Big Questions on Rifting the Lithosphere: A Seismological Perspective from the Mantle

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Big Questions on Rifting the Lithosphere: Perspective from the Mantle

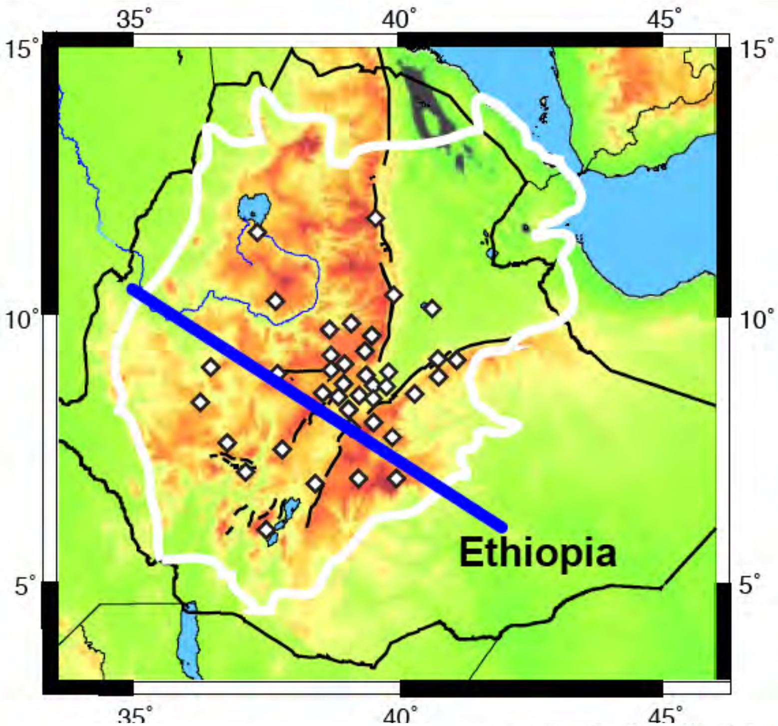
- What controls localization of deformation? Magmatism? Pre-existing heterogeneity?
- Did hot mantle upwelling accompany rifting?
- Are edge-driven and/or small-scale convection influencing margin evolution?
- Does rift segmentation (magmatic and/or structural) influence Mid-Atlantic Ridge segmentation?

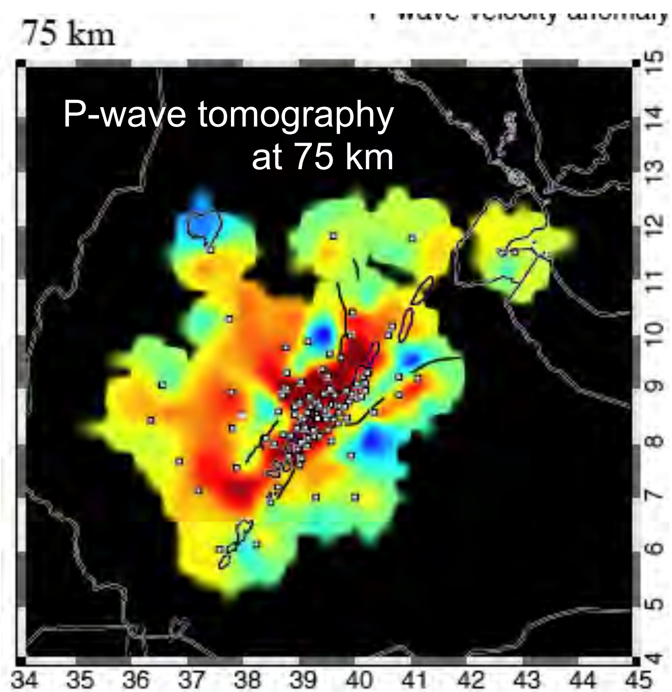
Big Questions on Rifting the Lithosphere: Perspective from the Mantle

Lithospheric rheology fundamentally controlled by composition, fabric, and melt

- Volume and distribution of melt
  - How much in the crust?
  - How much in the mantle?
  - What are the mechanisms of extraction (or not)?
- Localization of shear deformation
  - Controlled by melt?
  - Controlled by pre-existing fabric?
- Compositional heterogeneity
  - Pre-existing structure
  - Evolution during extension

