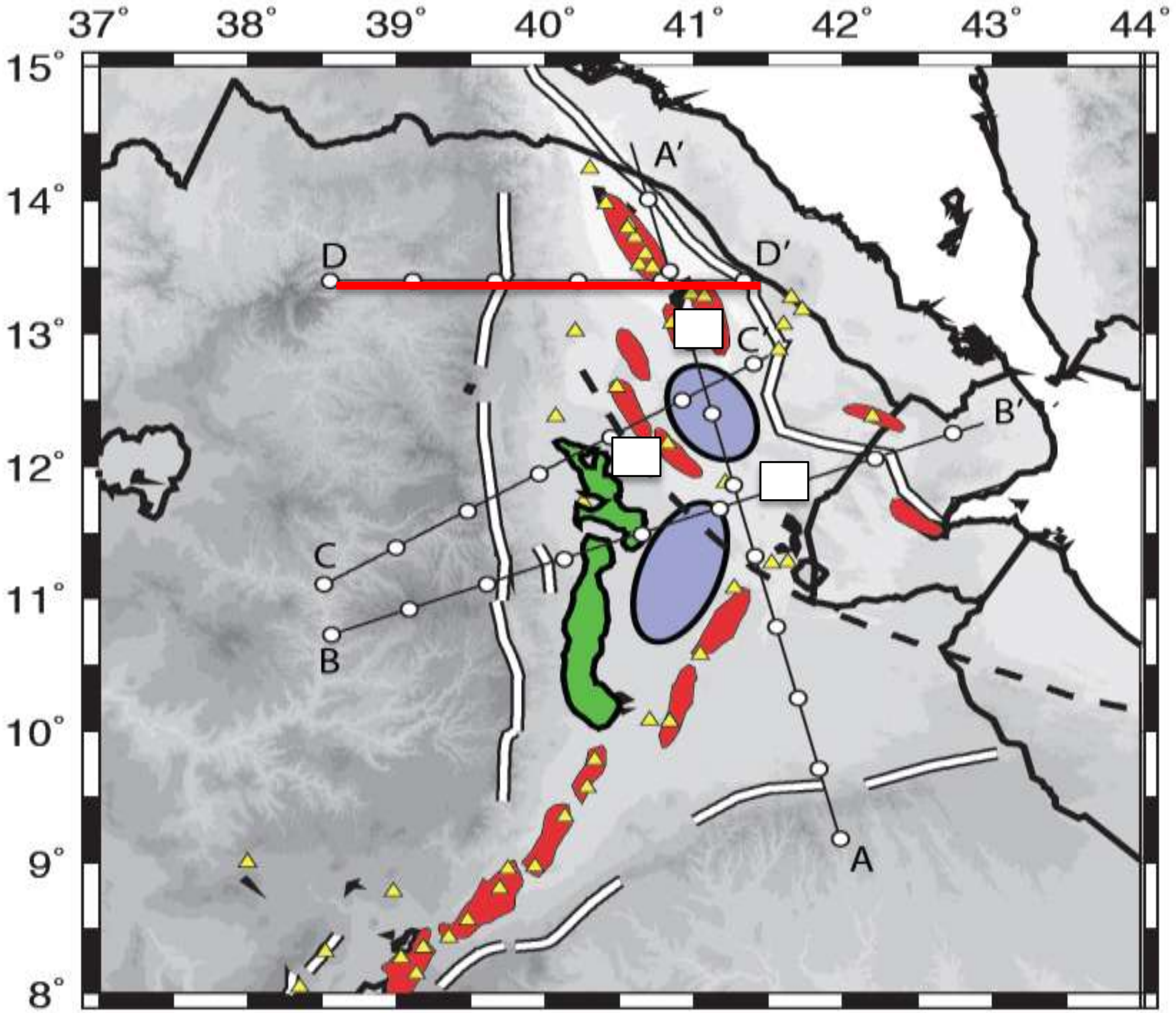




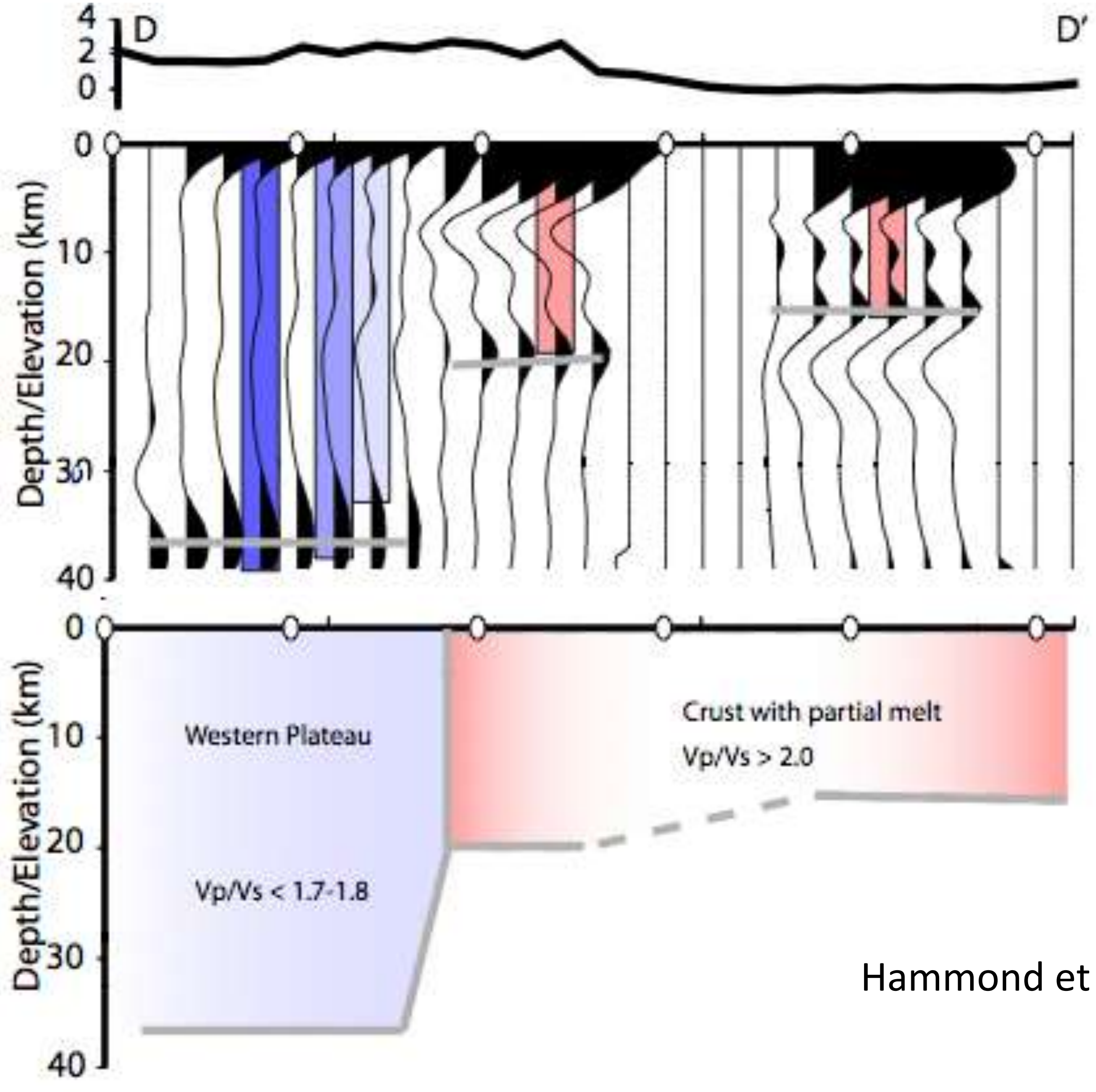


Angus et al., 2010

# Crustal Structure: CCP migration



# Crustal Structure: CCP migration

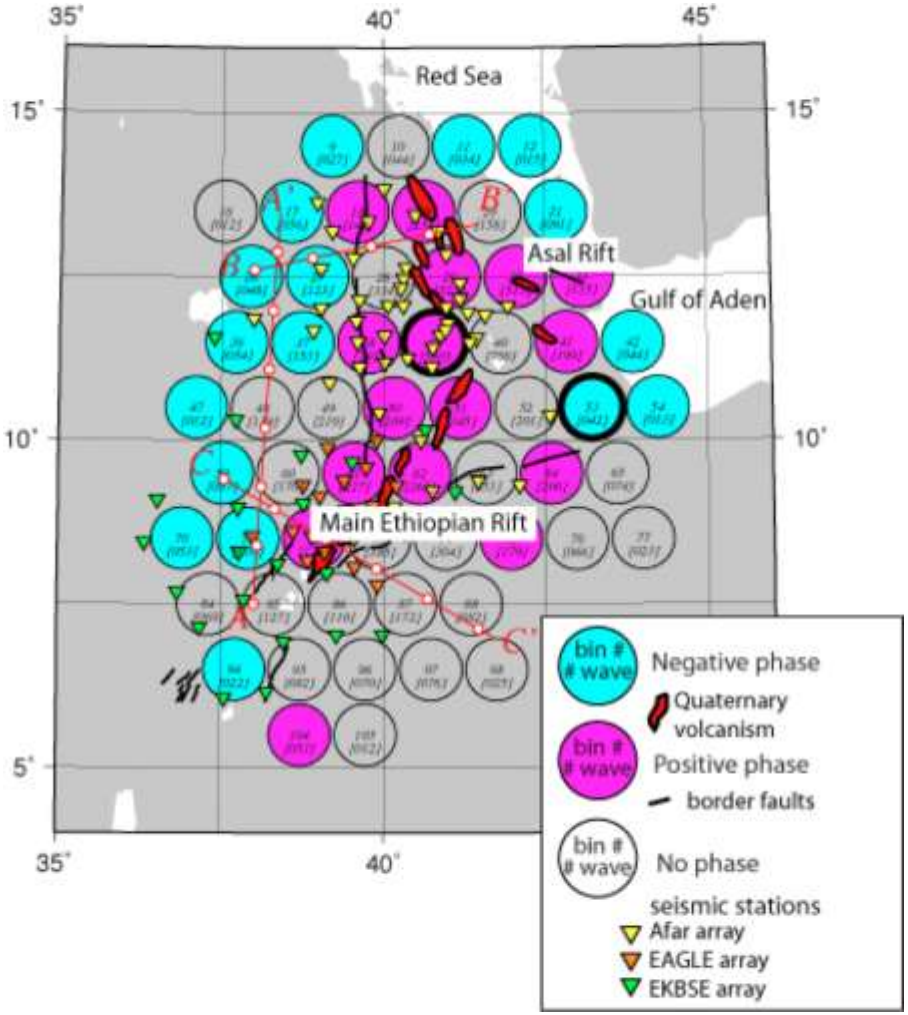


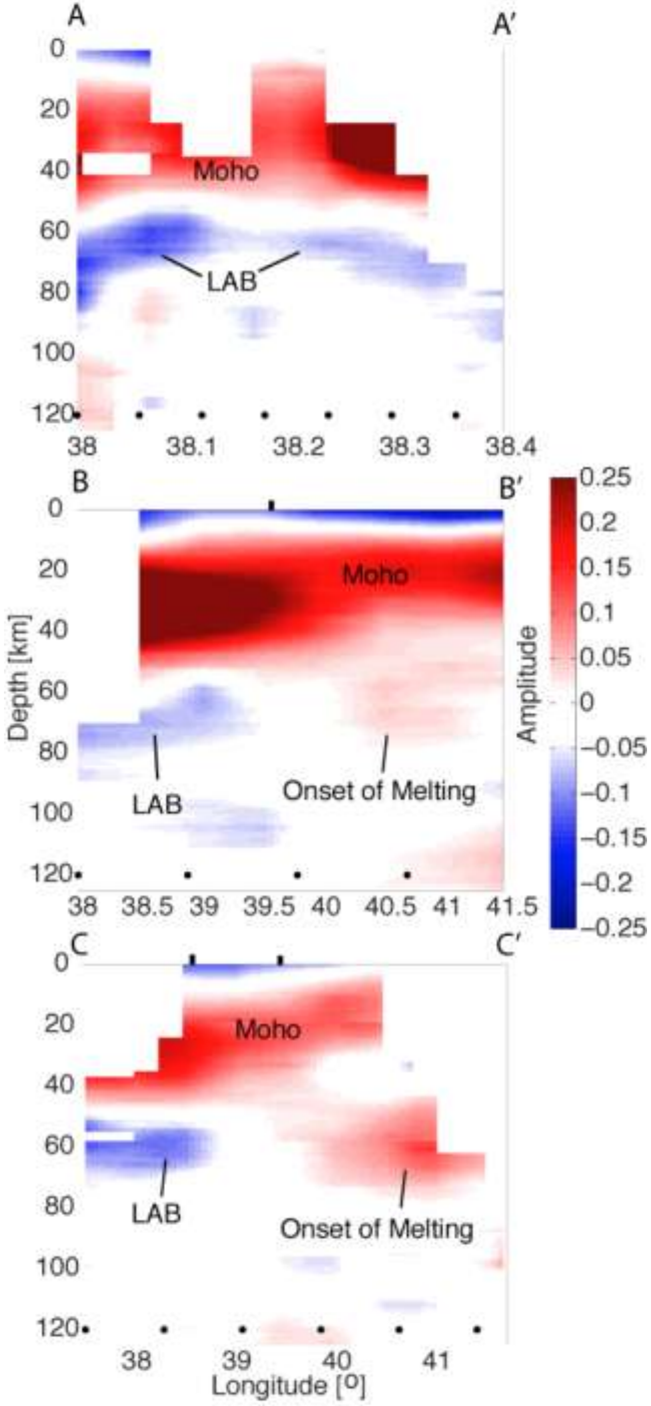
Hammond et al. 2011

# The Lithosphere-Asthenosphere Boundary

- S-P conversion
- Common Conversion Point migration
- Clear differences between plateau and rift

