Melt Intrusion and Plate Stretching in Ethiopia

- Abundant evidence for magma intrusion in Ethiopia (a little evidence from EAGLE).
- How is melt intruded into the mantle lithosphere?
- Is there evidence for late-stage plate stretching in Afar.

Ian Bastow, Derek Keir, Mike Kendall, Graham Stuart, Sylvana Pilidou

January, 2012

EAGLE Wide-Angle & Gravity Constraints

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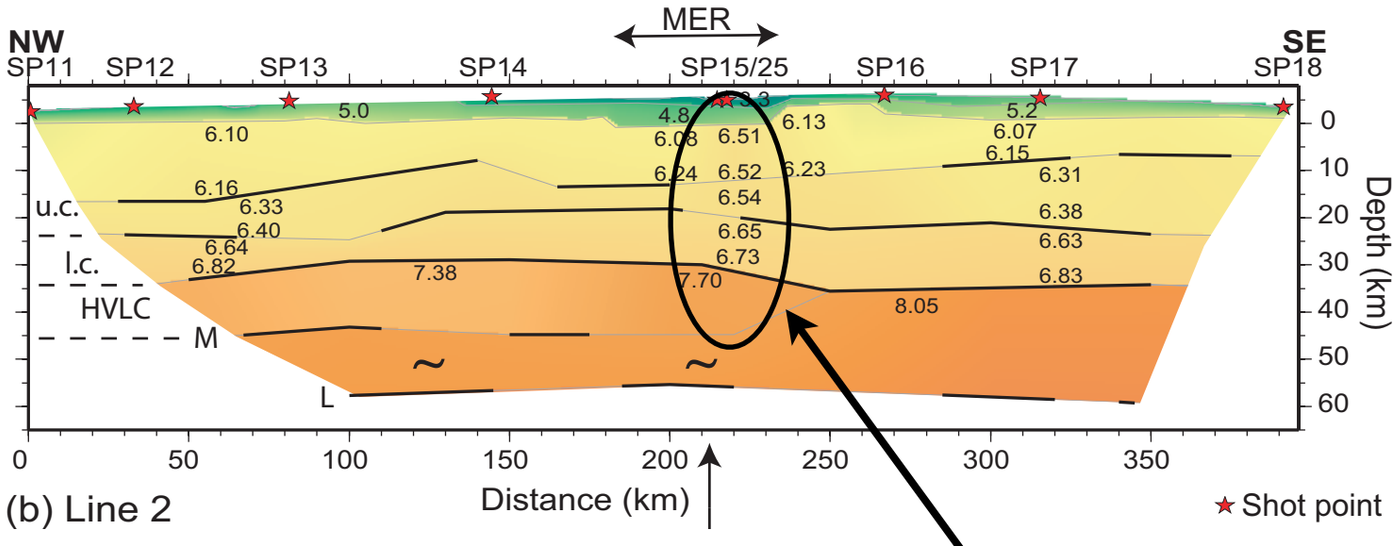
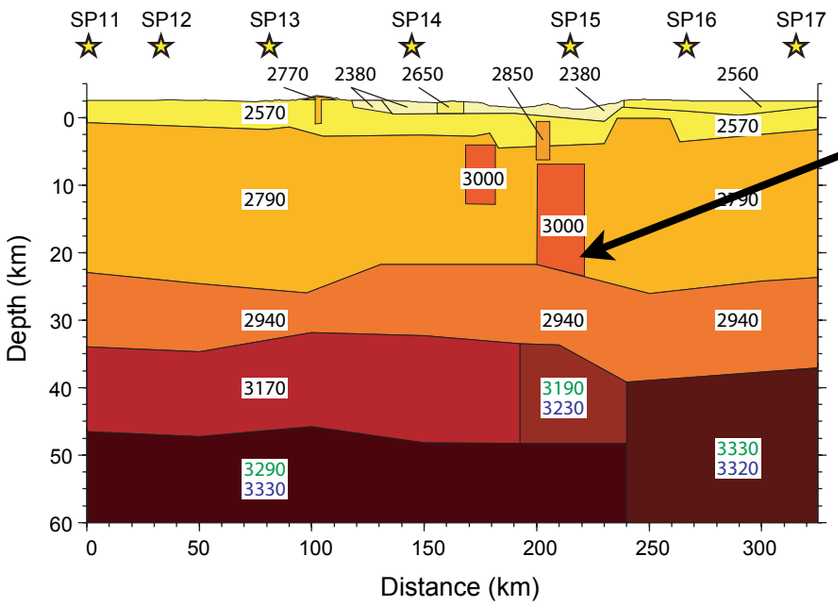
Cross-Rift Seismic Profile



Maguire et al., (GSL Spec. Pub, 2006)

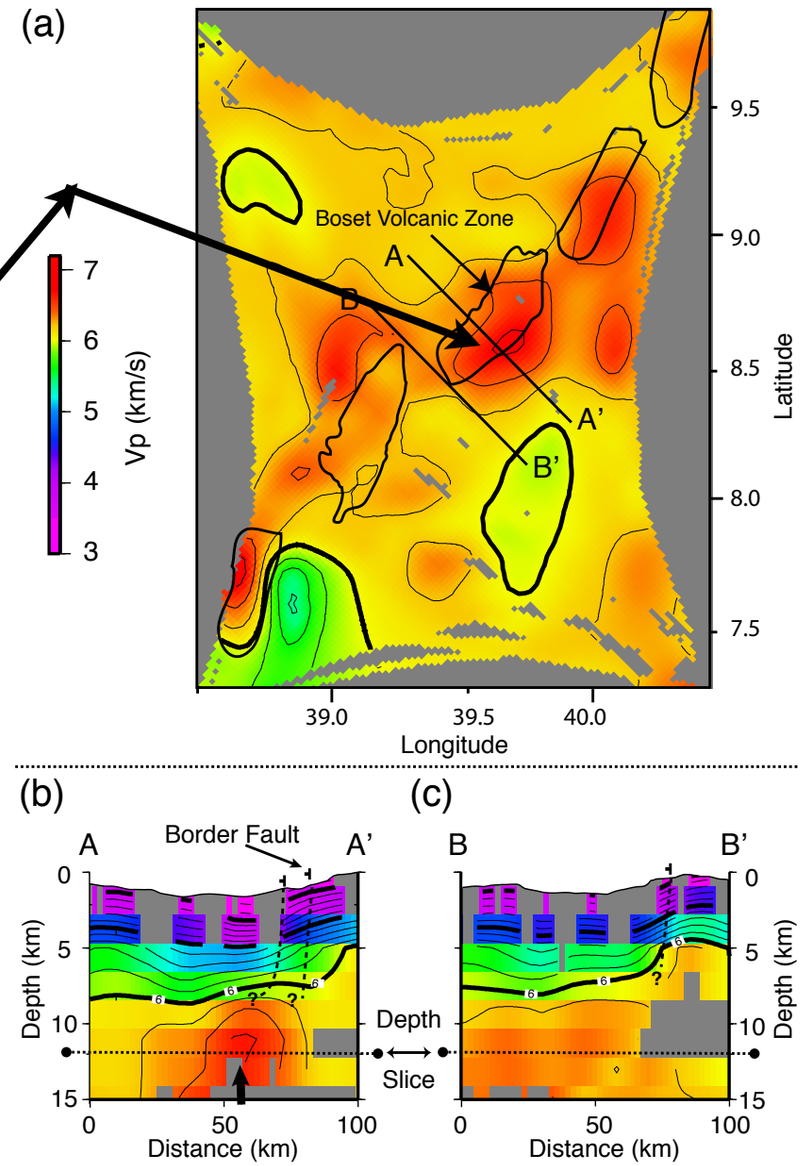
High velocity, high density, intrusions beneath Quaternary magmatic segments

Cross-Rift Gravity Profile



Cornwell et al., (GSL Spec. Pub., 2006)

MER Crustal Tomography



Keranen et al., (Geology, 2004)