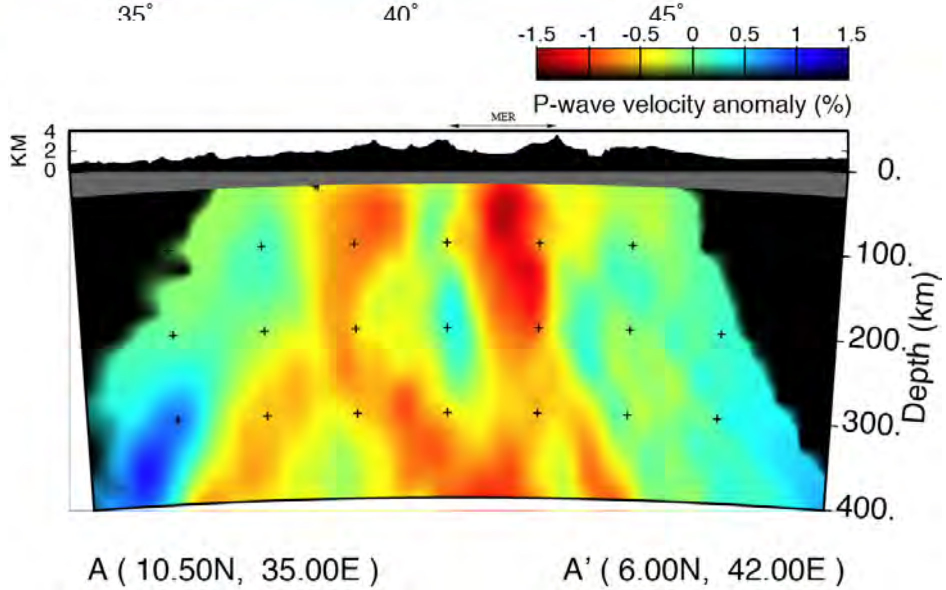
Imaging Magmatism and Extensional Deformation

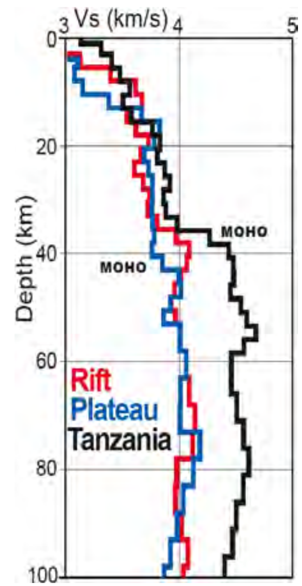




Modern example from East African Rift and adjacent Ethiopian Plateau

Bastow, Nyblade, Stuart, Rooney & Benoit, *G-cubed*



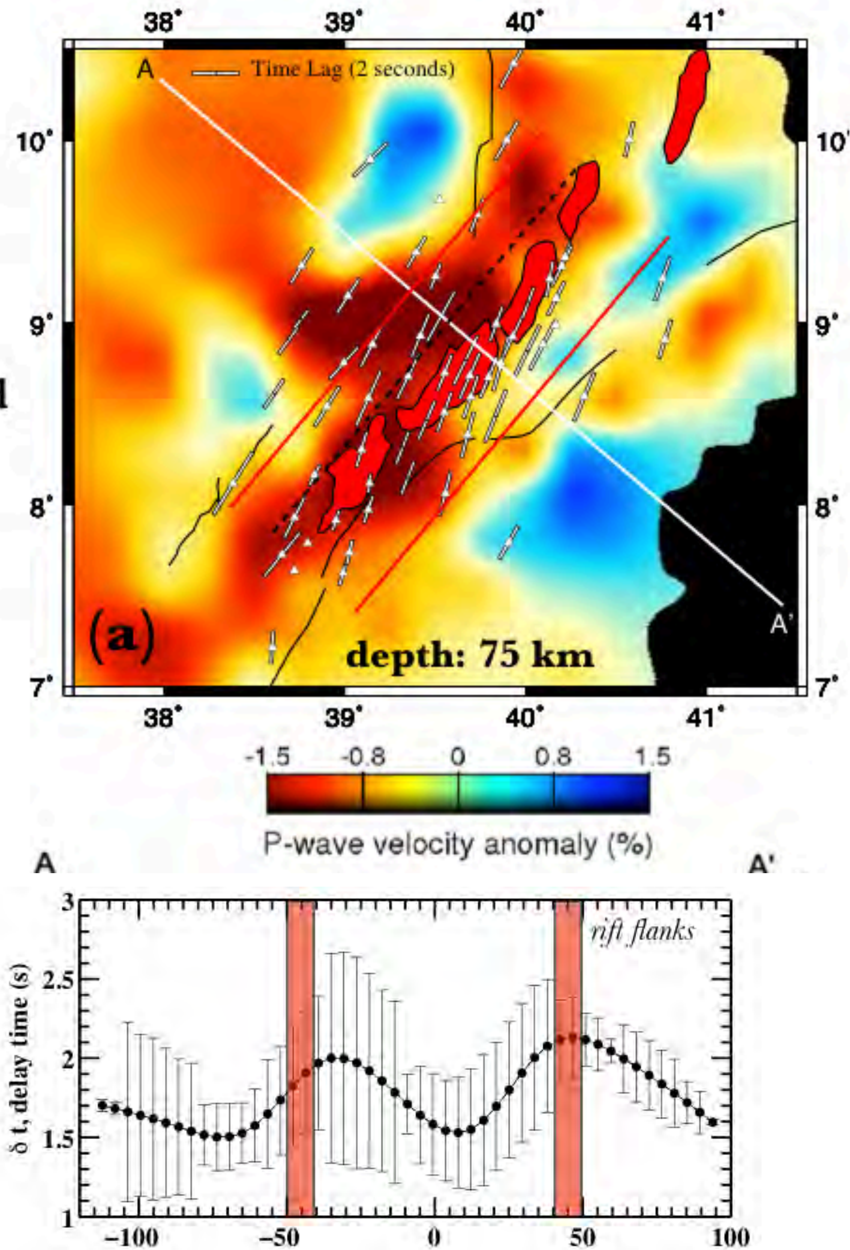


- Very low velocities – extensive partial melt
- Plume influence?
- Variations over few 100 km beneath rift and plateau
- Contrast in volcanic productivity in rift and on plateau