# The LAB beneath Ethiopia: migrated images





- At ~75km S-wave receiver functions show a velocity decrease beneath the Plateau and a velocity increase beneath most of Afar

(Rychert et al., 2012)

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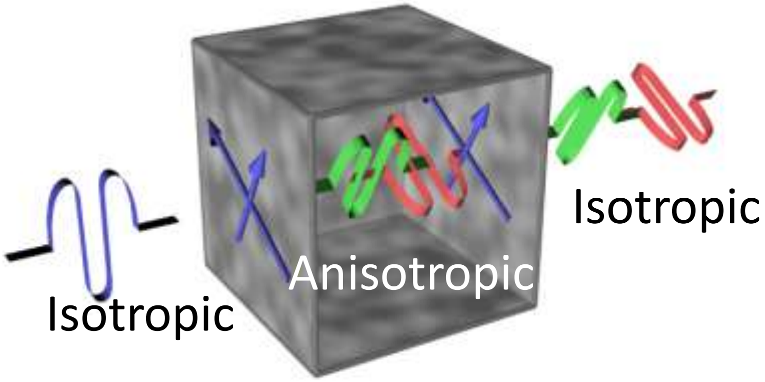
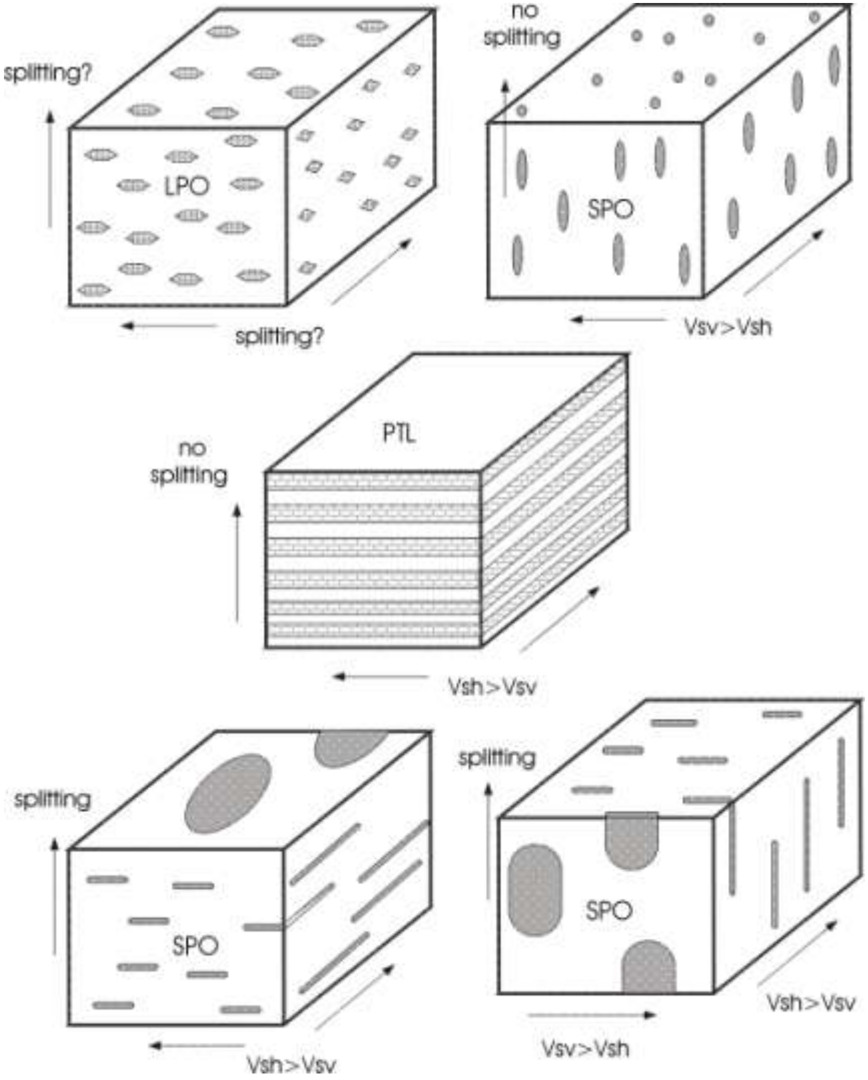
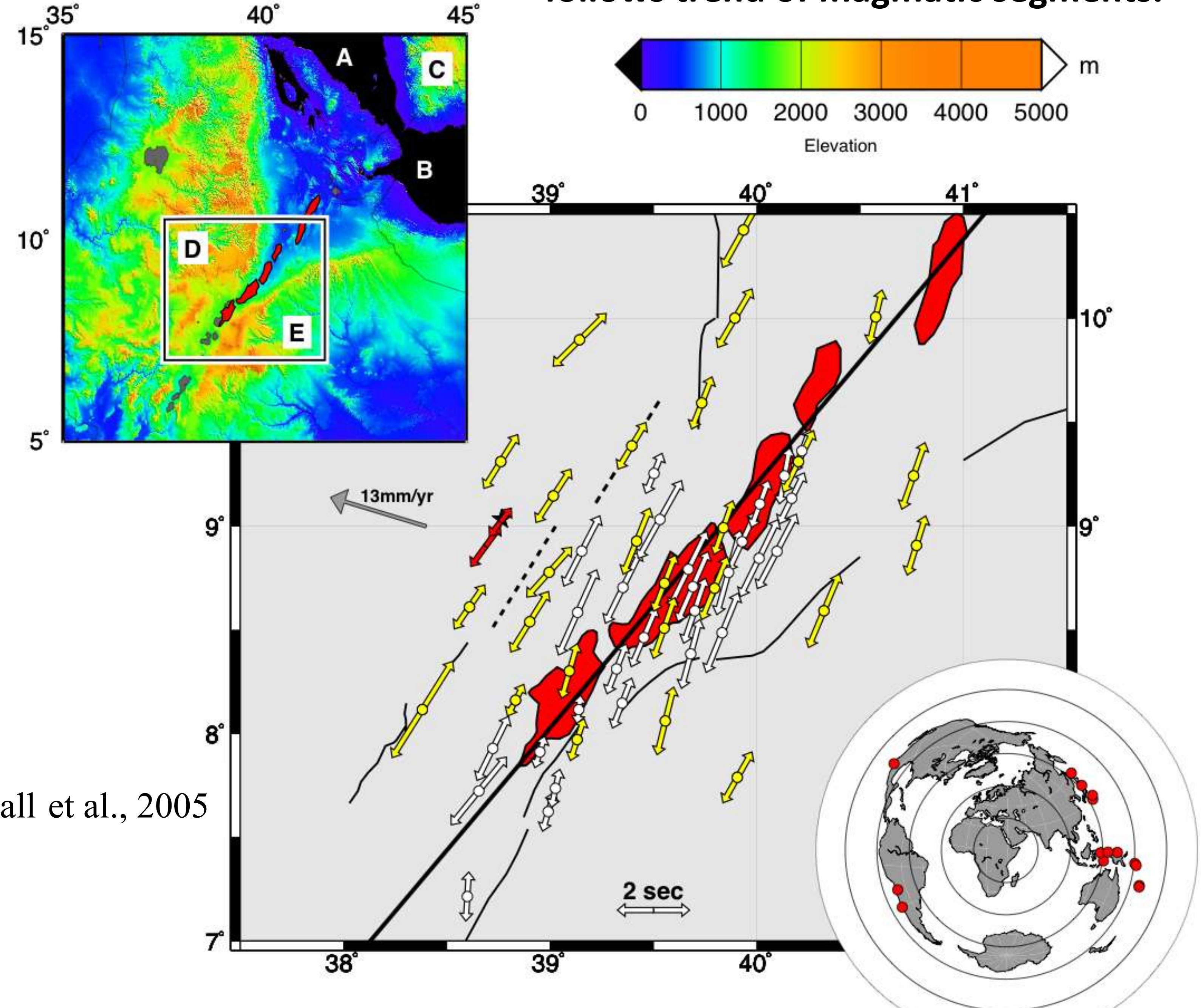
# Seismic anisotropy: *Shear-wave splitting analysis*.