Evidence From the (Near-) Surface

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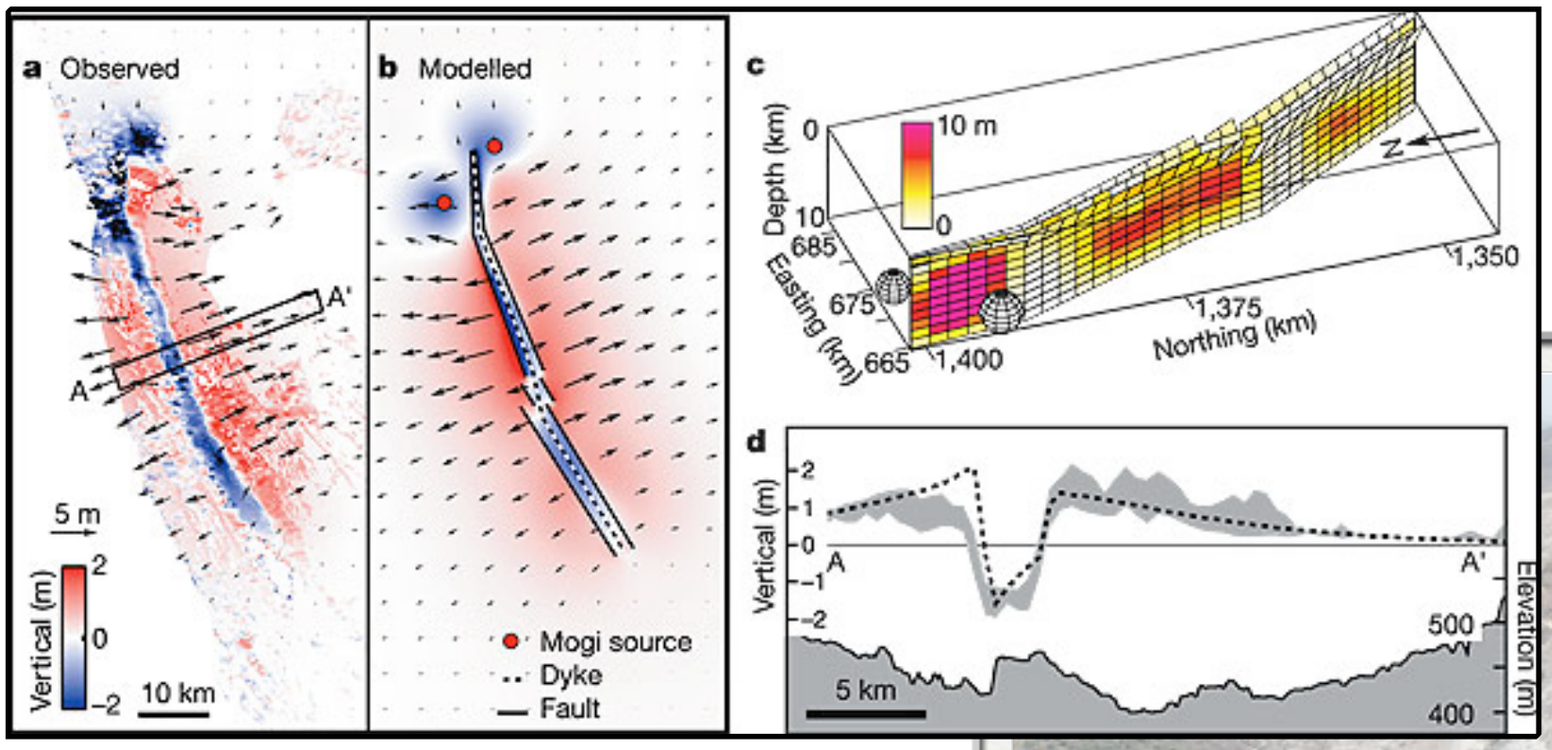
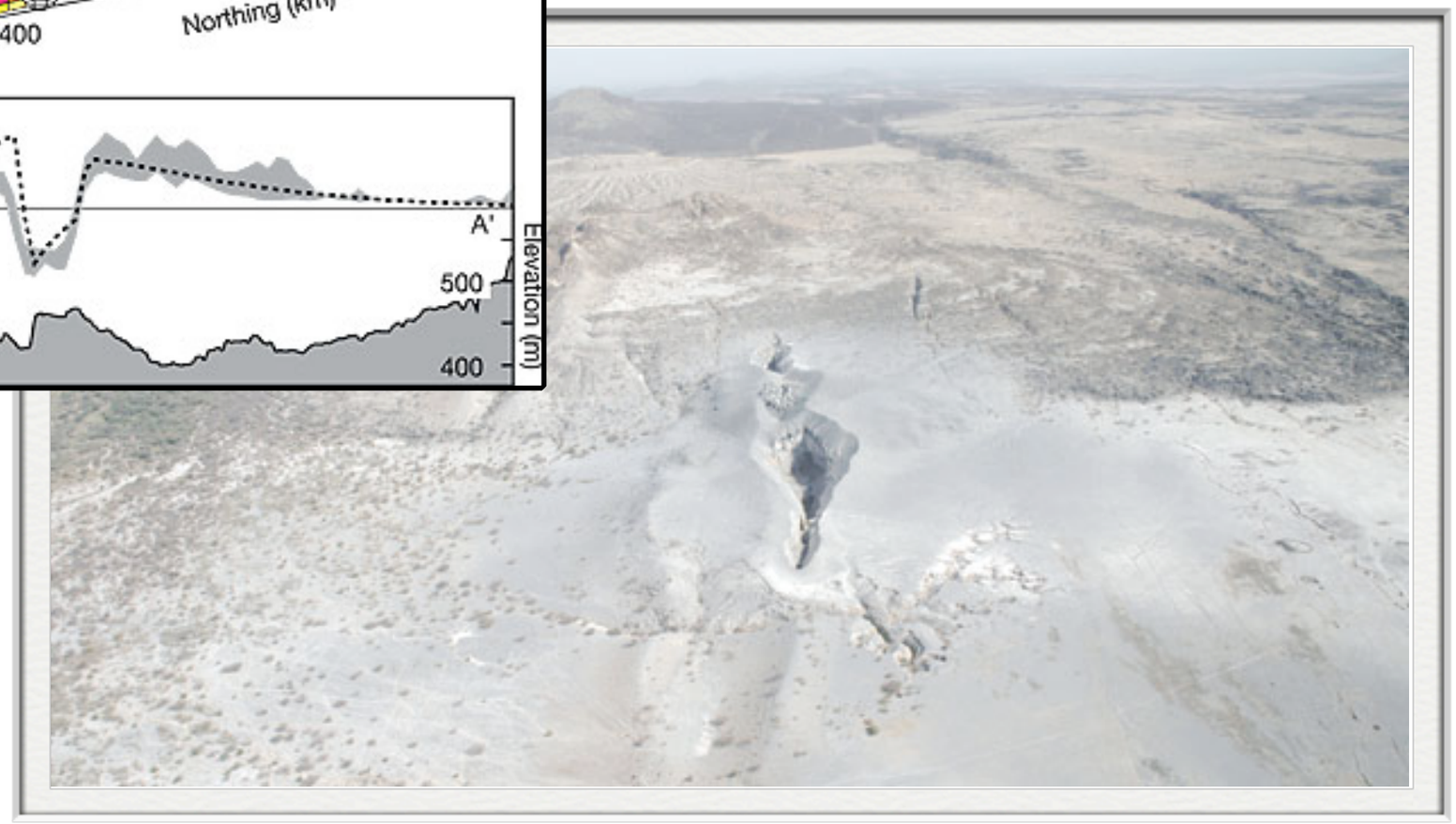
✦ Surface observations and InSAR indicate low aspect-ratio magma intrusions (ie dikes) in the upper 10km in Afar.

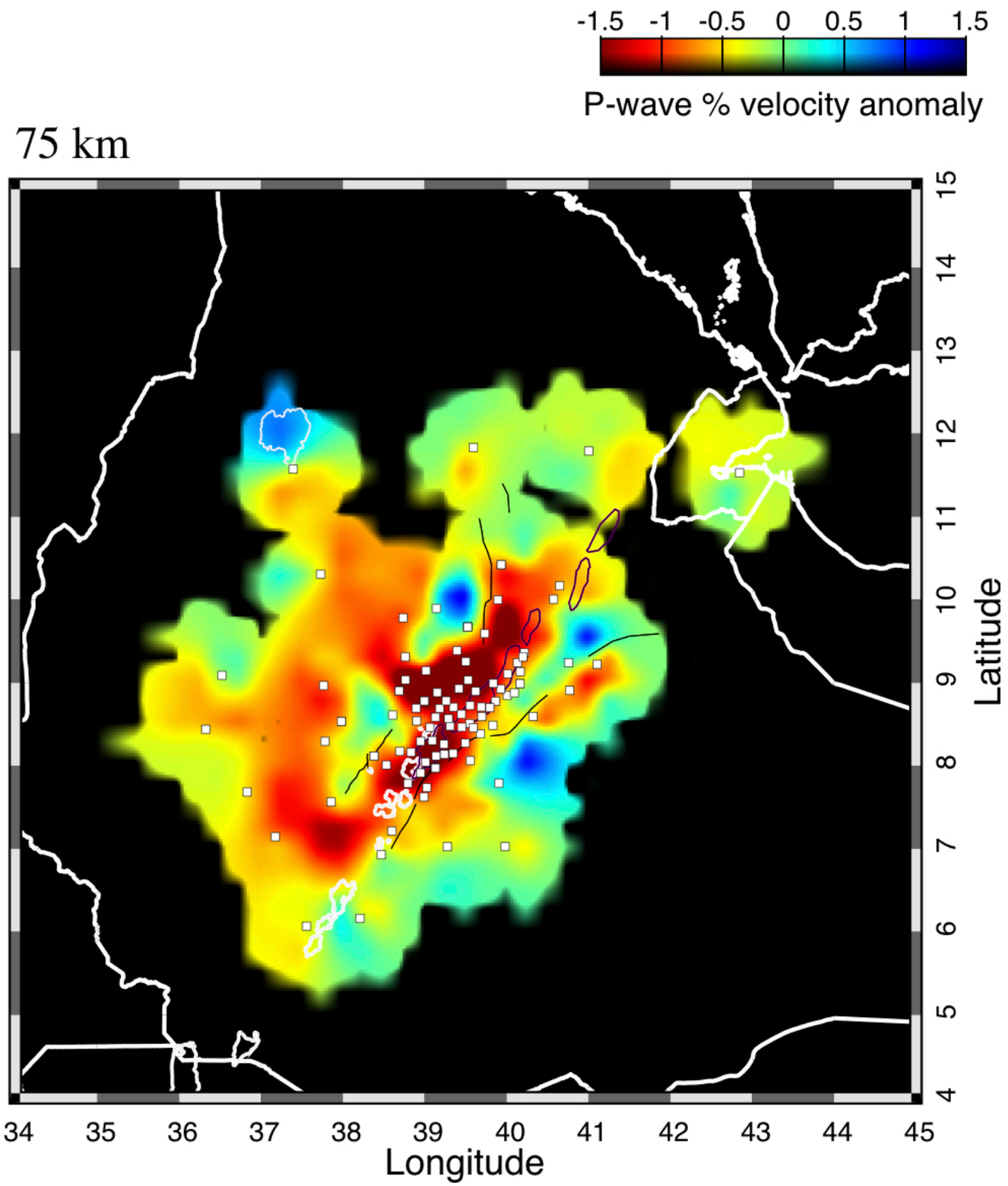


Wright et al., (Nature, 2006)

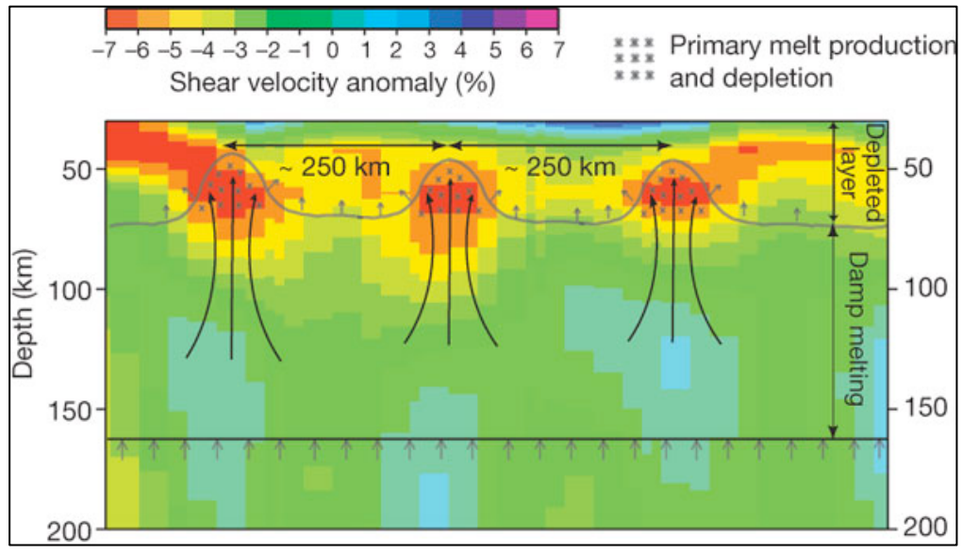


✦ What about intrusion at greater depths (the mantle lithosphere)?