Keranen et al., 2009

Imaging Magmatism and Extensional Deformation

From work of Ian Bastow, James Hammond and others in Mike Kendall's group, Bristol

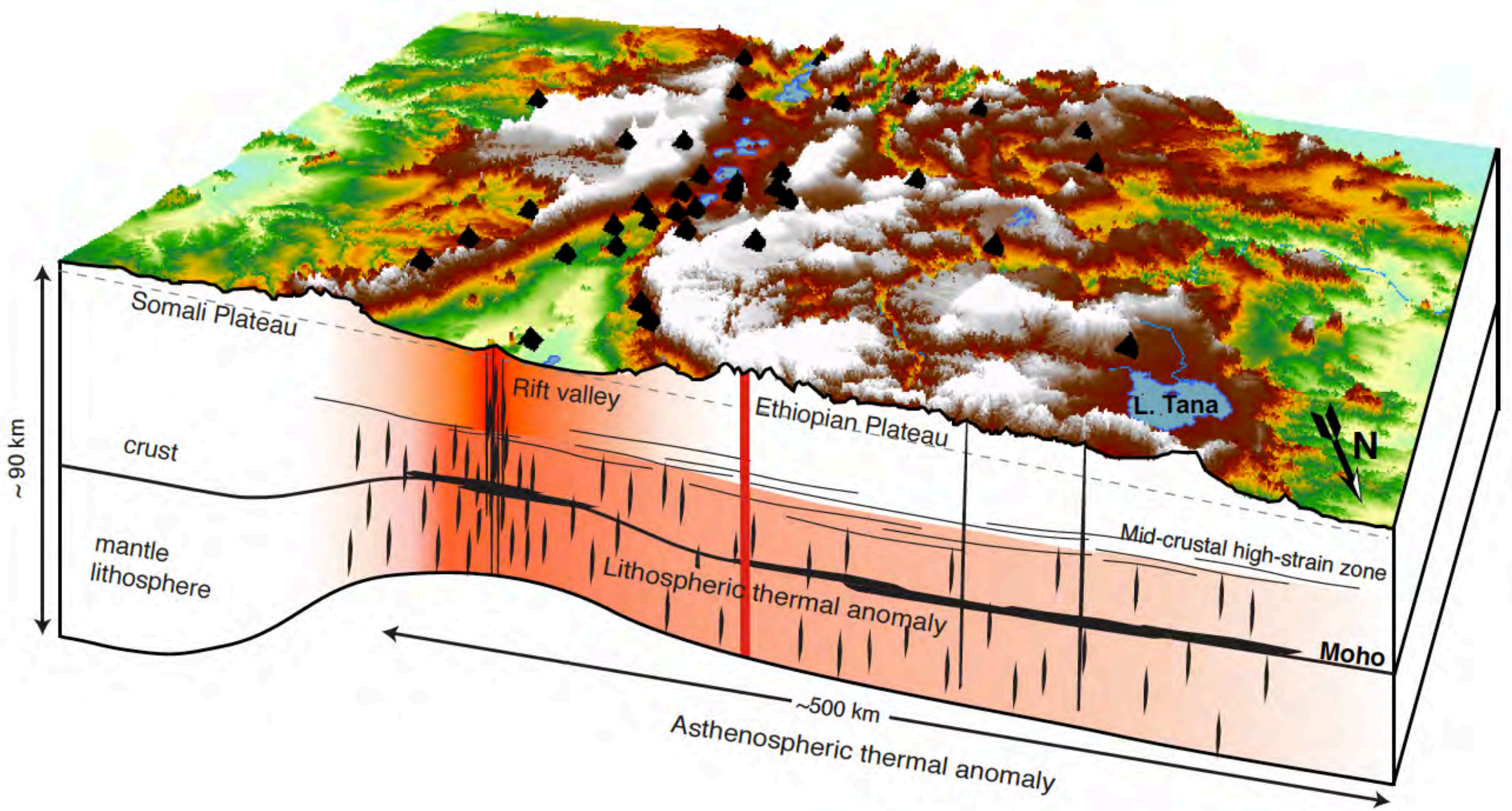


Modern example from East African Rift and adjacent Ethiopian Plateau

Bastow, Nyblade, Stuart, Rooney & Benoit, *G-cubed*

- Shear-wave splitting directions correlate with volcanic edifaces
- Splitting times strongest at rift flanks
- Interpreted in terms of aligned melt channels