**Unravelling mechanisms for anisotropy**

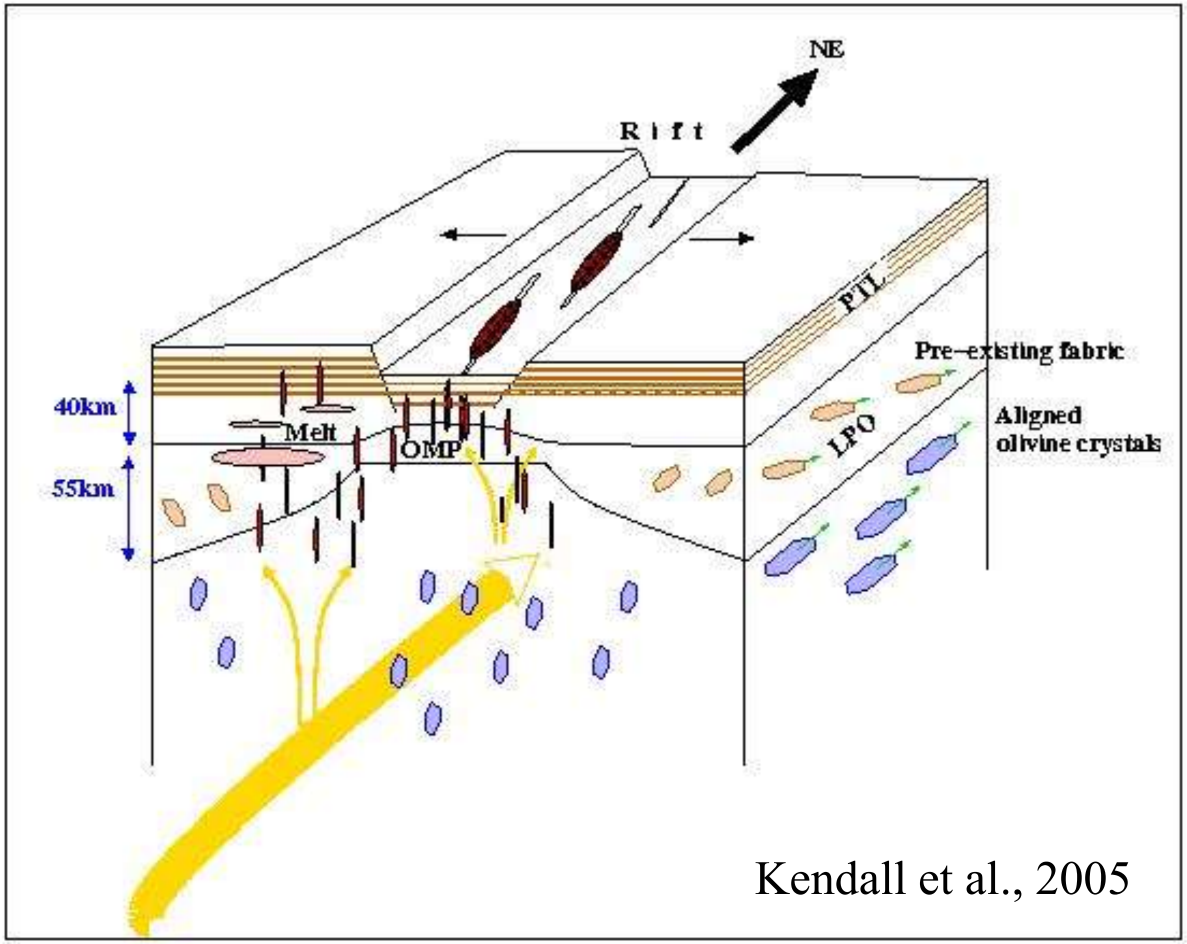
- Counter-clockwise rotation within rift valley
- - follows trend of magmatic segments.



Kendall et al., 2005

# Mechanisms for anisotropy:

- Working model for anisotropy beneath East Africa Rift



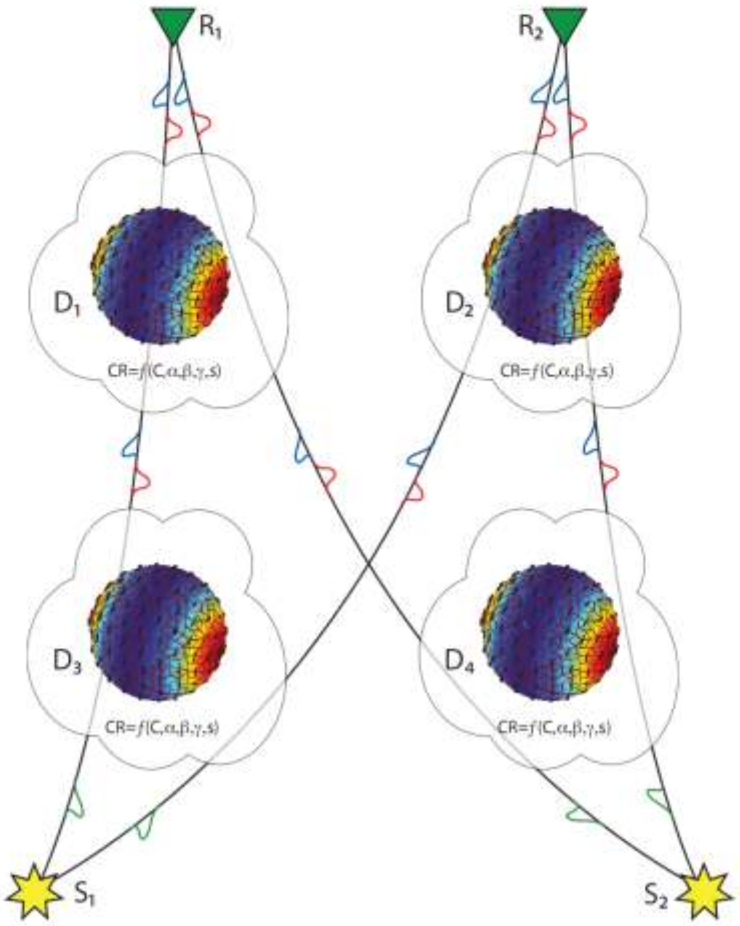
Kendall et al., 2005

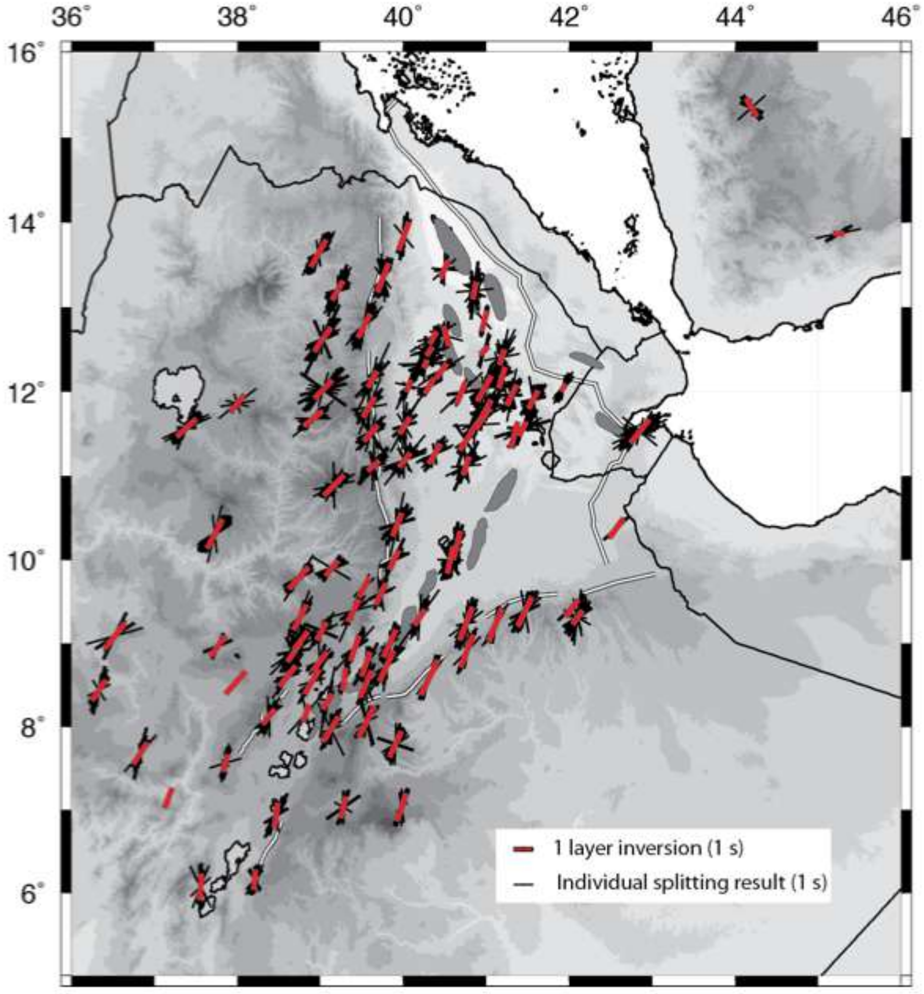
- Large-scale flow beneath eastern Africa associated with super-swell.
- Melt focused at plate boundaries - leads to oriented vertical pockets of melt.
- Contribution from pan-African fabric in lithosphere away from Main Ethiopian rift and continental slivers within Afar.