Seismic Tomography



Bastow et al., (GCubed 2008)

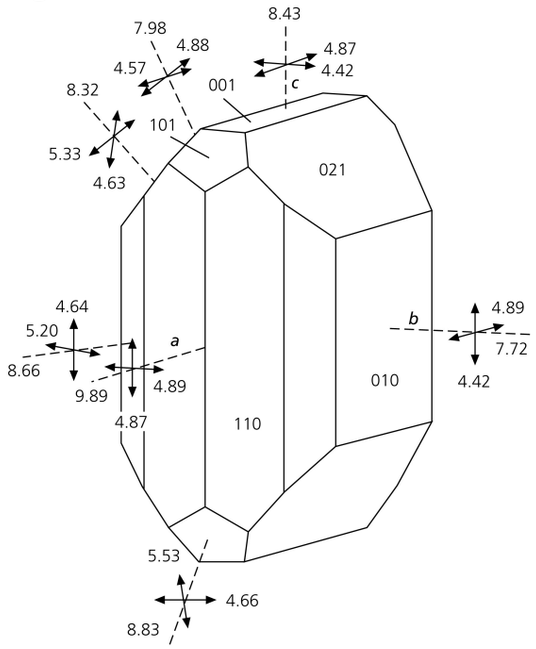


Gulf of California: Wang et al., (Nature, 2009)

- Early rift development is asymmetric - begins with half graben morphology (e.g., Ebinger & Hayward, 1996).
- Half graben early rift development still controls the mantle low velocity regions....not punctuated upwellings as at a sea floor spreading centre.
- Note the abrupt decrease in amplitude of anomaly north of ~10N.

Seismic Anisotropy

Seismic velocity is variable with direction in anisotropic media (e.g., Olivine).



Produces shear-wave splitting

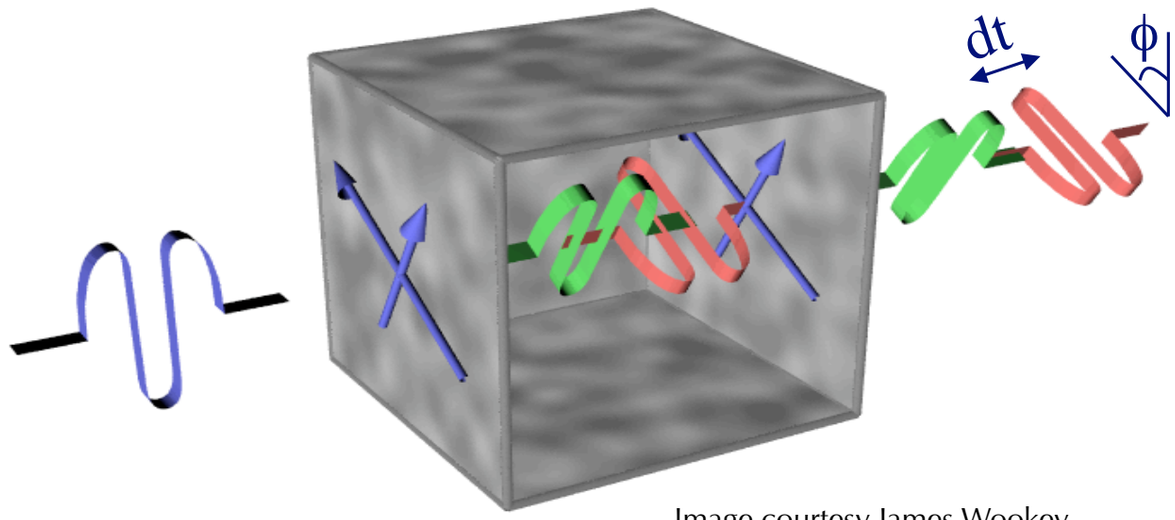


Image courtesy James Wookey

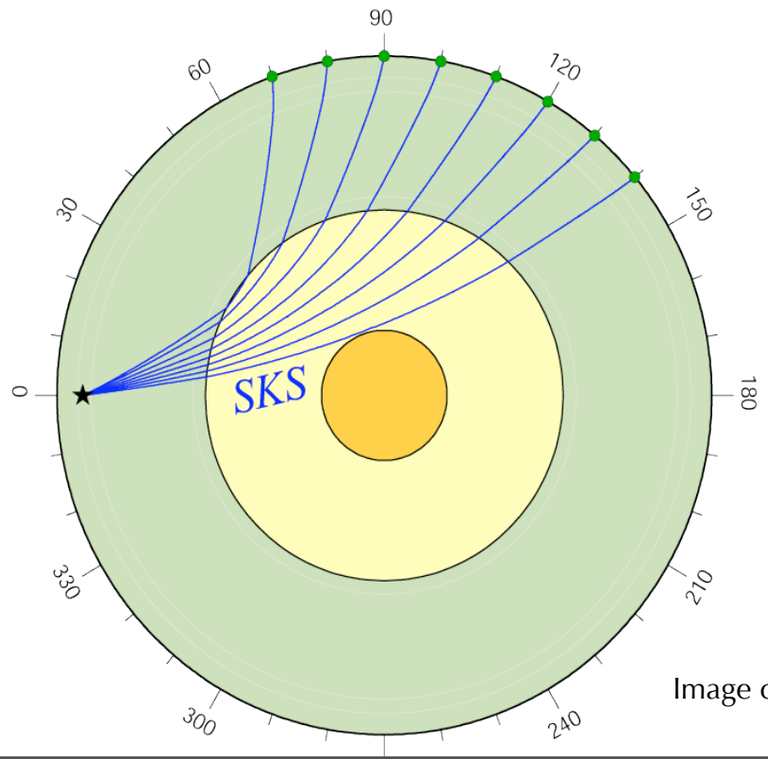
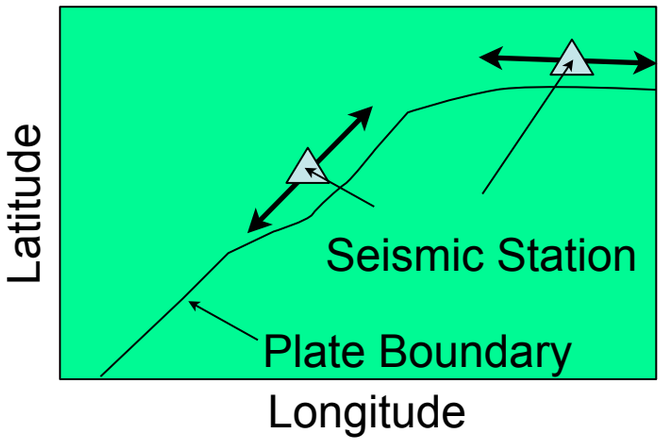


Image courtesy Ed Garnero

- SKS propagates as an S wave through the mantle and as a P wave as through the core.
- Measuring splitting parameters (δt, φ) can then be related to surface features on the tectonic scale.
- Shown in the literature as vectors on a map.