Imaging Magmatism and Extensional Deformation



K. Keranen, 2011.

Imaging Magmatism and Extensional Deformation

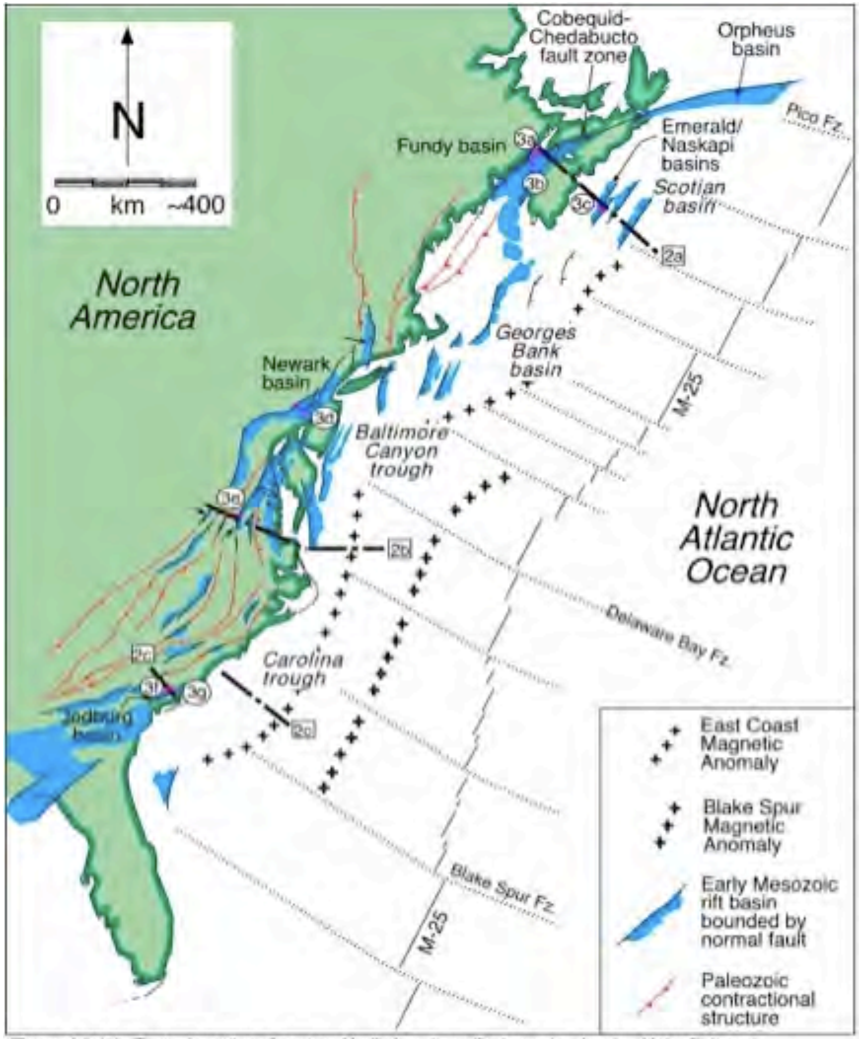
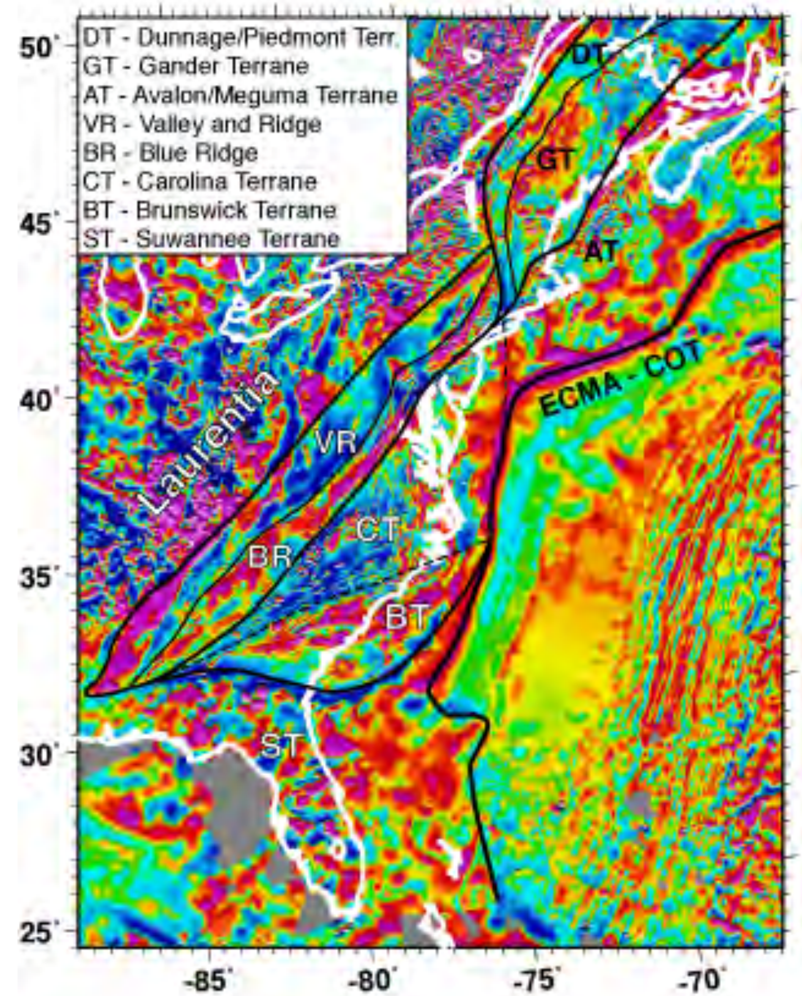