- See also Obrebski et al., 2010; Gao et al., 2010; Bastow et al., 2010

# Shear-wave splitting tomography

- Based on Wookey (2012)
- Two layer inversion across multiple tectonic domains





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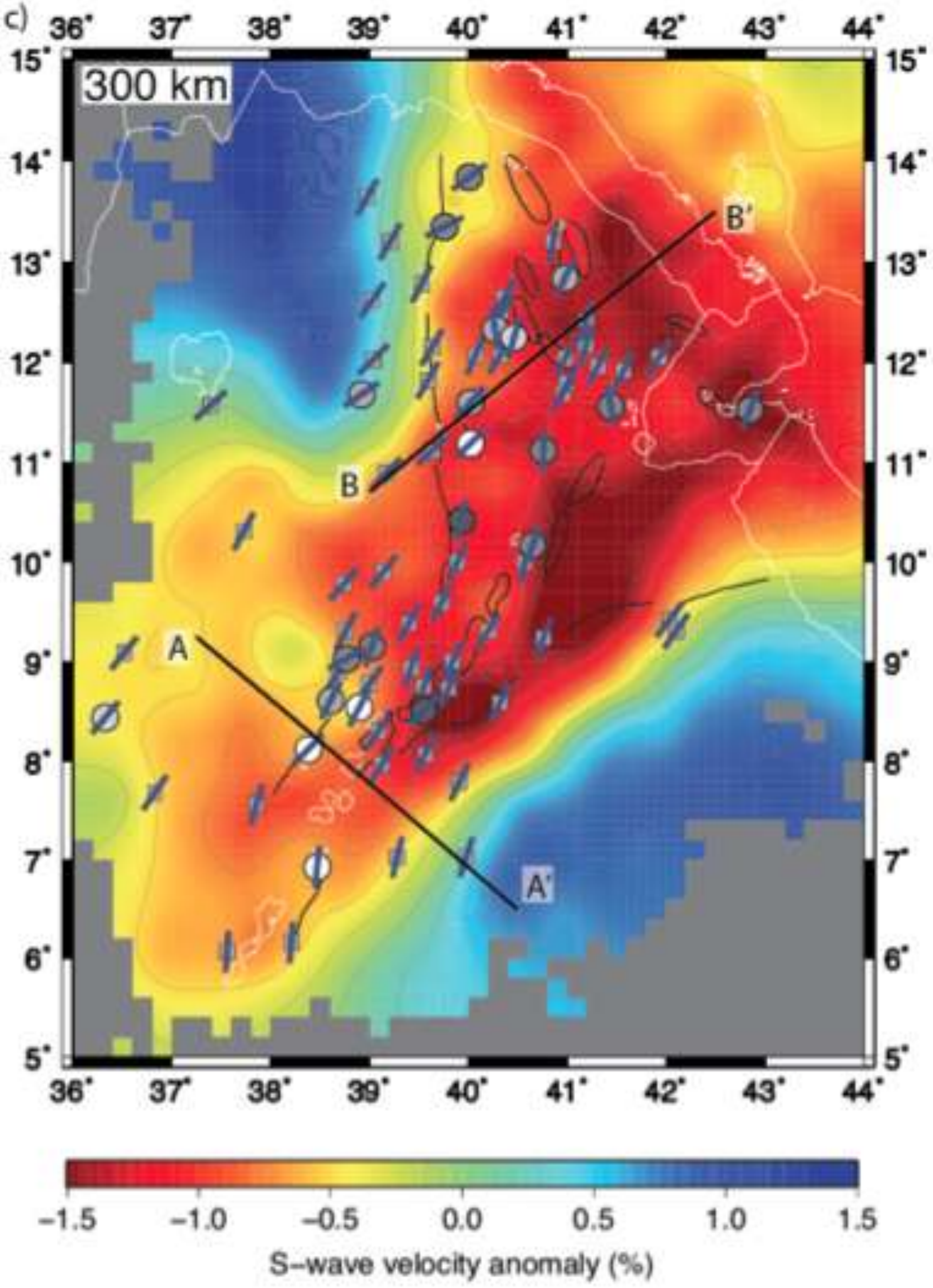
Lower layer aligned with density driven mantle flow



Hammond et al., 2013

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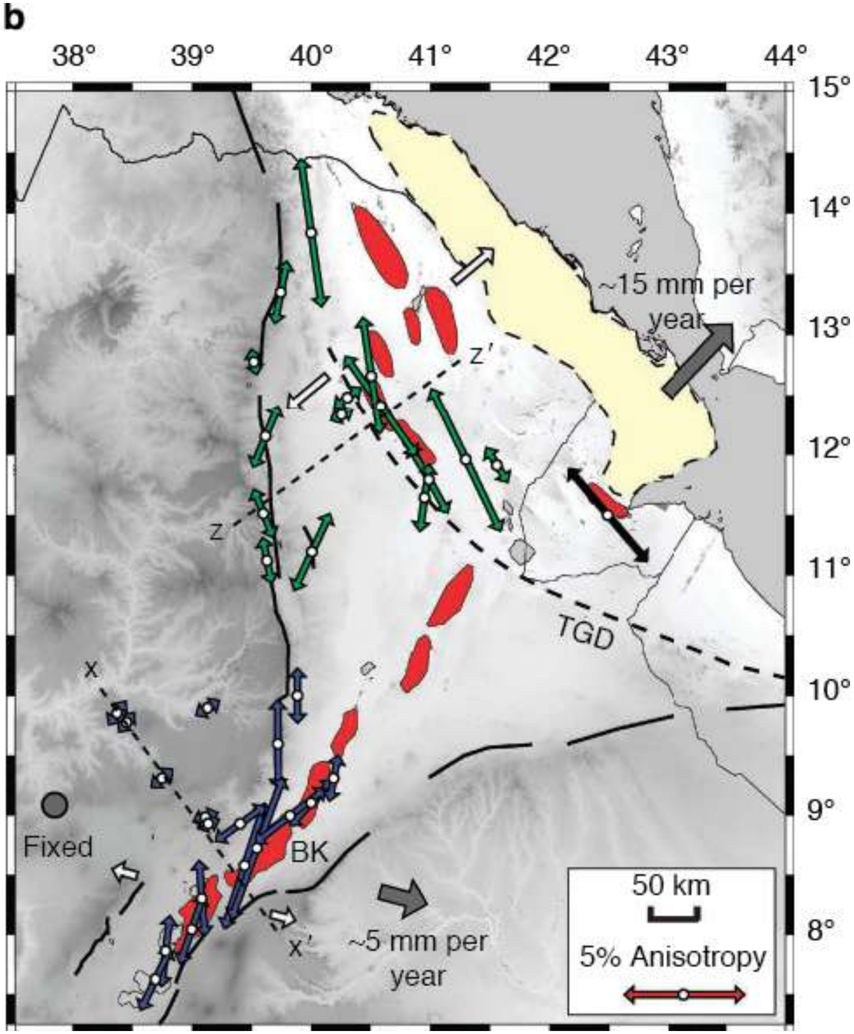
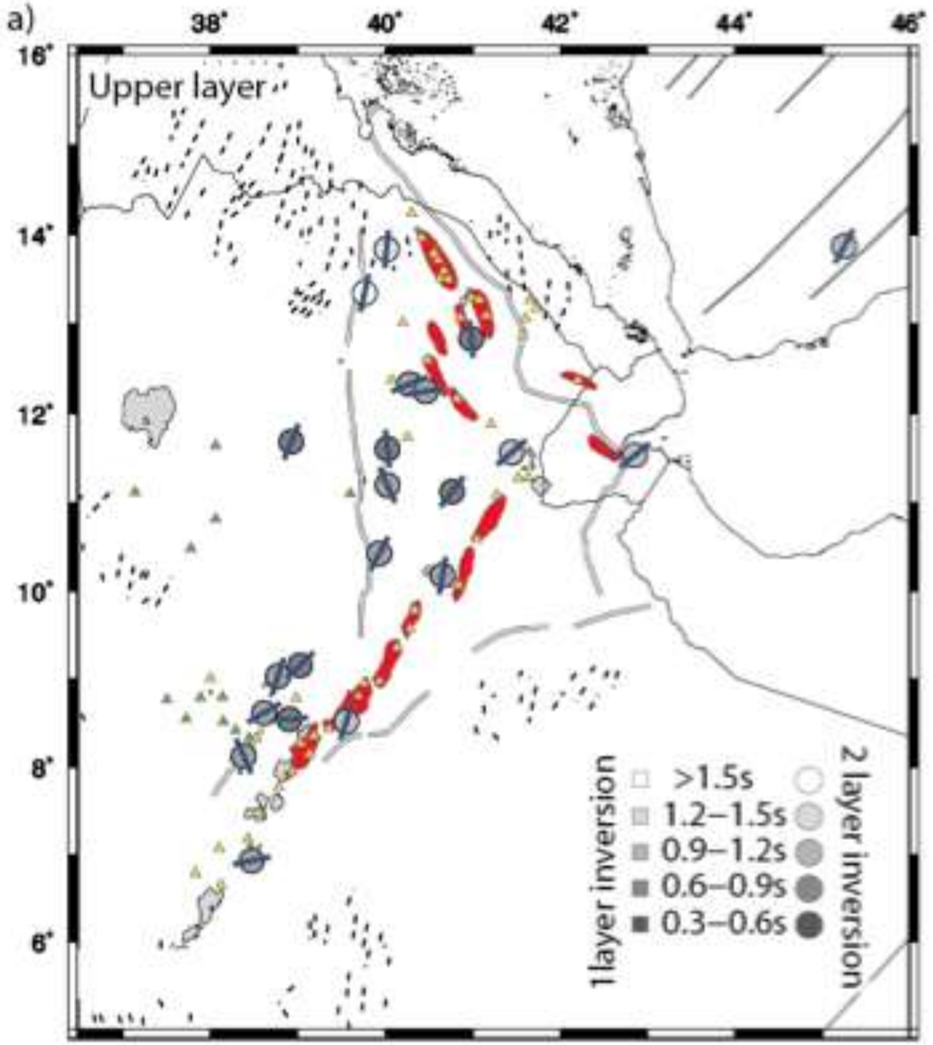
# Upper layer – fossil fabric and melt-induced anisotropy