SKS Splitting

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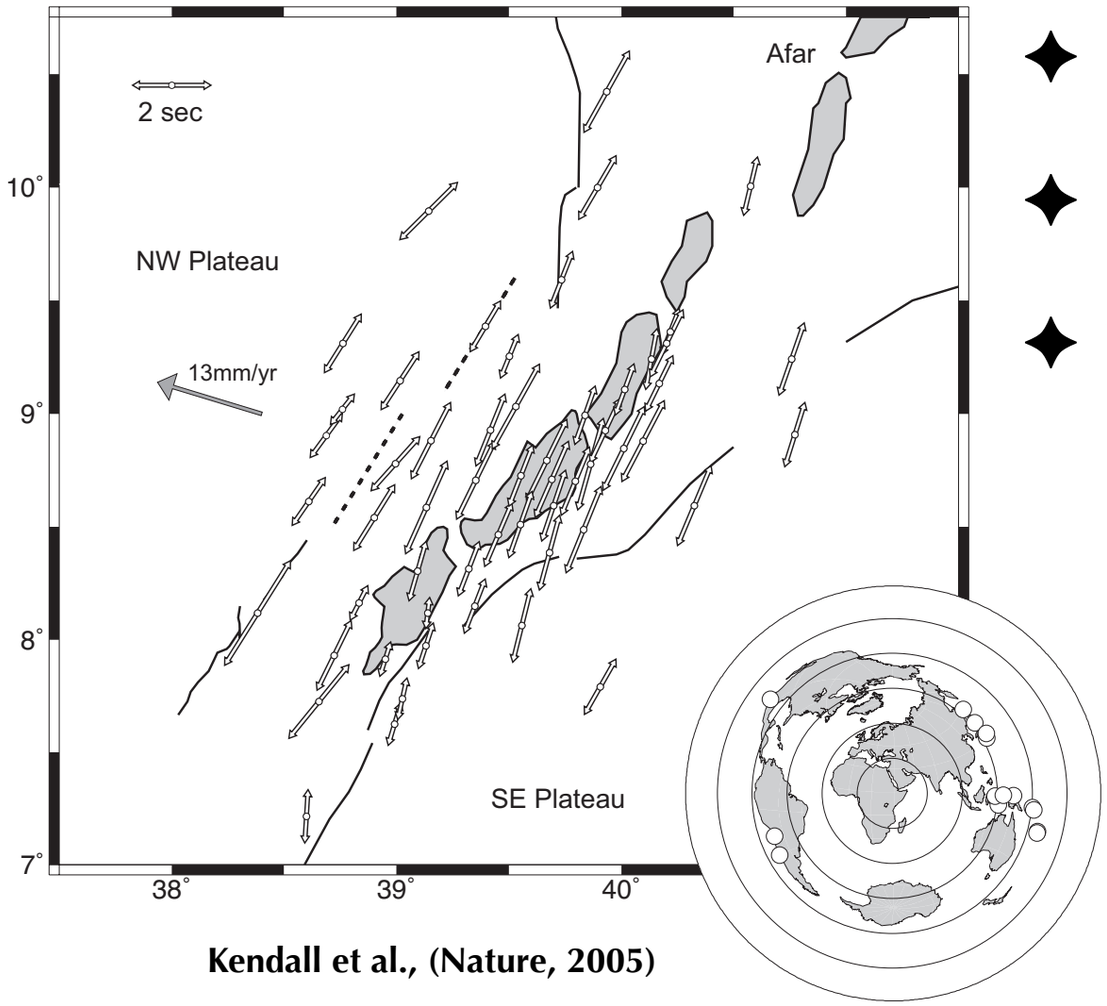
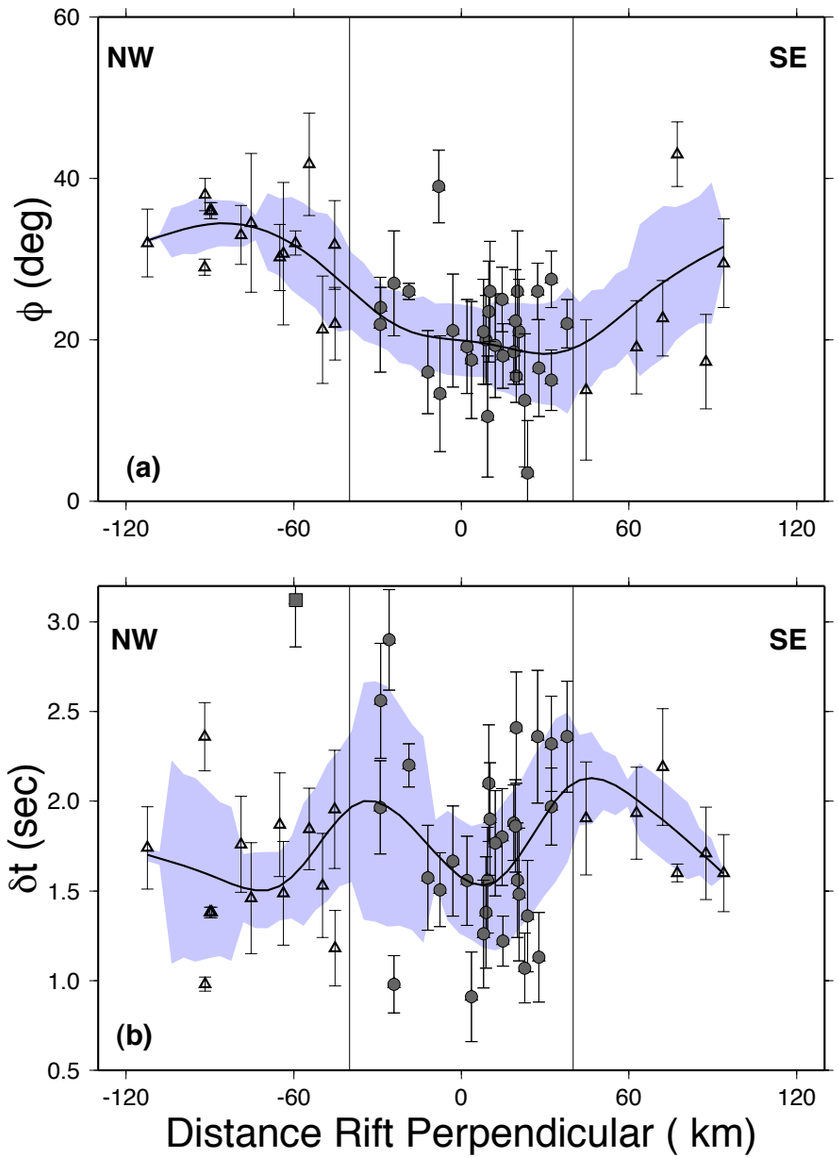


Kendall et al., (Nature, 2005)

- SKS data show δt up to ~3.1s.
- φ sensitive to changes in extension direction at ~2Ma.
- Vertical LPO would yield no SKS splitting.



- SKS can't discriminate unambiguously between horizontal LPO and OMP-type anisotropy.

LPO & OMP Anisotropy

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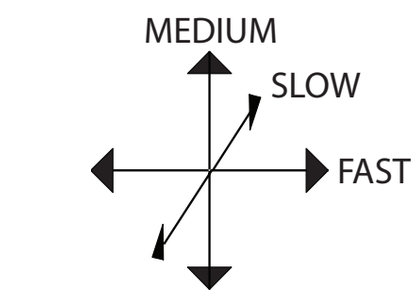
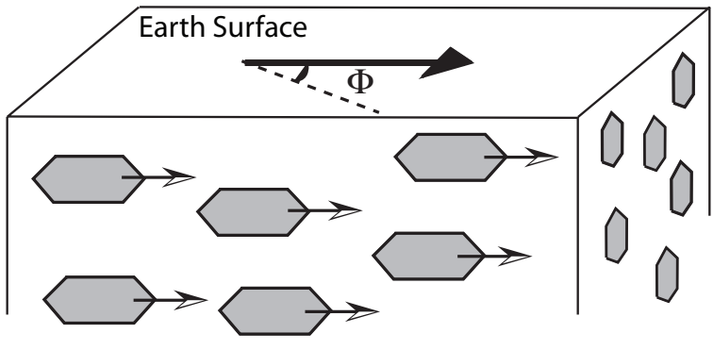
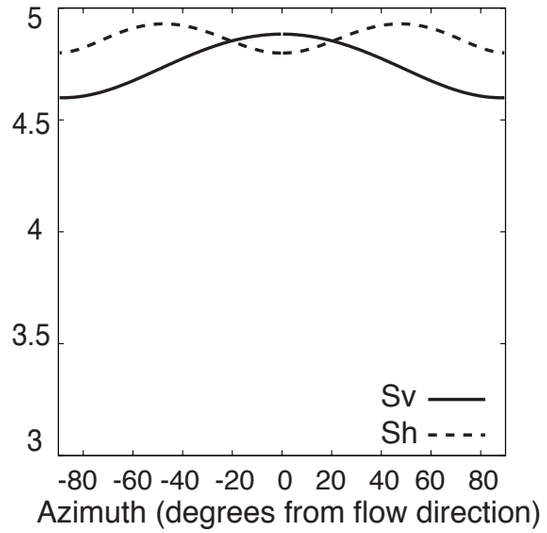
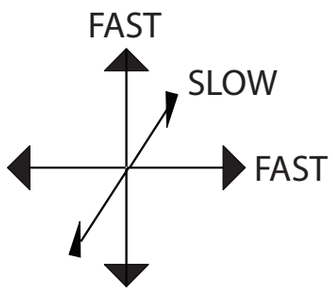
Bastow et al., (GCubed, 2010)



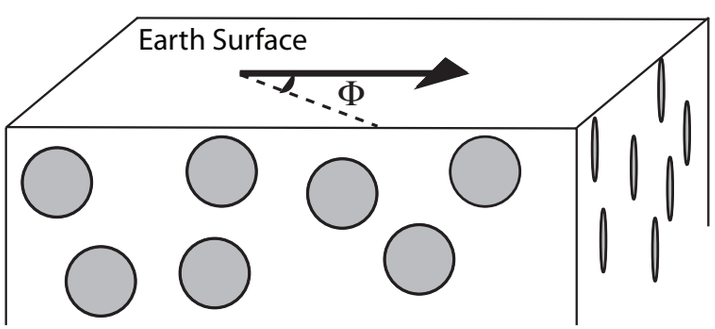
Olivine LPO

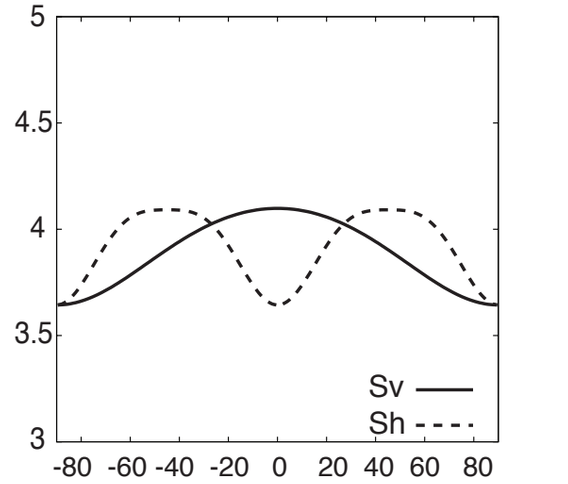






Oriented Melt Pockets





- SKS splitting cannot discriminate readily between lateral flow (LPO) and OMP.
- Sv and Sh vary predictably and distinctively for LPO and OMP-type anisotropy.
- OMP model assumes oblate spheroids, 0.1% melt, aspect ratio 0.02.