Figure 4.2.1.1. Tectonic setting of eastern North American rifted margin, showing Major Paleozoic compressional structures and early Mesozoic rift basins and key tectonic features of the eastern North Atlantic Ocean (Benson and Doyle, 1988; Klitgord et al., 1988; Manspeizer and Cousminer, 1988; Costain and Coruh, 1989; Olsen et al., 1989; Tankard and Welsink, 1989; MacLean and Wade, 1992; Sheridan et al., 1993; Rankin, 1994). Thick dashed lines and squares with notation show location of transects in Figure 4.2.1.2; purple lines and ellipses with notation show location of sections in Figure 4.2.1.3. (Modified from Withjack et al., 1996.)

Withjack et al, 1998

The Historical Perspective...



D. Lizarralde, 2010

Imaging Magmatism and Extensional Deformation

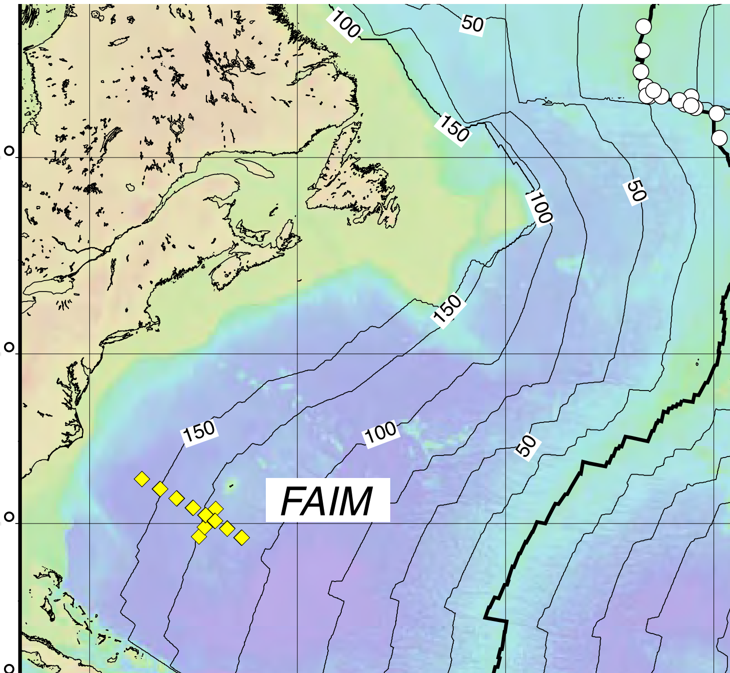
Passive Margins Fingerprint Rifting Process

- Lithosphere records history of rifting and rift evolution
    - Successes and failures
    - Relationship between rift and sea-floor spreading structures
- Complements studies focused on “active” processes
- Thermal signal is likely to be minimal
    - Melting produces resolvable compositional variations
    - Improved sensitivity of fabric (deformation) structure

Rift processes interesting over length scales of 10’s to 100’s km

- Generally larger (and deeper) than typical geological field scale
- A bit small for global or continental-scale imaging
- Focused studies that bring integrated active-source and array-based seismology with other tools

Imaging compositional changes in the mantle – an example from oceanic lithosphere