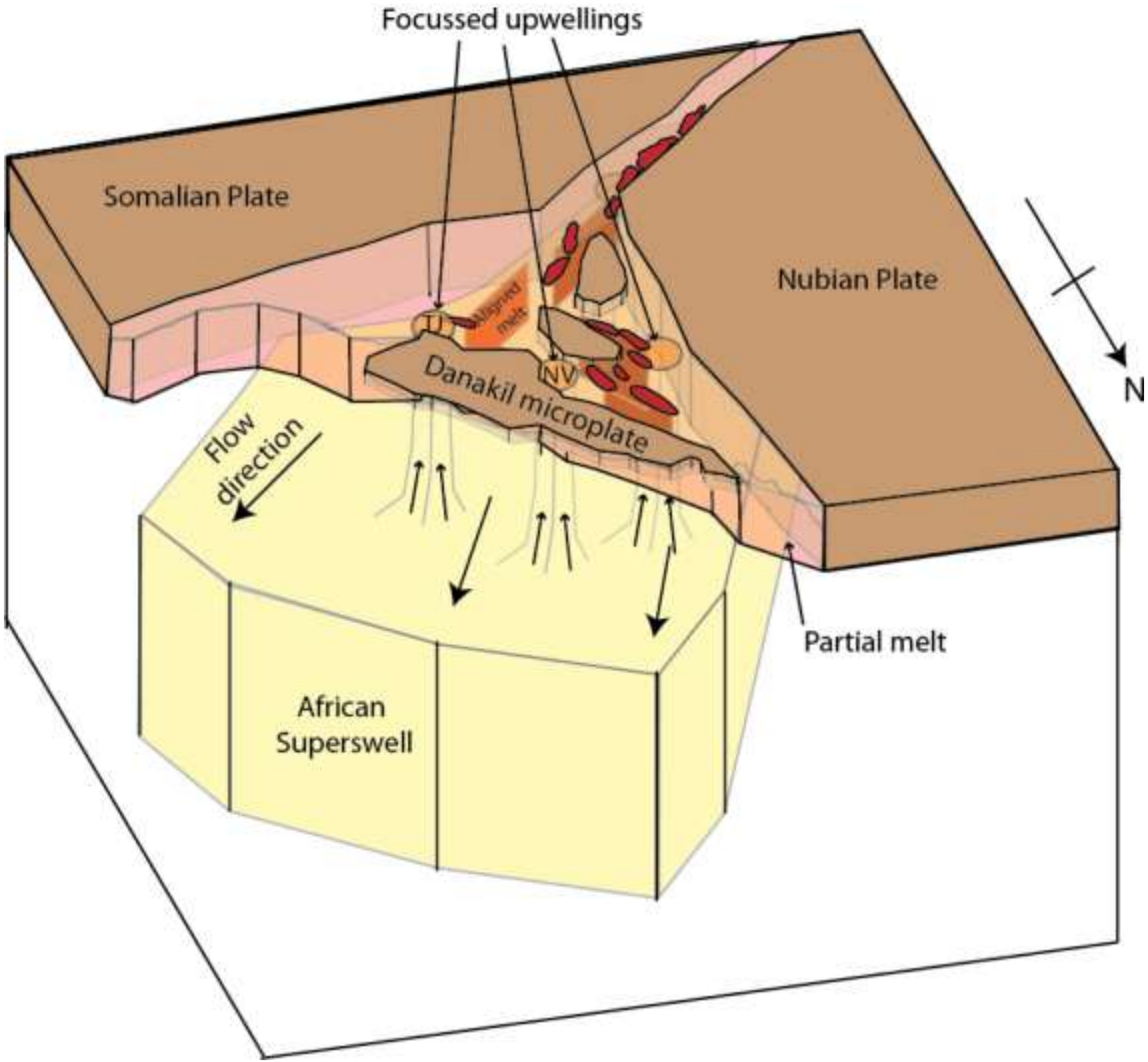


Crustal anisotropy; Keir et al., 2011



Upper layer; Hammond et al., 2013

# Stratified upper-mantle beneath the EAR



- Broad low-velocity region of density driven flow
- Focuses upwellings punctuation lithosphere and crust
- Microplate isolation in Afar

Hammond et al., in press, 2013

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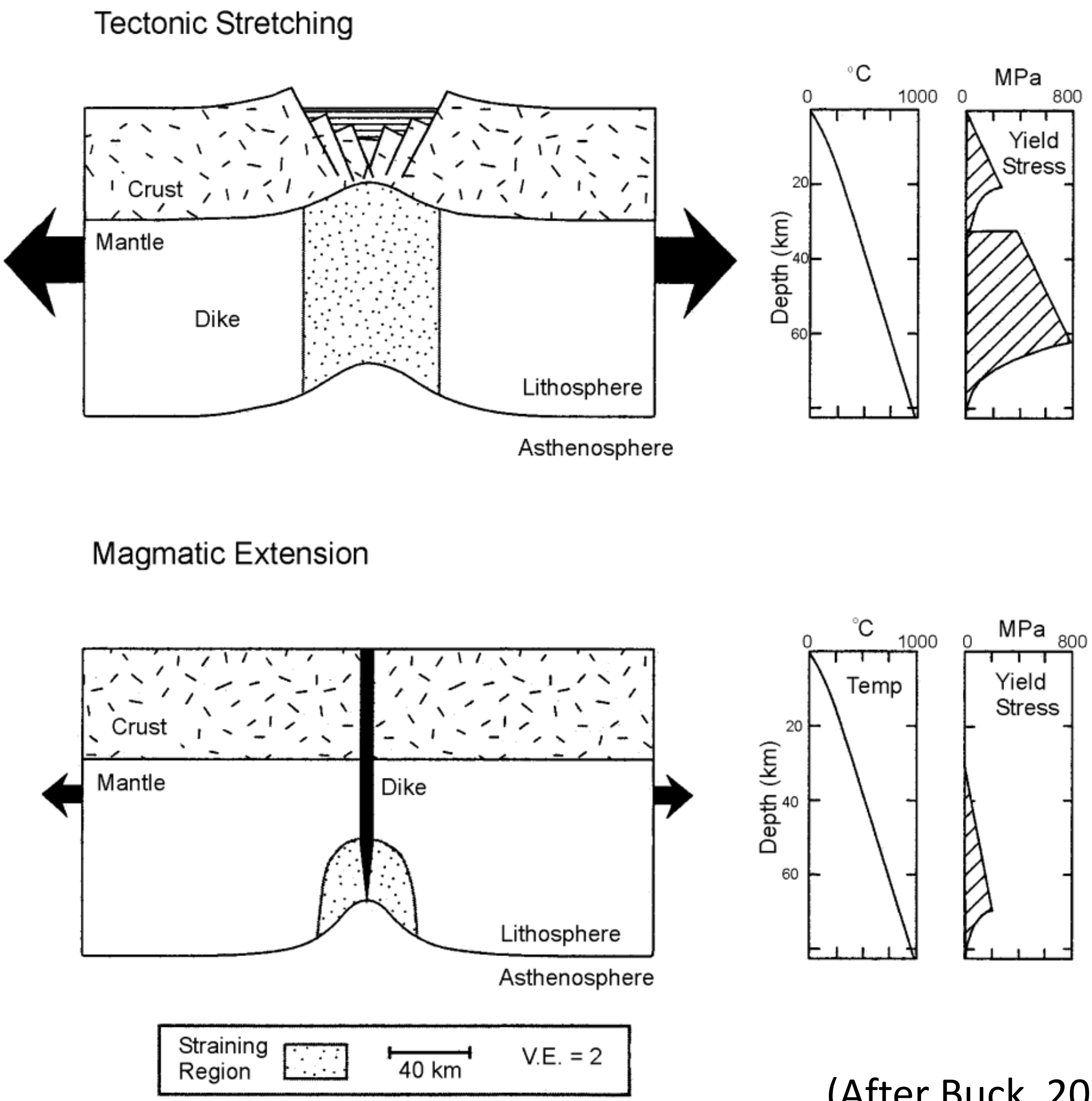
# Magma Assisted Rifting

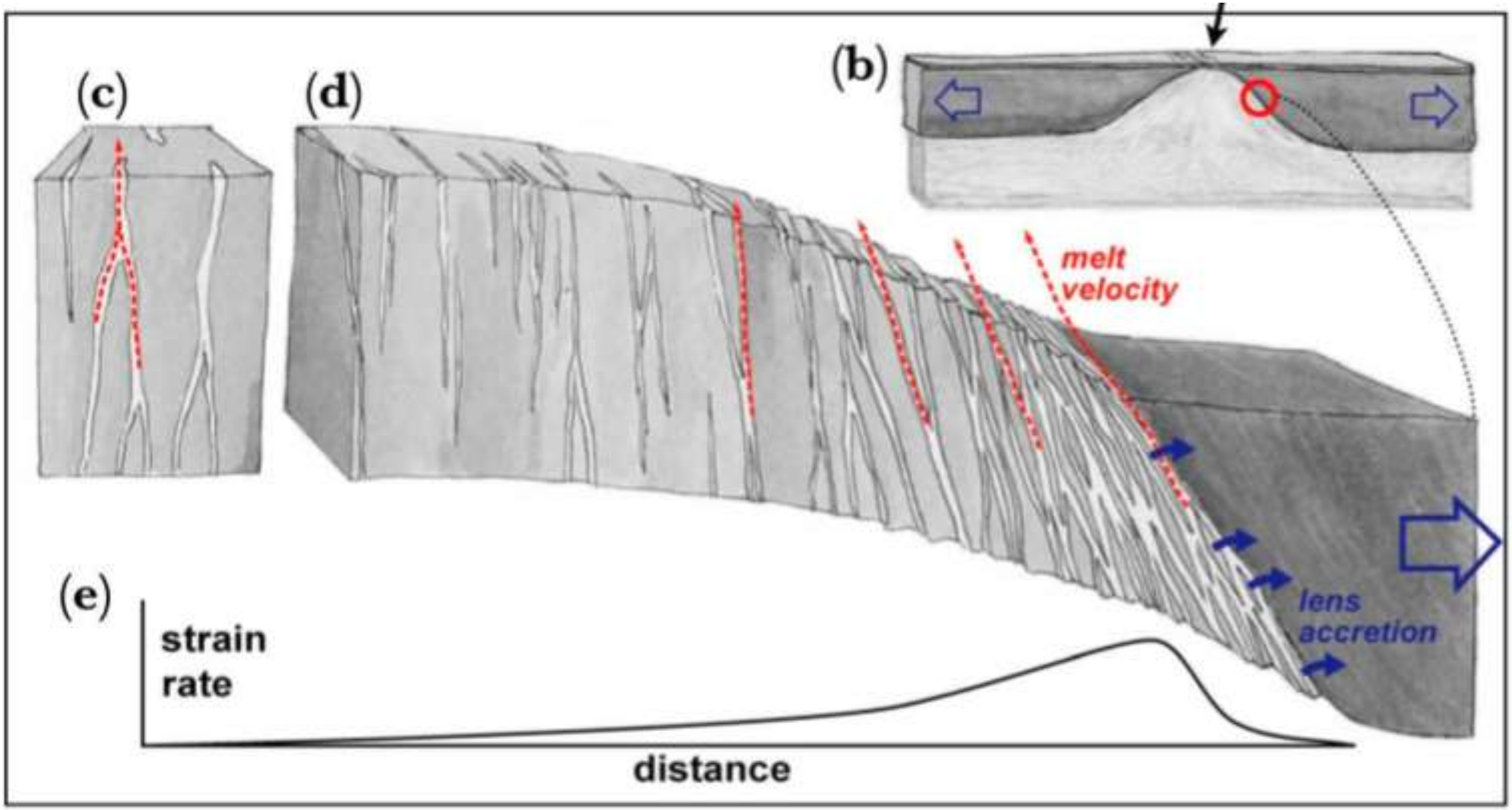


- Melt injection leads to much lower yield stresses.
- Deformation (strain) is focused at plate boundaries.