Surface Waves

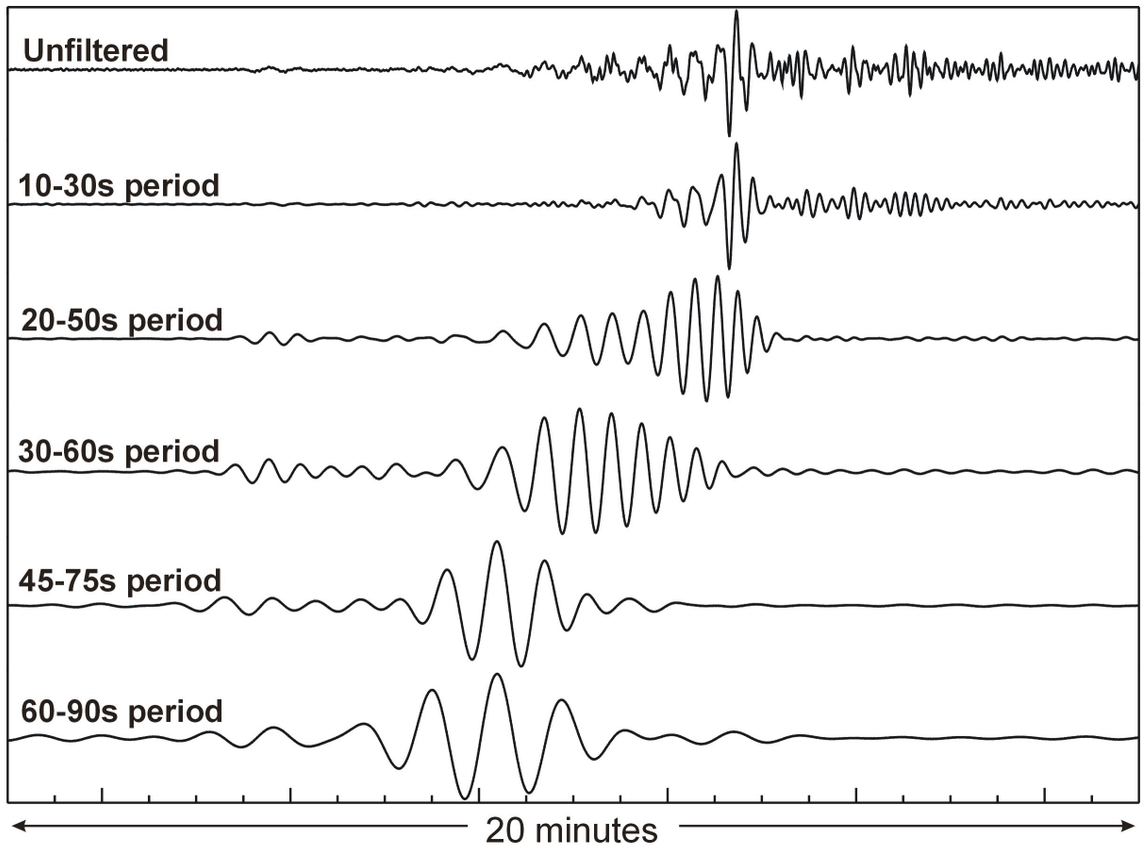
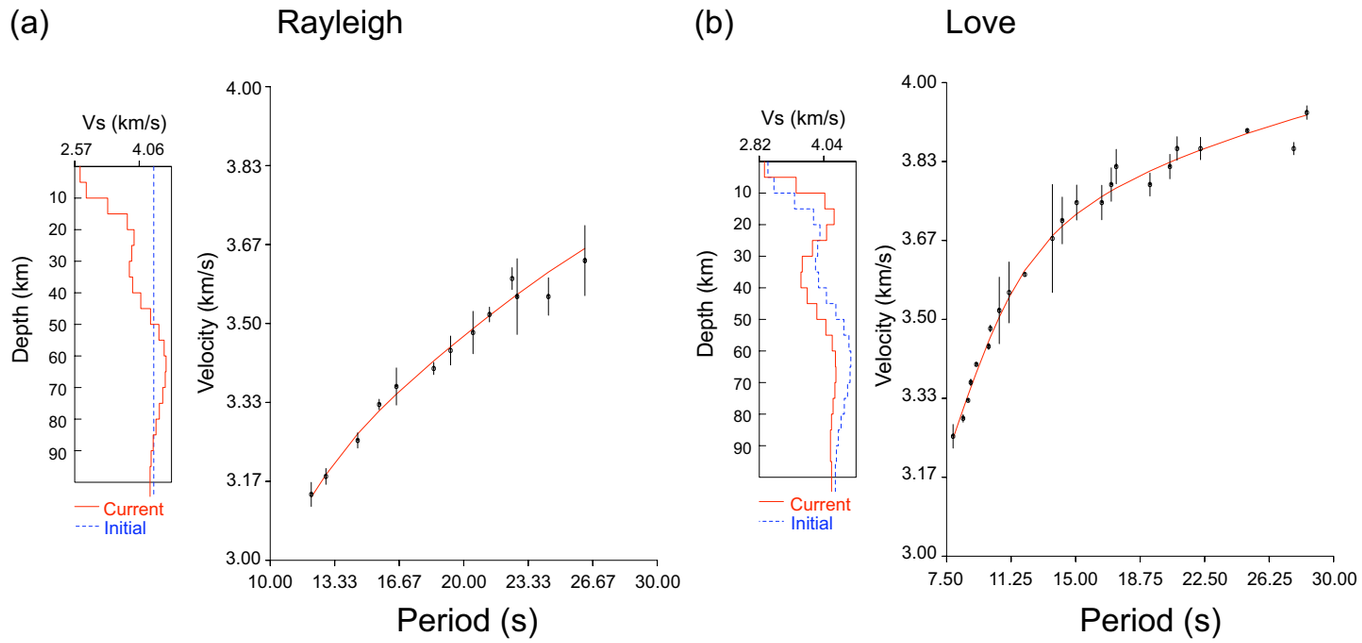


Image courtesy Fiona Darbyshire

- Surface waves are dispersive.
- Surface-wave particle motions decay with depth dependent on their wavelength. As such their velocity is period dependent.
- Measure phase velocities, invert for depth-velocity model.
- Analyse backazimuth dependence in Sv an Sh.



Bastow et al., (GCubed, 2010)

Variations in Sv and Sh

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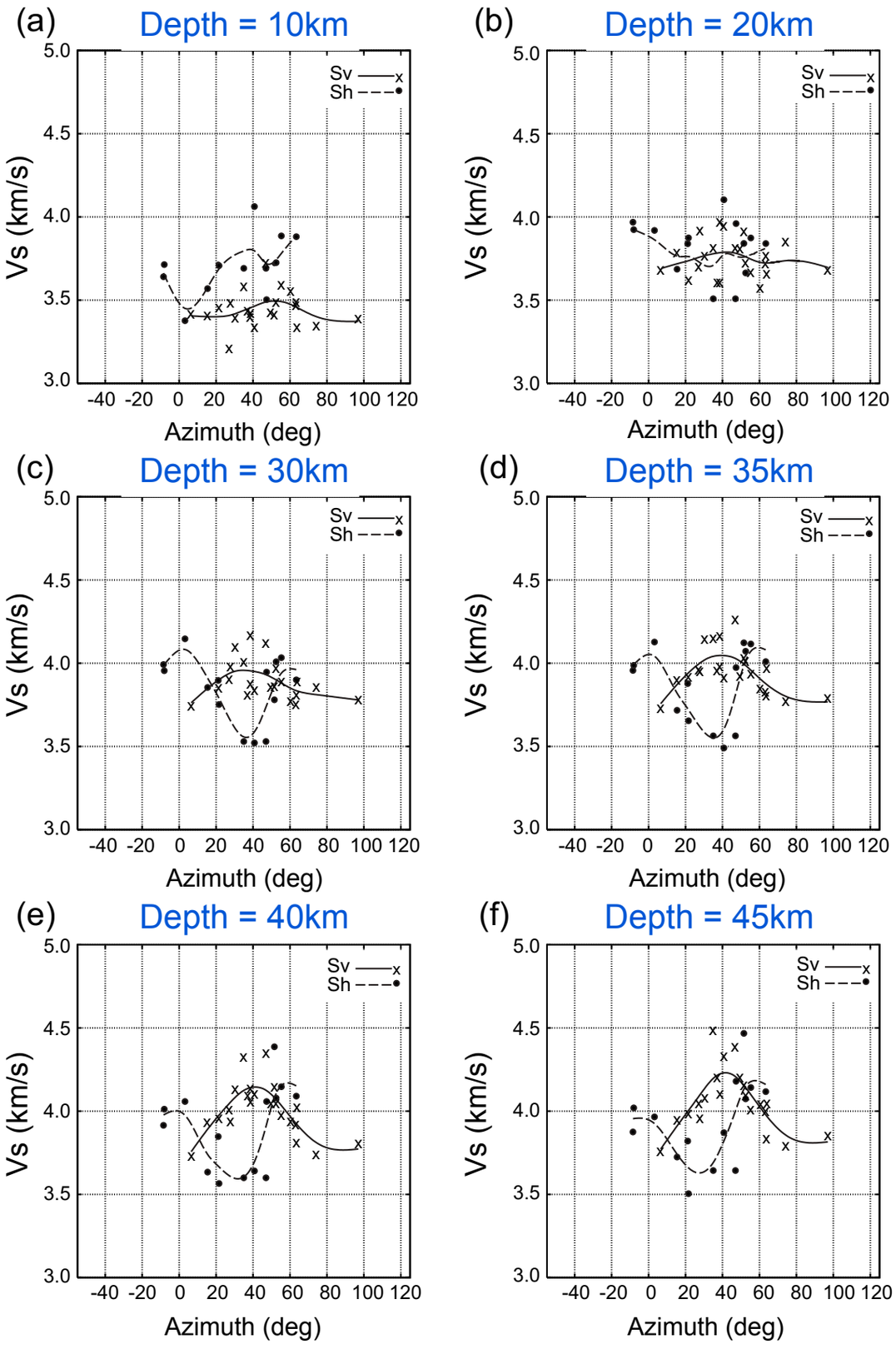
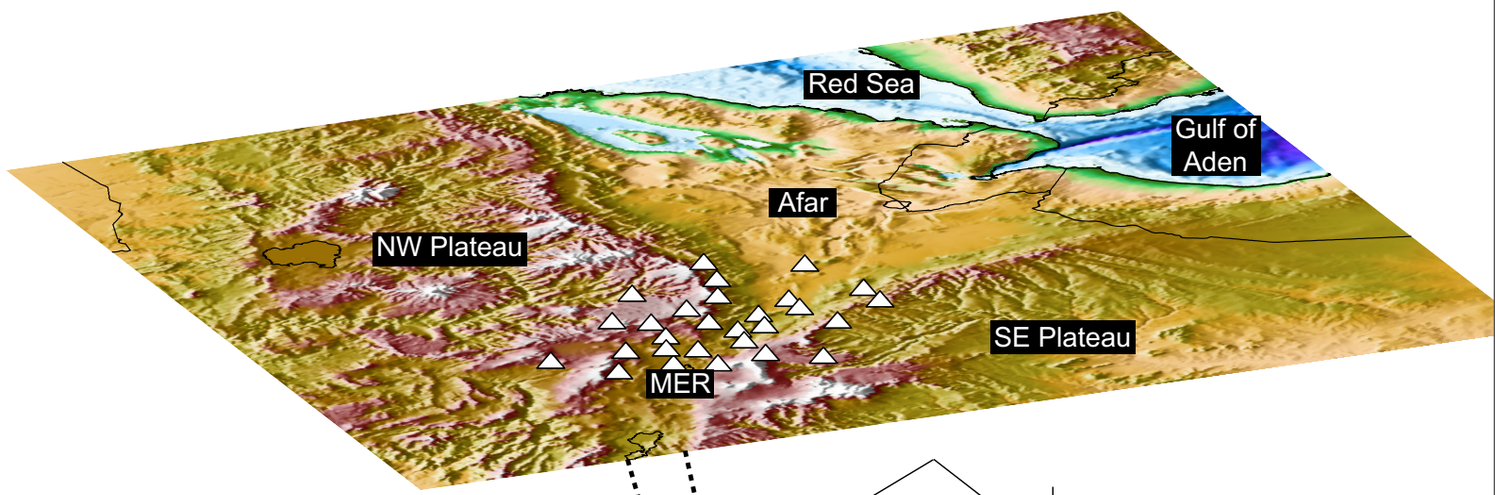
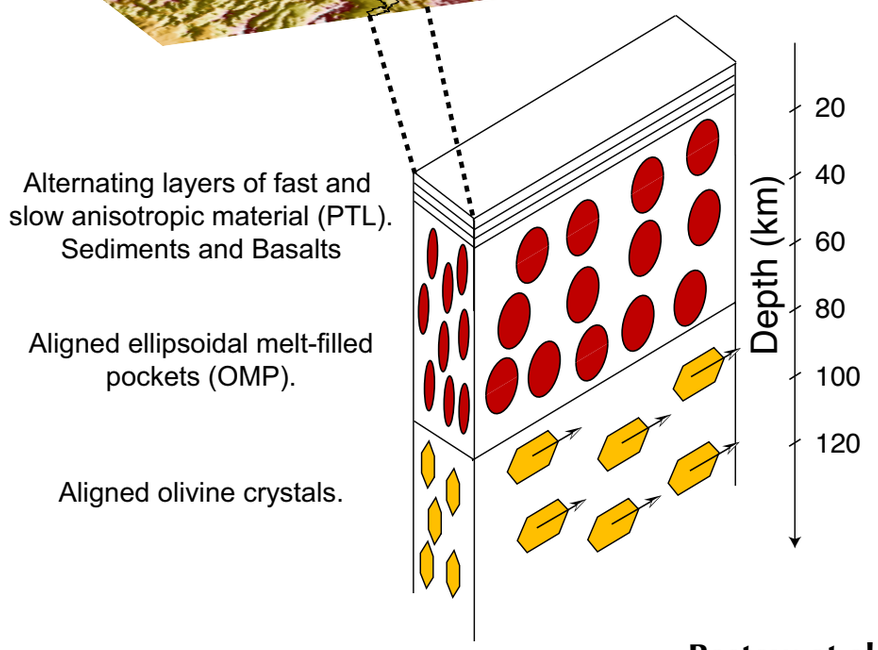