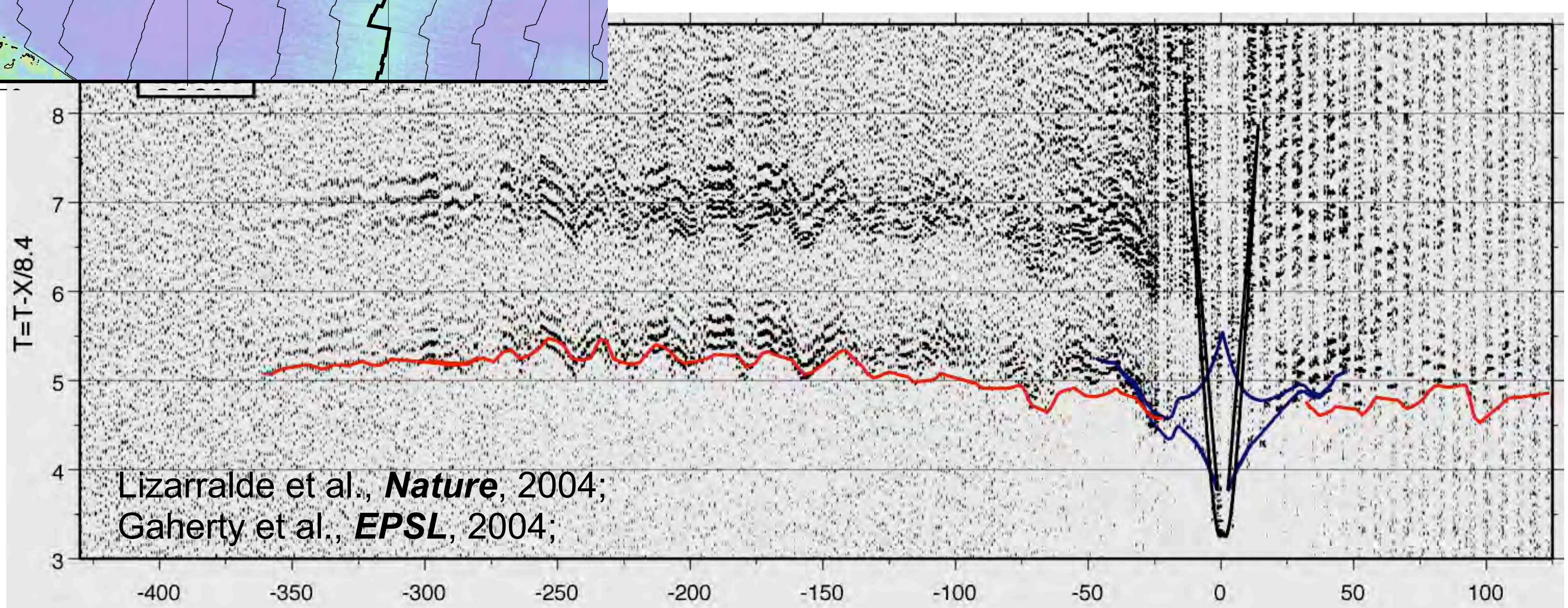


Wide-Angle Active-Source Refraction survey to image P-velocity structure of upper-mantle

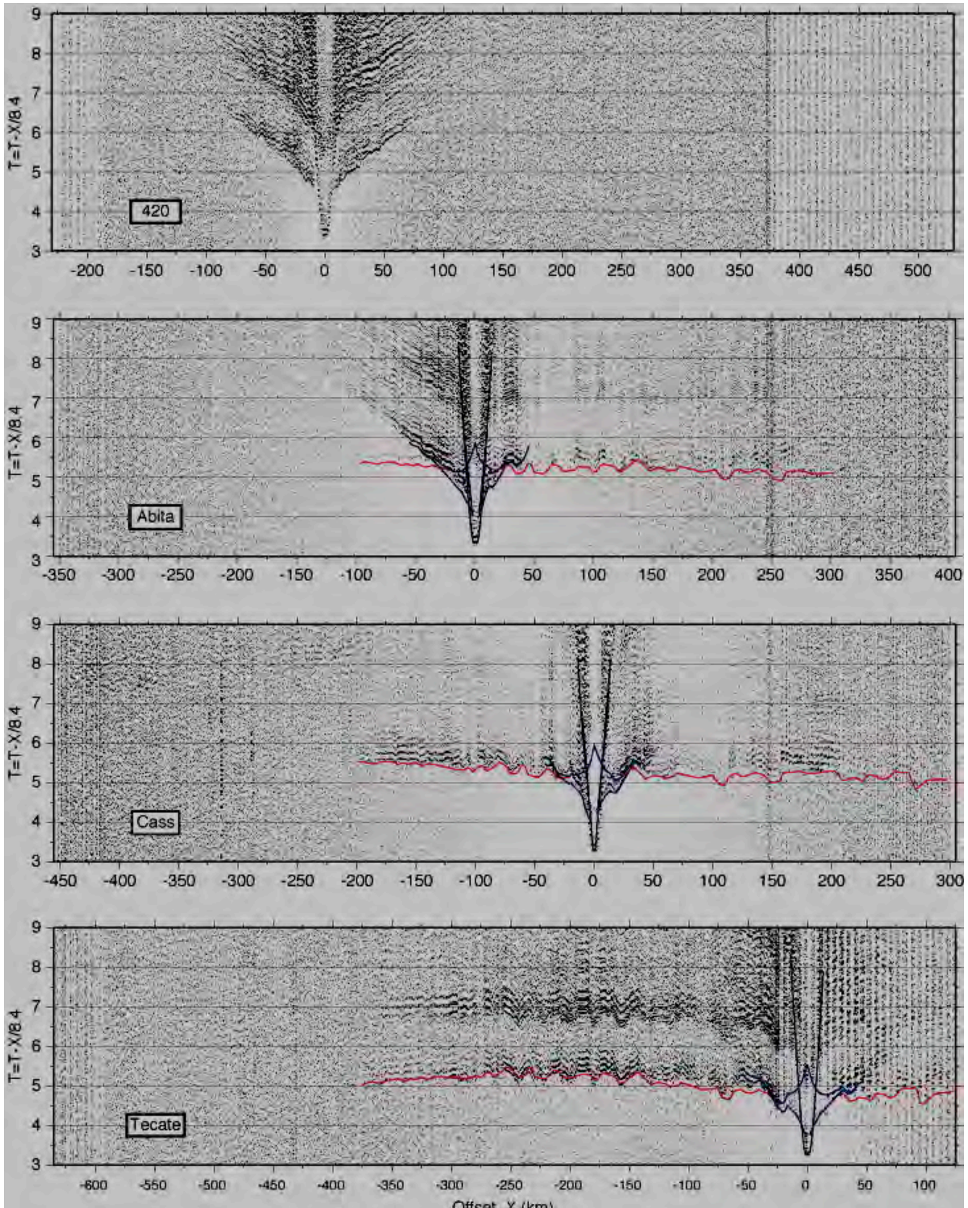
Line 1 - 800 km, parallel to fossil spreading, 16 OBS