(After Buck, 2004)

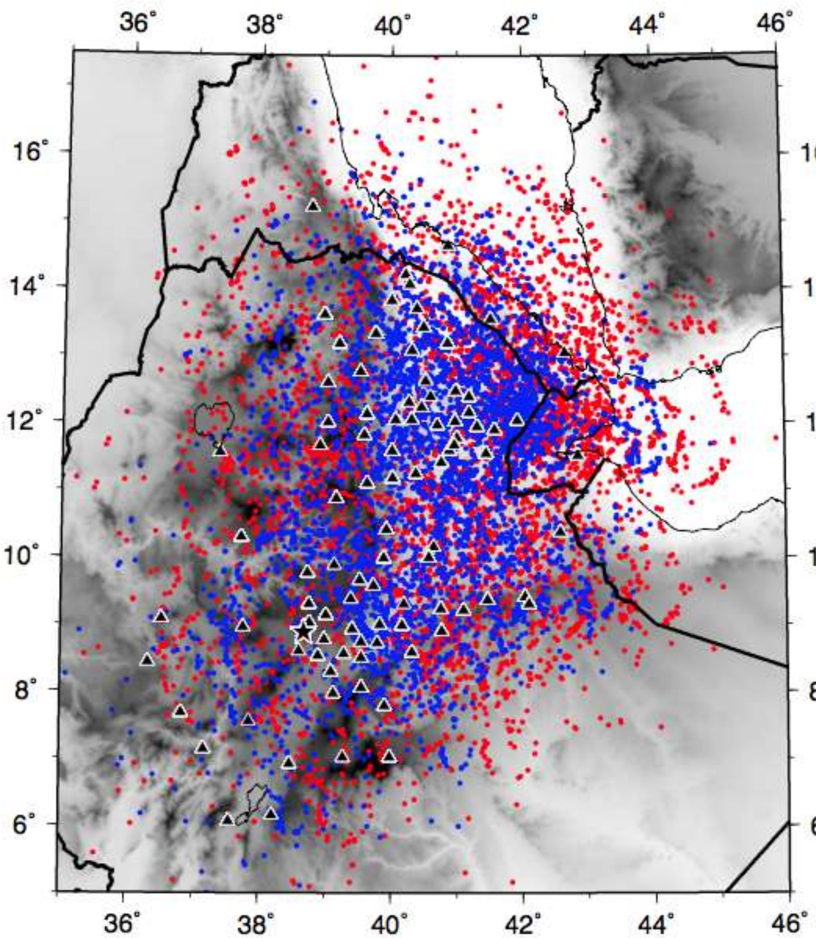
# Stress driven melt segregation

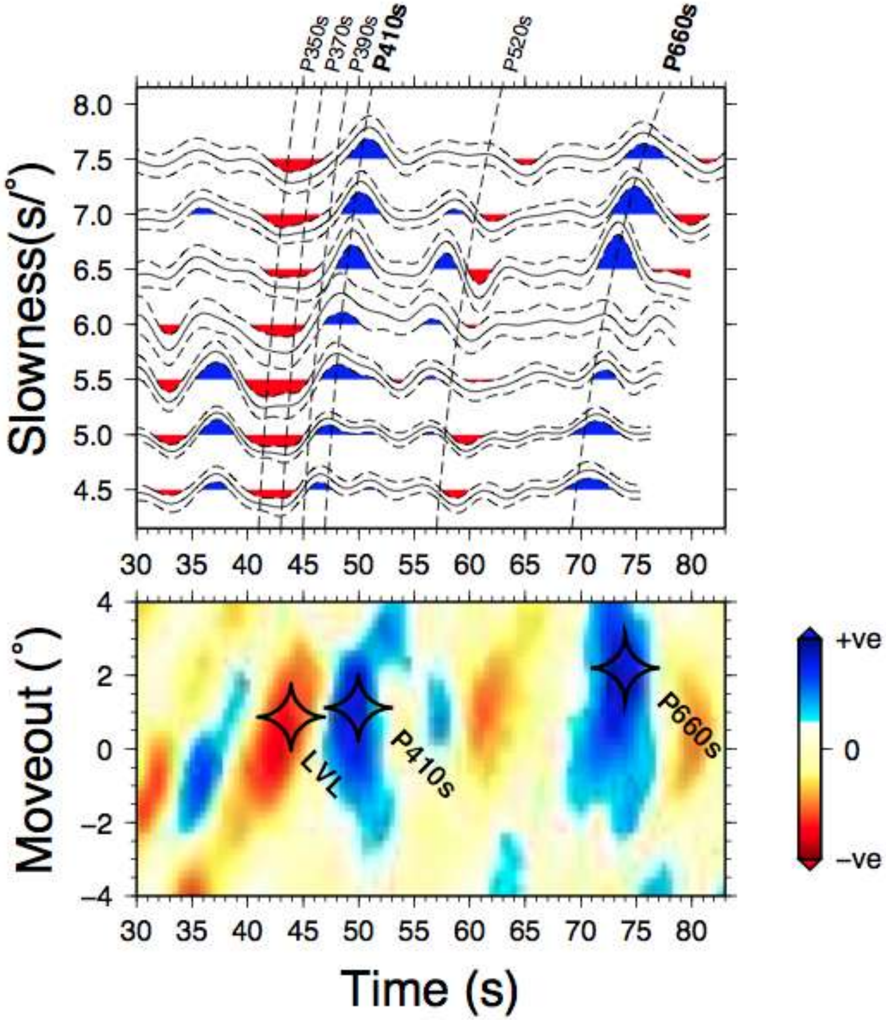
## - most effective at flanks (marginal LAB)