- Three layers of anisotropy:
  - PTL - periodic transverse layering in upper 10km.
  - OMP - oriented melt pockets between ~20-75km depth.
  - LPO in the mantle beneath.





Bastow et al., (GCubed, 2010)

Tectonic Summary for the MER

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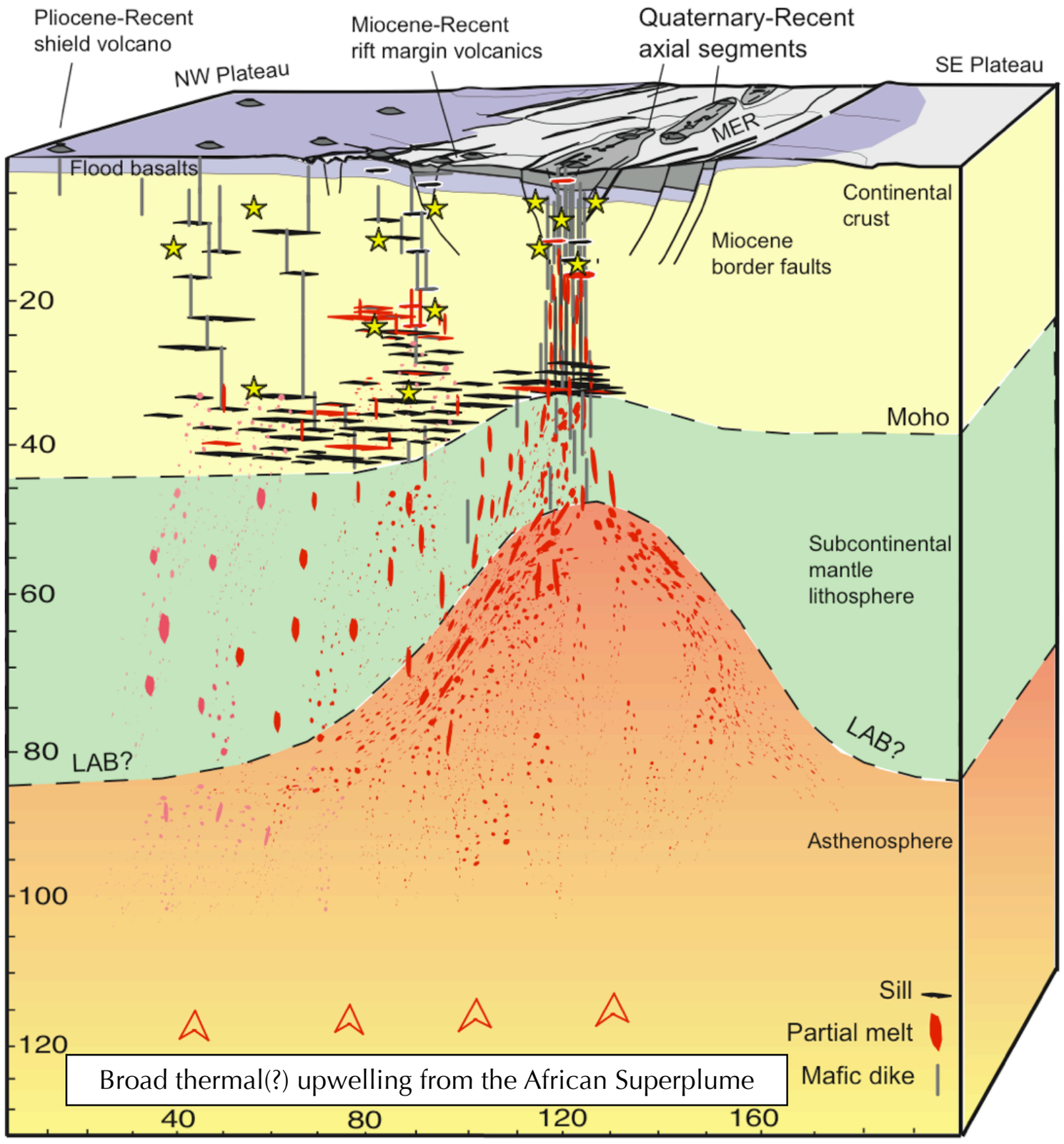

- Constraints on structure and process.

Bastow, Keir & Daly (GSA Spec. Pub. 2011)

Final Stages of Breakup?