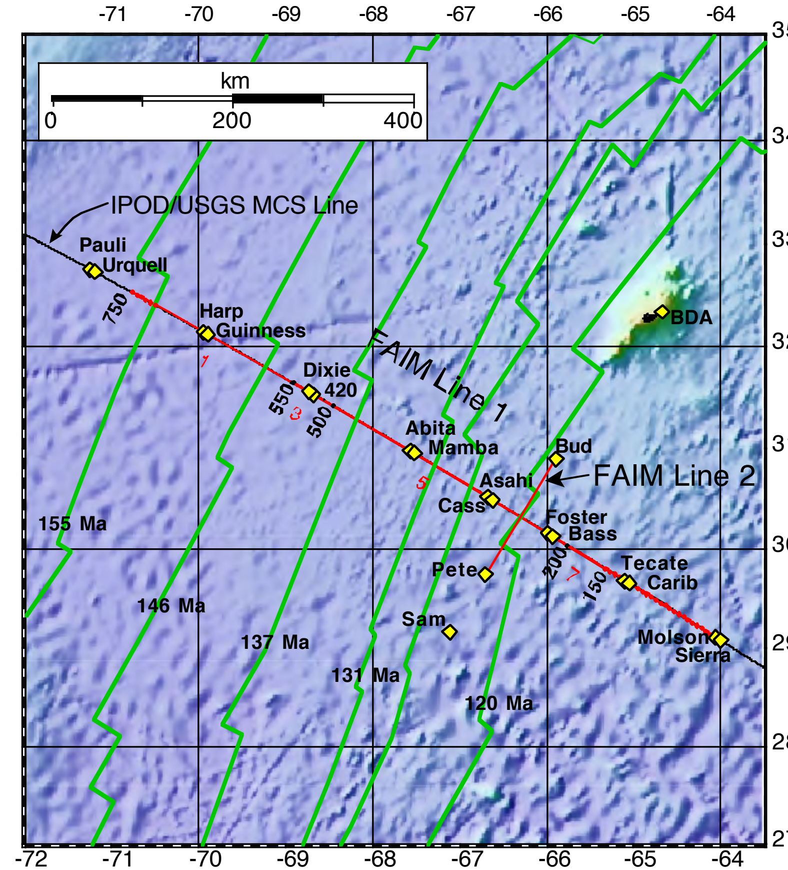
Line 2 -- 150 km, perpendicular to paleo spreading, 3 OBS

Offline instruments provide constraints on anisotropy.