Holtzman and Kendall, G3, 2010

# Evidence for plume in the mantle transistion zone?





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Thompson et al., 2013

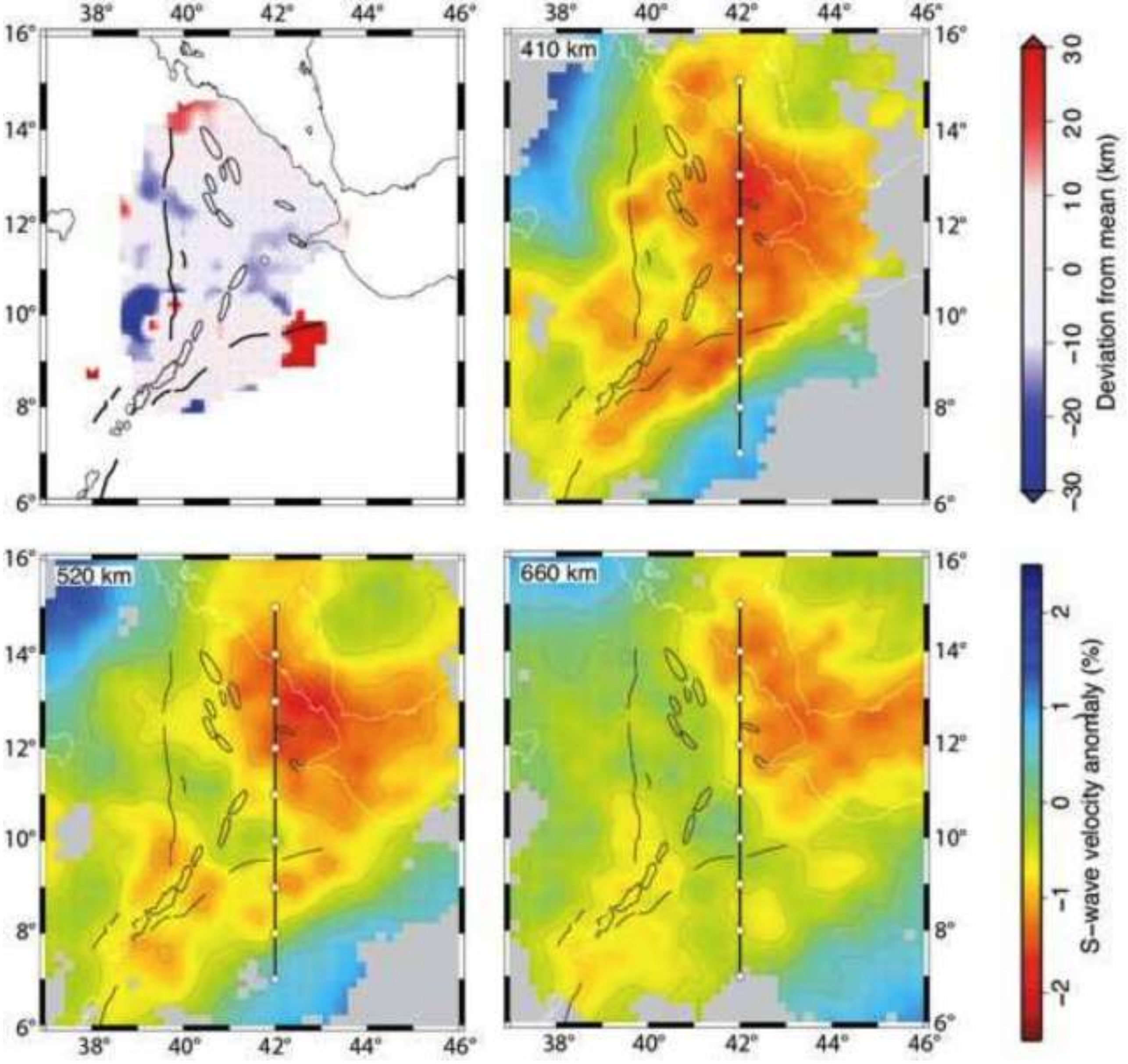
# Mantle transition zone

Little topography on the 410 and 660 km

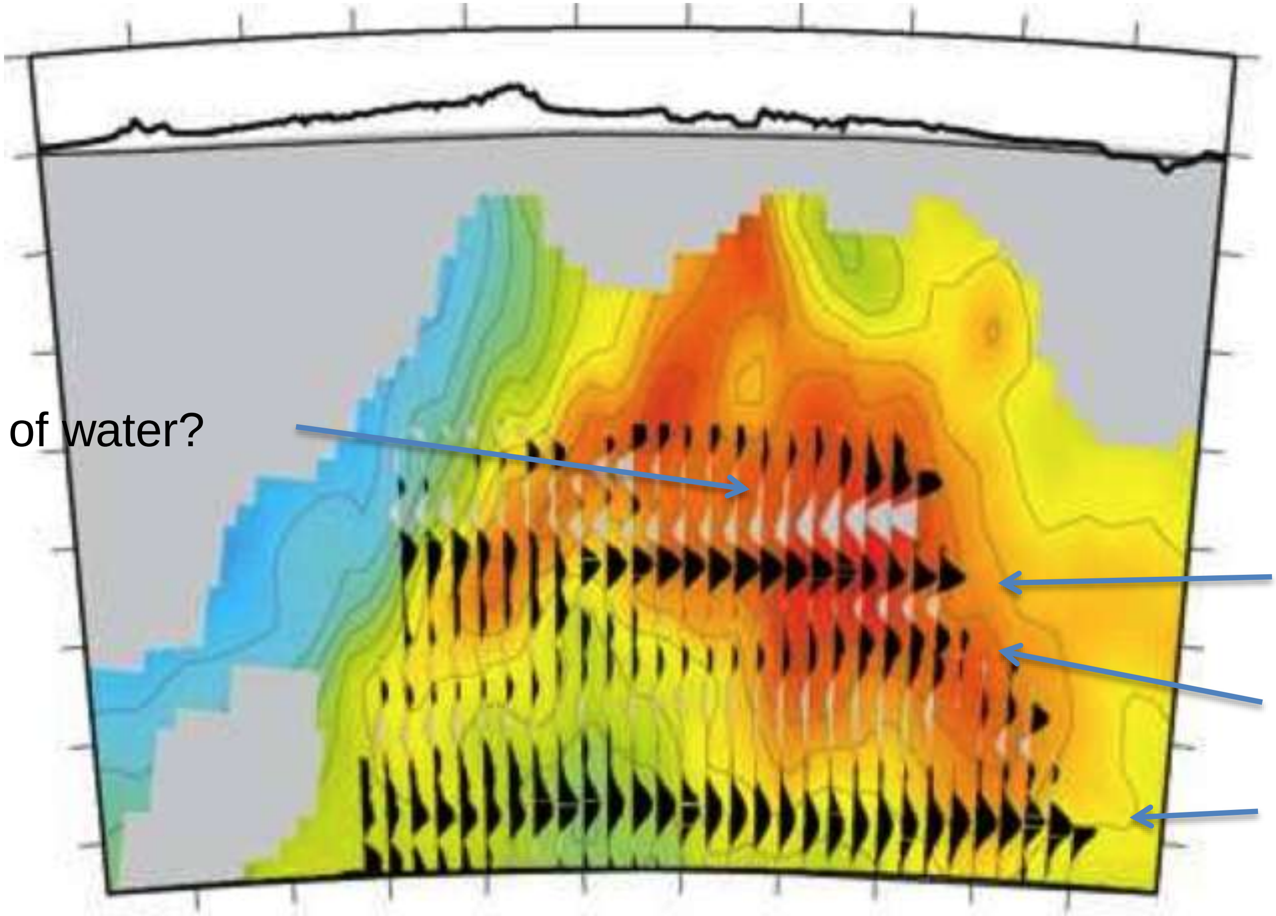
Localised upwelling in the MTZ

Little evidence for thermal anomaly

Thompson et al., 2013



# Mantle transition zone



Evidence of water?

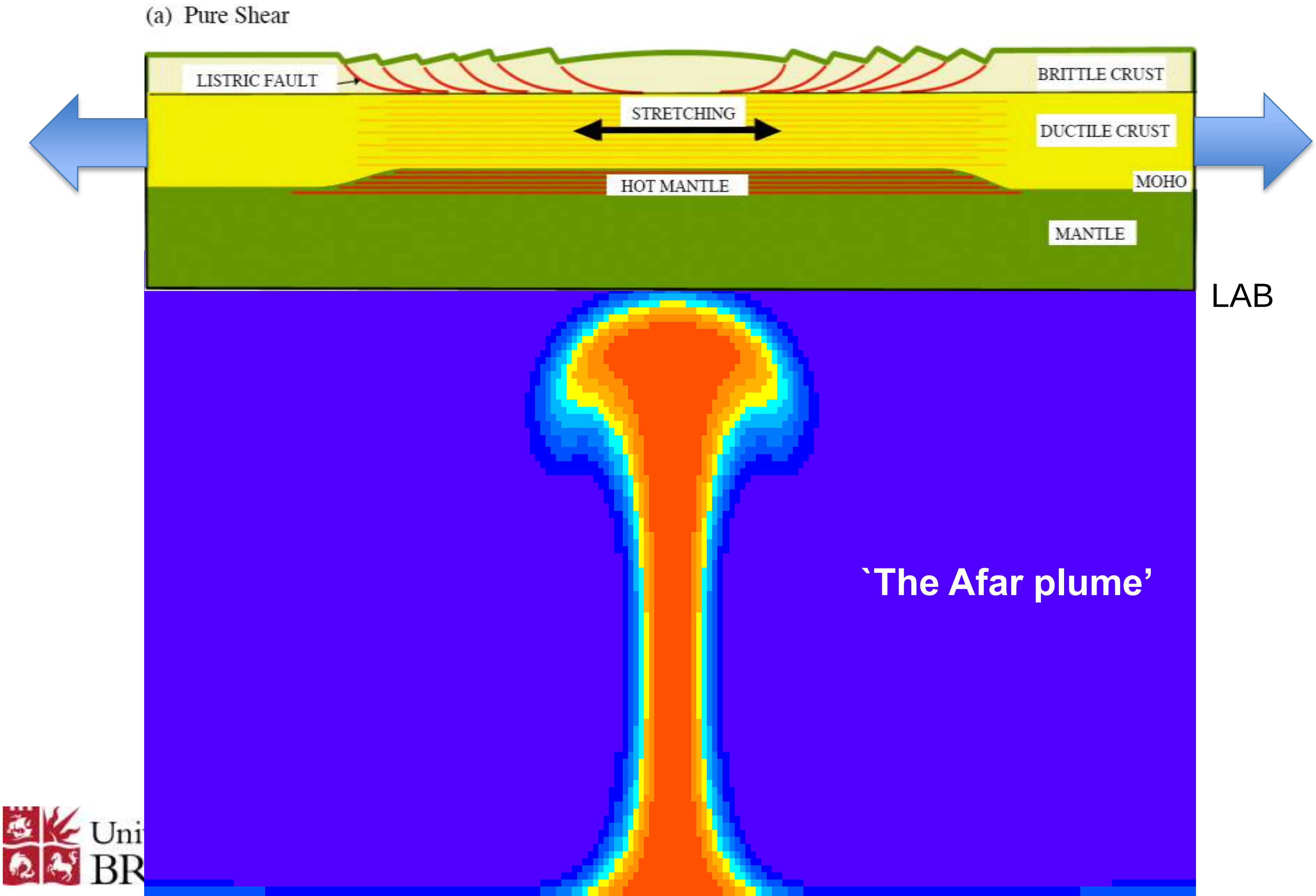
410 km

520 km?