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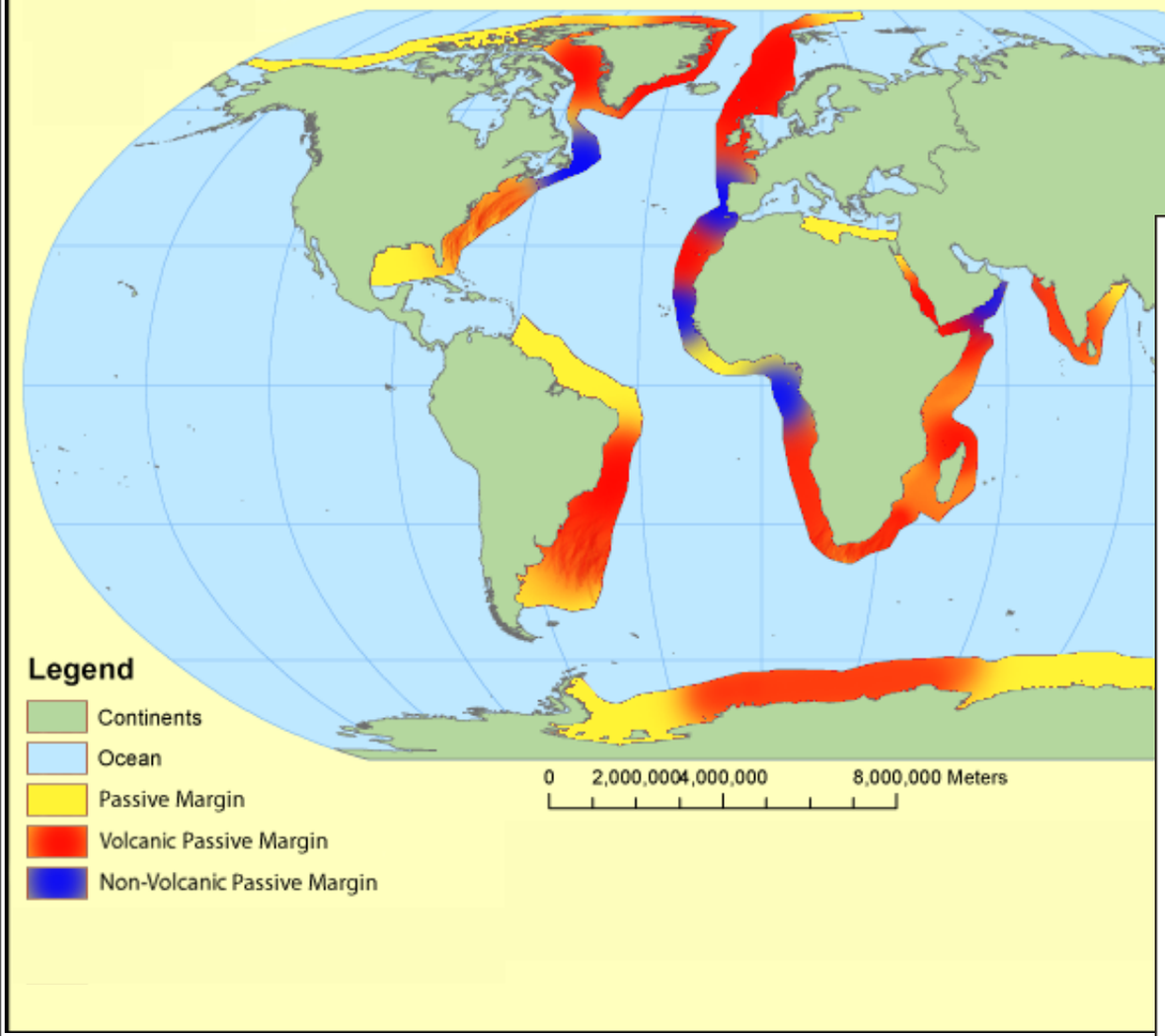
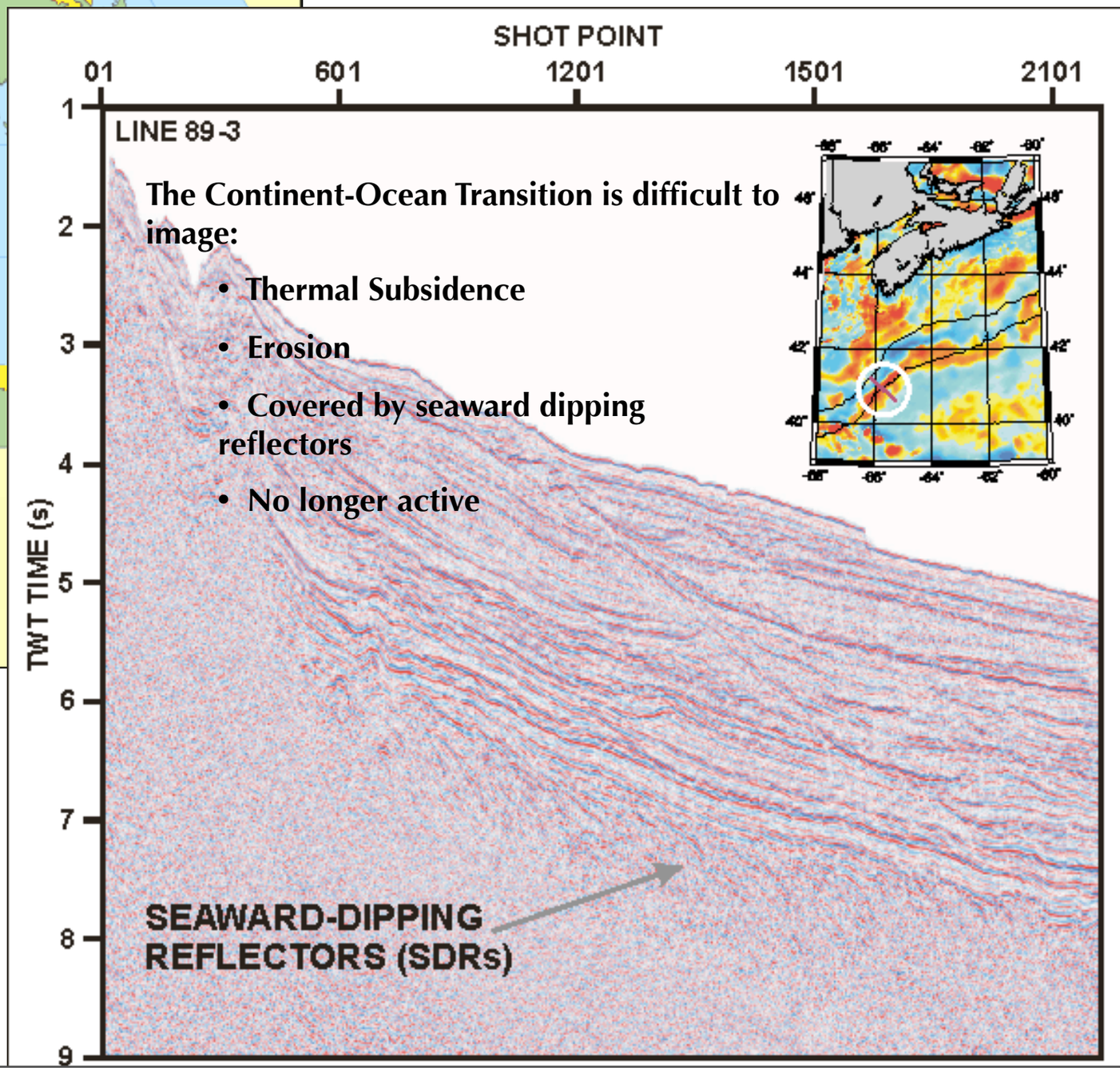
Global Distribution of Rifted Margins





Final Stages of Breakup

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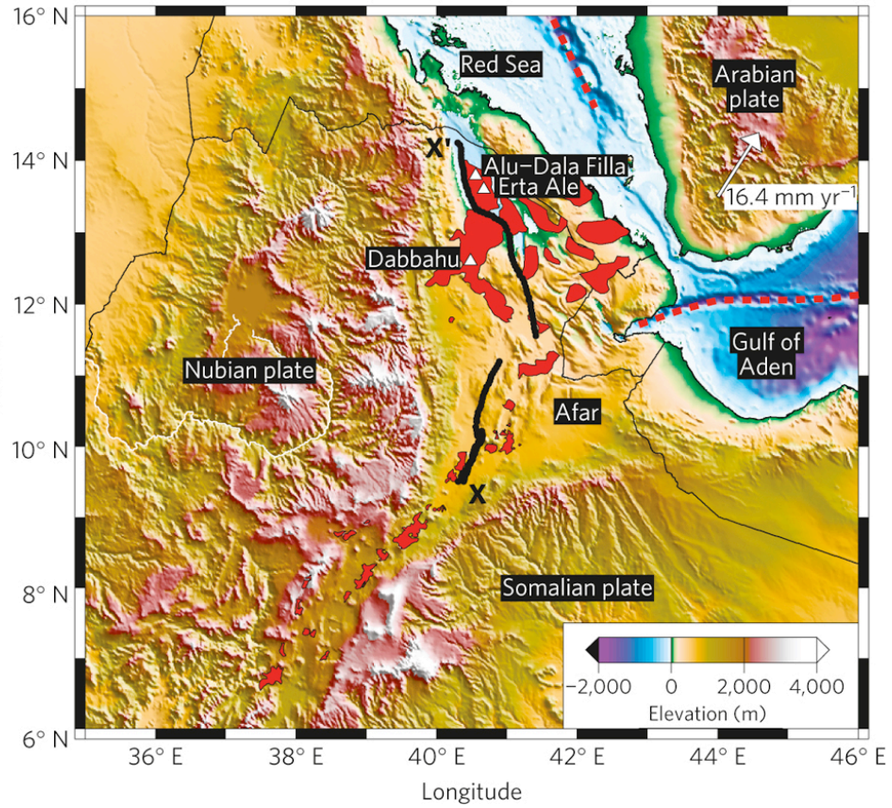

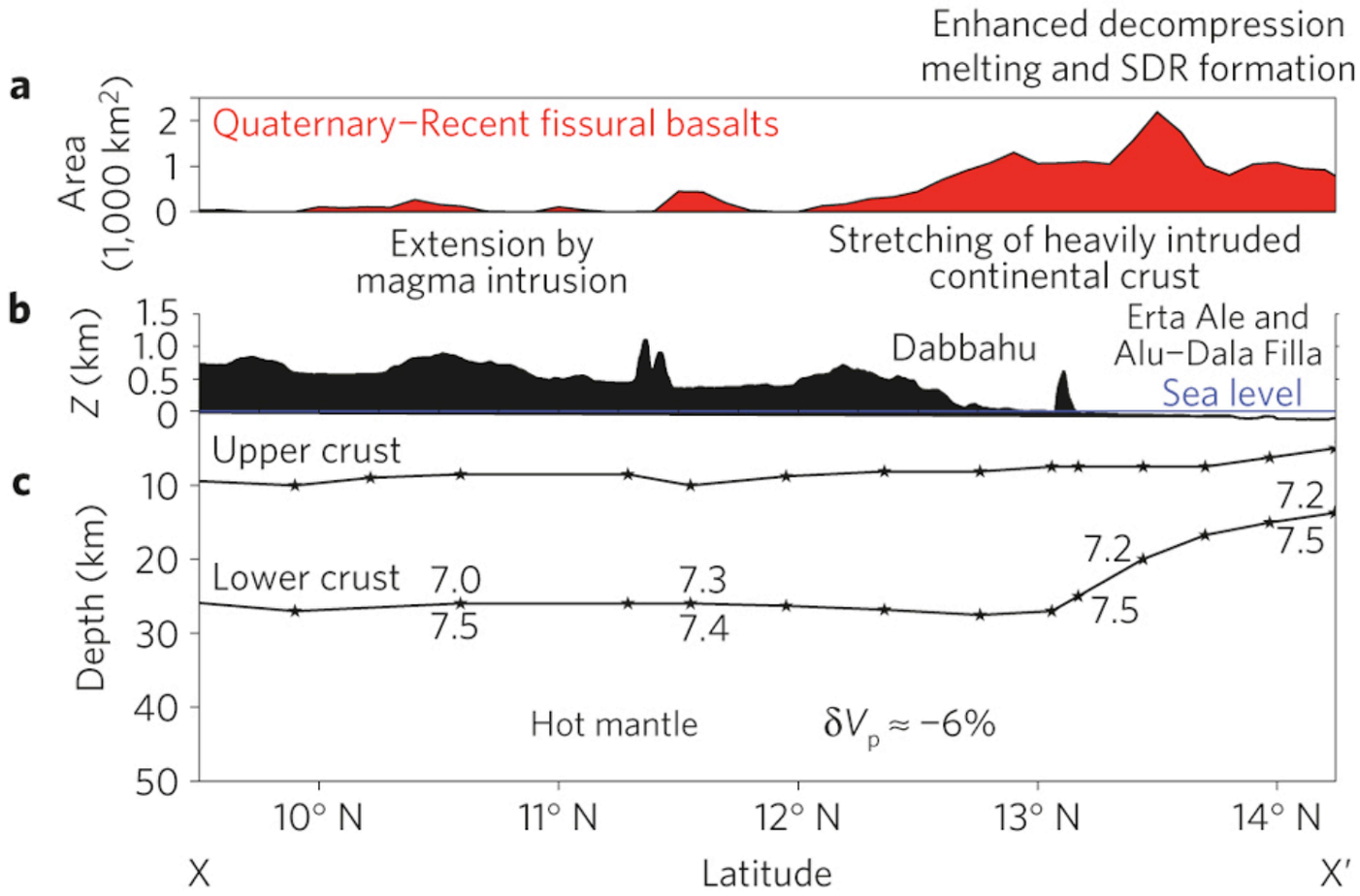

Bastow & Keir (N. Geosci, 2011)

✦ A pulse of Quaternary-Recent basaltic volcanism, coincides with subsidence towards and below sea-level, and a marked thinning of the crust (esp. lower crust) in northernmost Afar.