660 km

Thompson et al., 2013

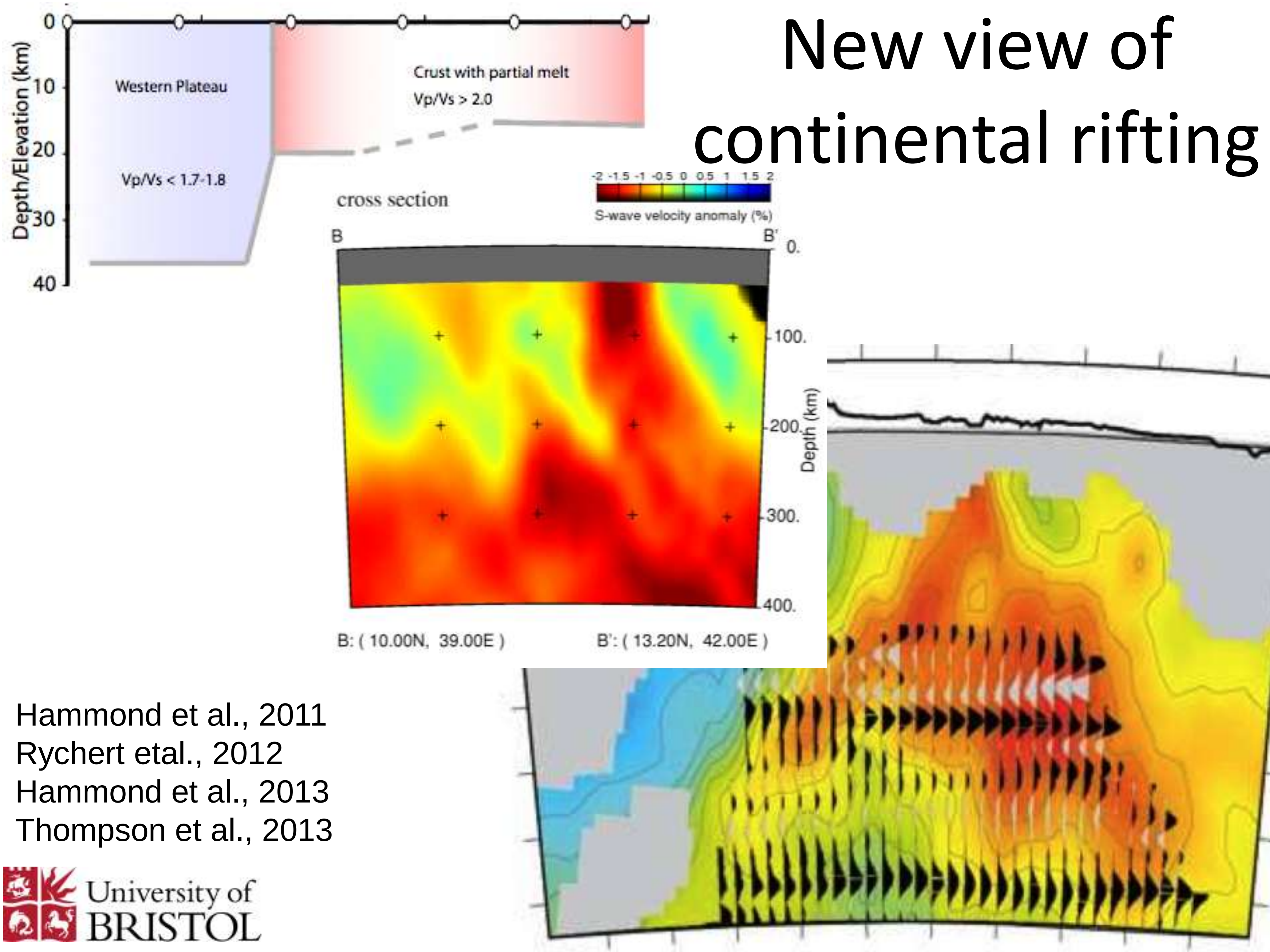
# The old view



LAB

`The Afar plume’

# New view of continental rifting



Hammond et al., 2011
Rychert etal., 2012
Hammond et al., 2013
Thompson et al., 2013

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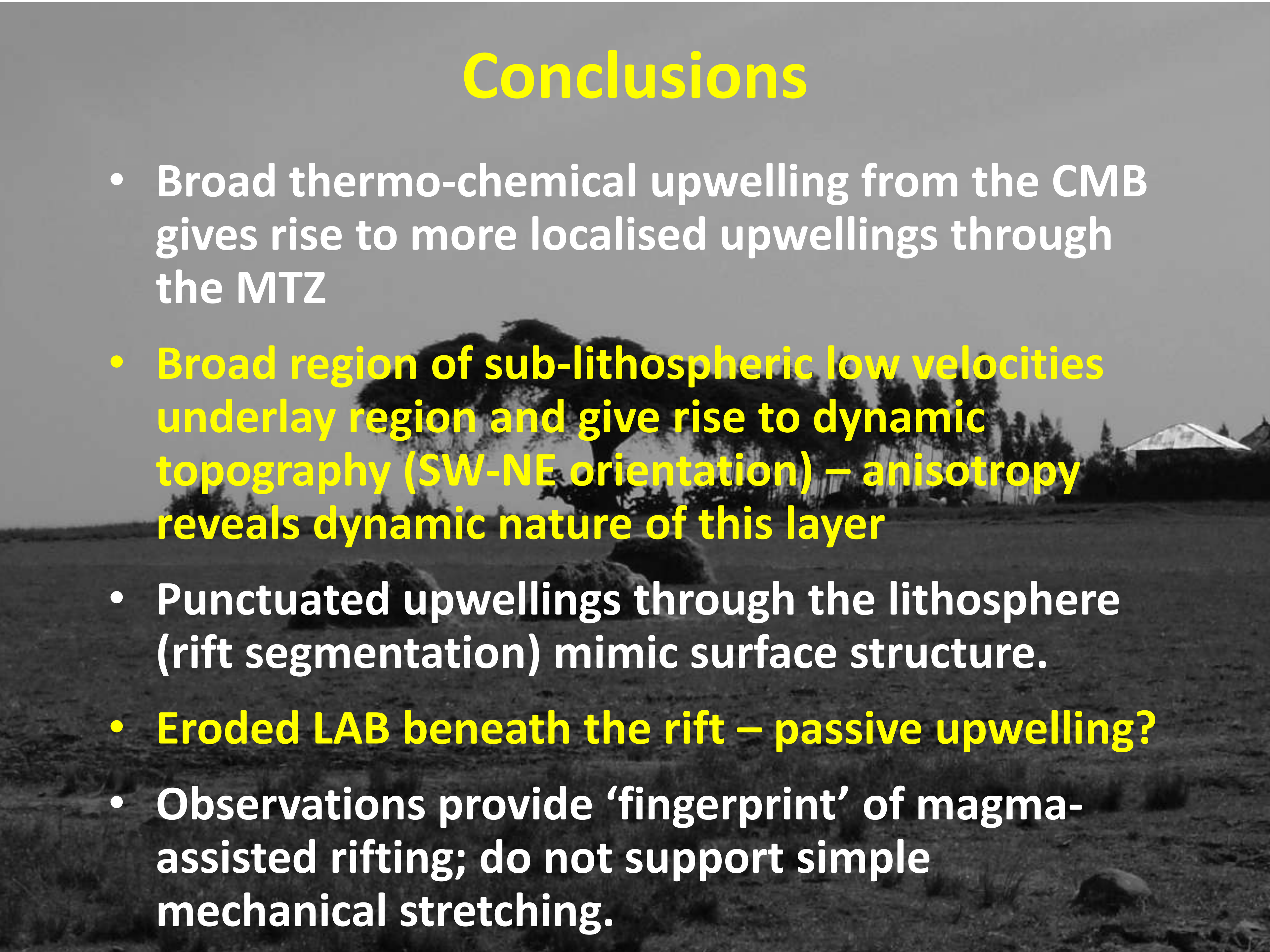
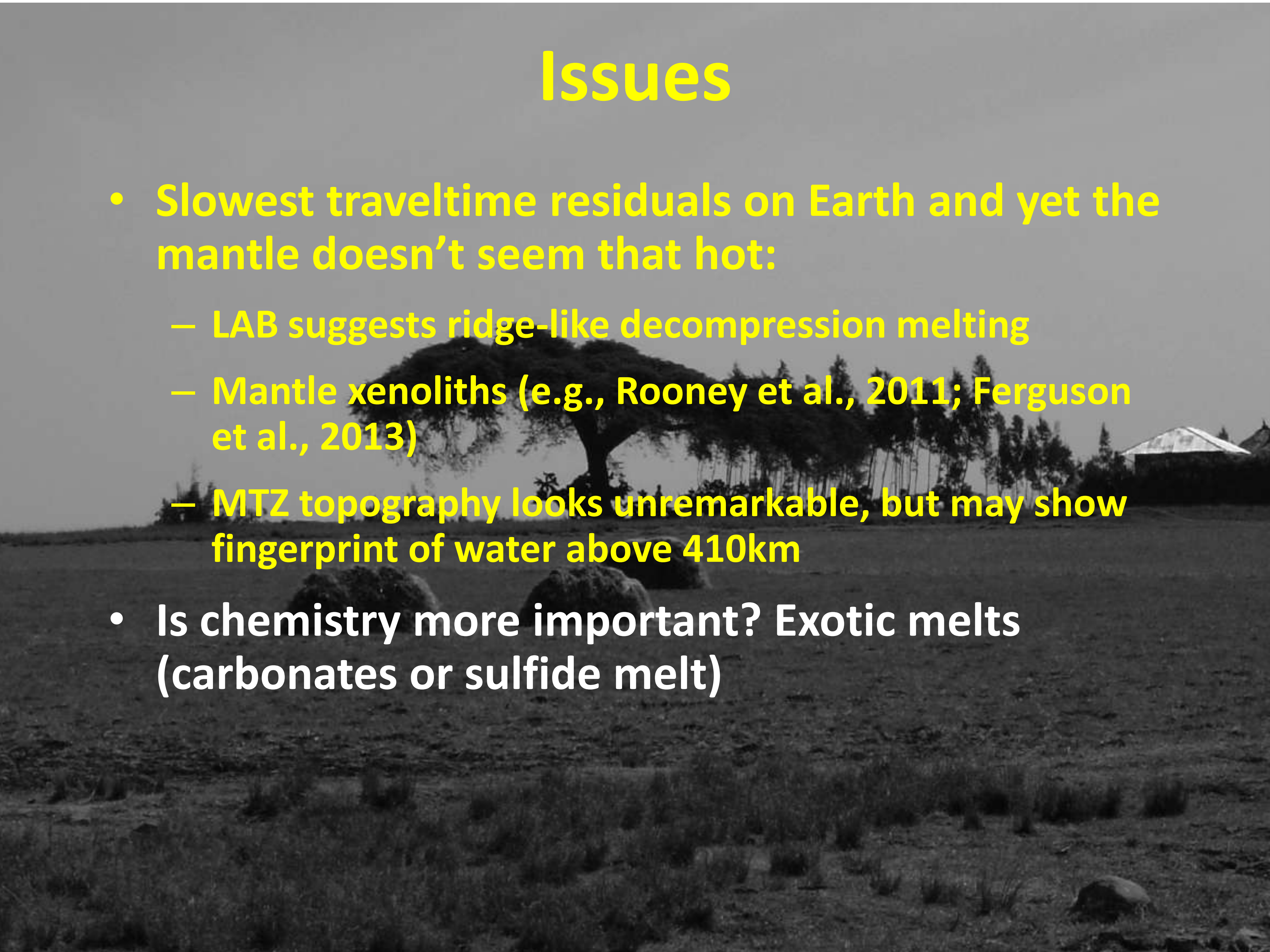
# Conclusions



- Broad thermo-chemical upwelling from the CMB gives rise to more localised upwellings through the MTZ
- Broad region of sub-lithospheric low velocities underlay region and give rise to dynamic topography (SW-NE orientation) – anisotropy reveals dynamic nature of this layer
- Punctuated upwellings through the lithosphere (rift segmentation) mimic surface structure.
- Eroded LAB beneath the rift – passive upwelling?
- Observations provide ‘fingerprint’ of magma-assisted rifting; do not support simple mechanical stretching.

# Issues



- Slowest traveltime residuals on Earth and yet the mantle doesn’t seem that hot:
  - LAB suggests ridge-like decompression melting
  - Mantle xenoliths (e.g., Rooney et al., 2011; Ferguson et al., 2013)
  - MTZ topography looks unremarkable, but may show fingerprint of water above 410km
- Is chemistry more important? Exotic melts (carbonates or sulfide melt)