✦ Young (Pliocene) sediments in the Danakil basin indicate stretching has occurred since ~5Ma.

✦ SDR formation perhaps triggered by a late-stage thinning of the plate, immediately prior to sea-floor spreading.

Summary

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✦ A great deal of extension in Ethiopia has been accommodated by magma intrusion, without marked crustal (and plate?) thinning.

✦ Plate stretching is likely important as well. Understanding precisely why faulting, stretching and magma intrusion devolve as they do during breakup is still poorly understood.

✦ Future work in Ethiopia could usefully pay more attention to the varying strength/ thermal structure of the plate during breakup.

Thank you.....any questions?

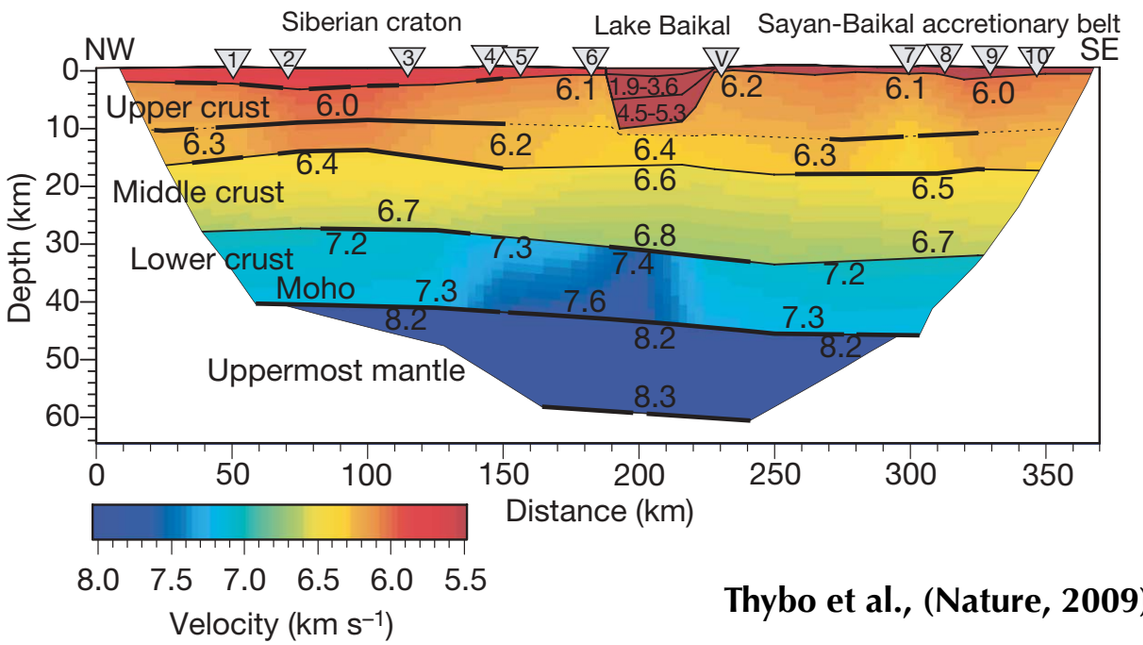
Erta Ale 2010

University of BRISTOL

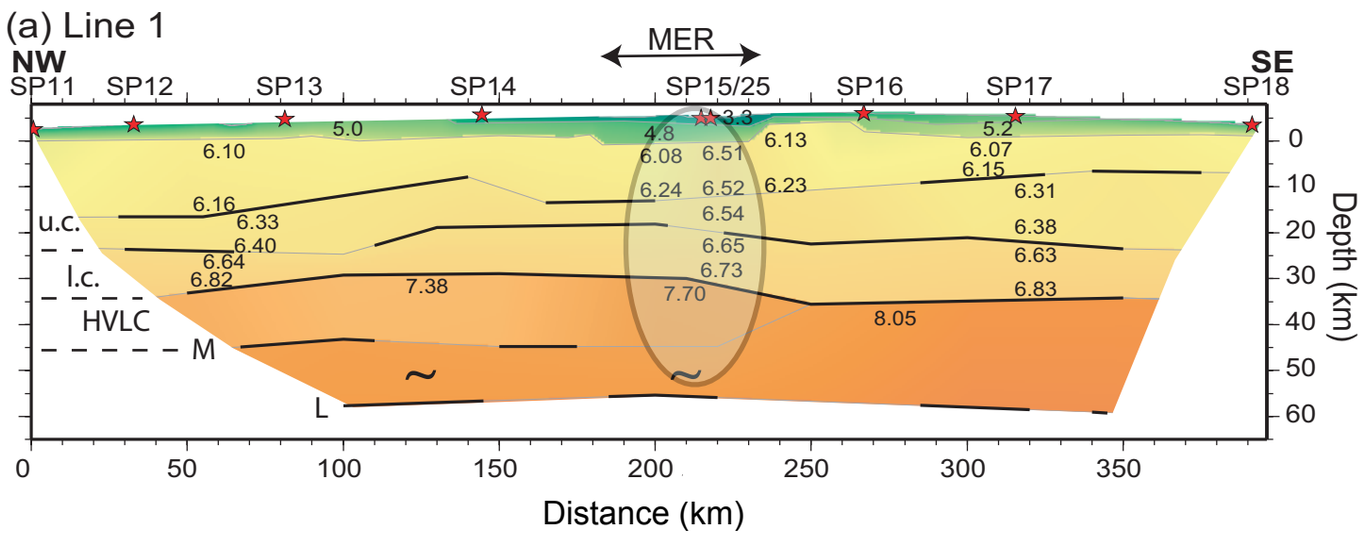
Perhaps the first basaltic eruption to be witnessed first hand in Ethiopia

Photo and video - Lorraine Field, Univ. Bristol.

Evidence From Rifts Worldwide



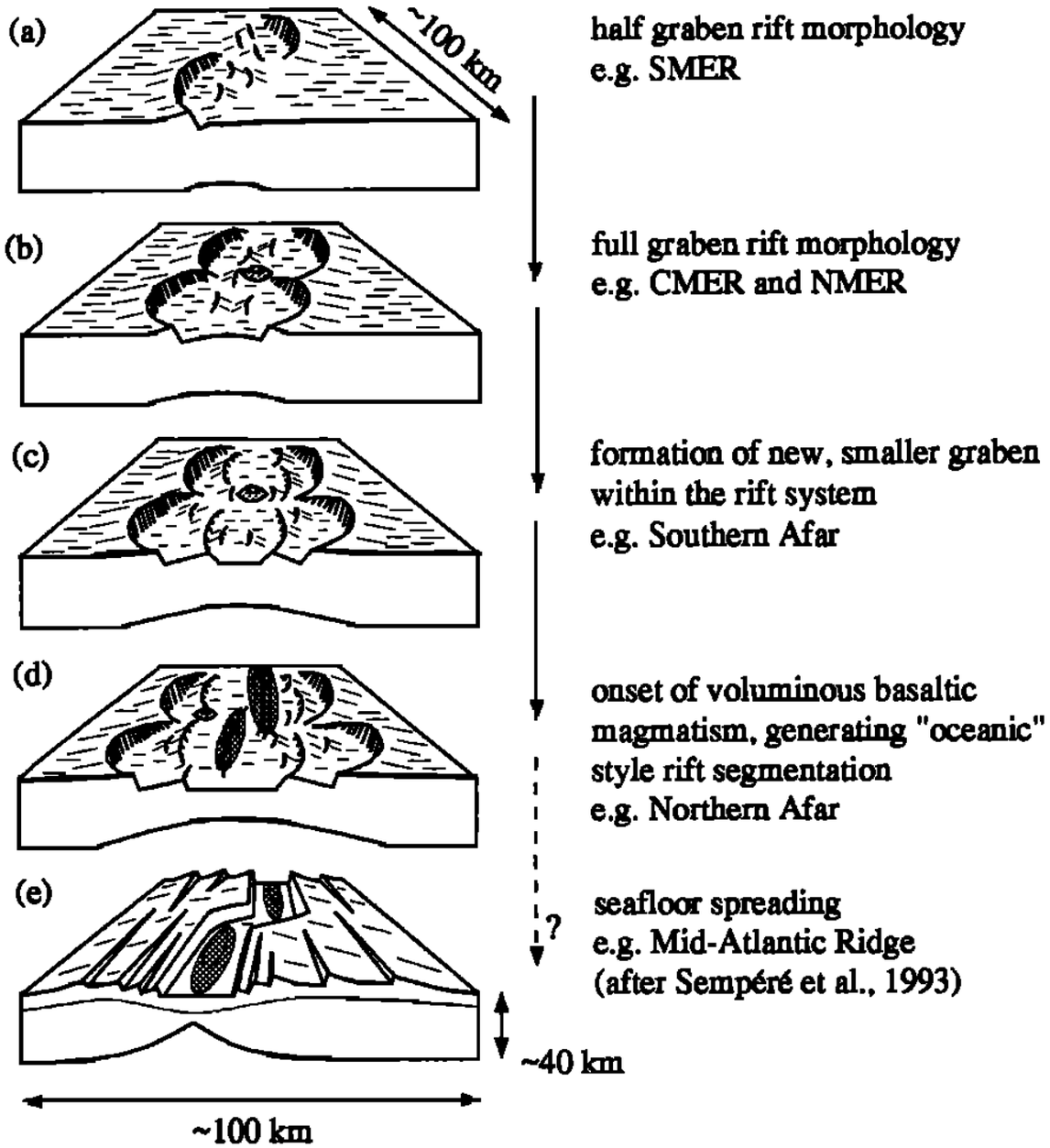
Thybo et al., (Nature, 2009)



Maguire et al., (GSL, 2006)

- e.g., Baikal and Ethiopia.
- Magma intrusion accommodates extension without marked crustal thinning.
- Important implications for estimation of stretching factors.
- Plate reconstructions predict β = 3 in Afar, but seismic data in southern Afar indicate β=1.7.

Early Rift Development



Hayward & Ebinger, (1996)