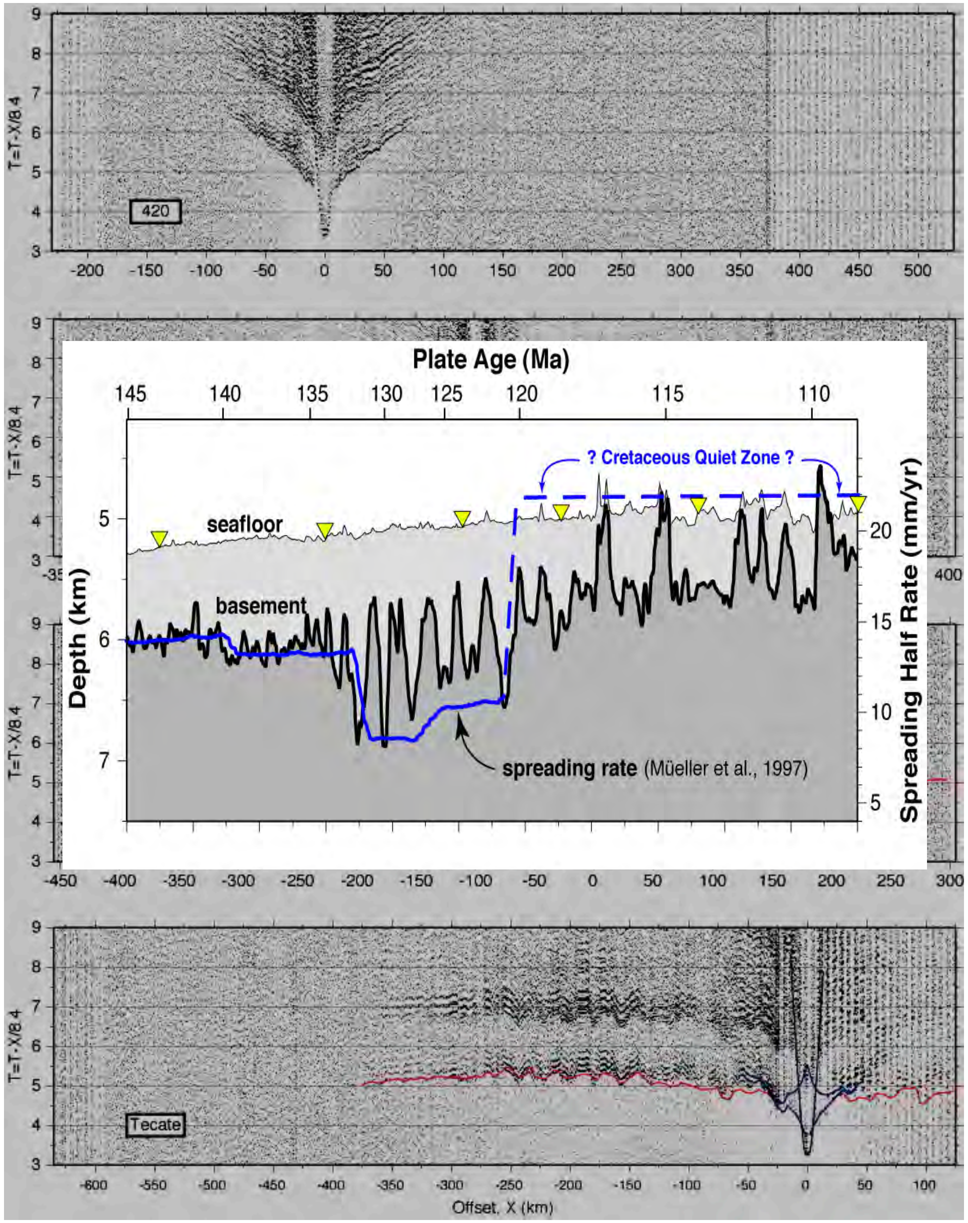
Compositional changes in the mantle – an example from oceanic lithosphere

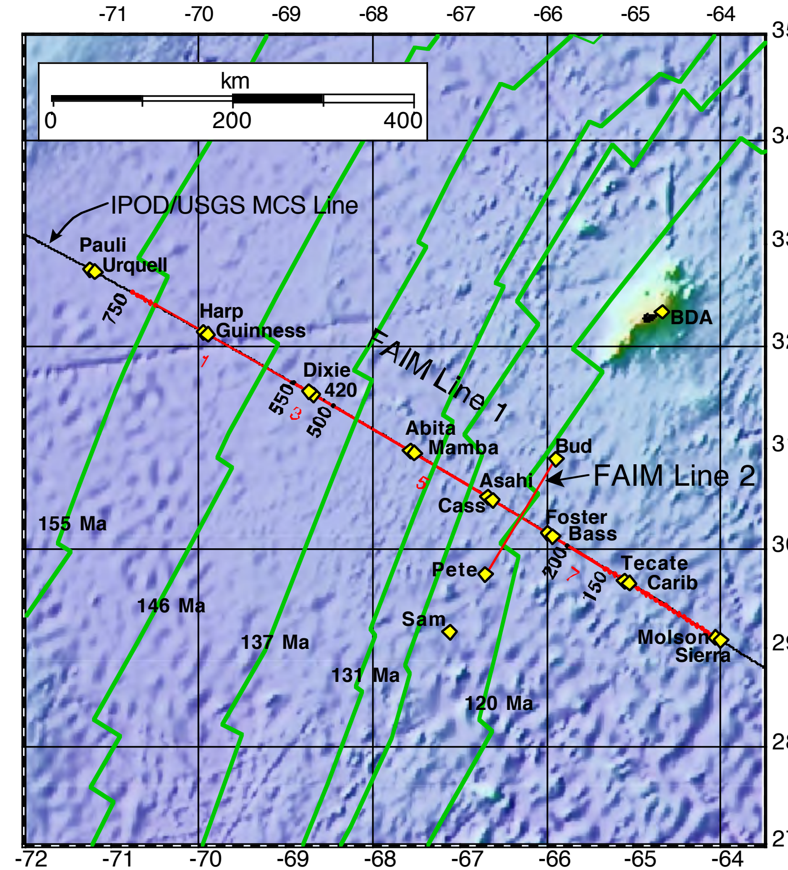




- Instrument gathers laid out NW to SE
- Reduction velocity 8.4 km/s

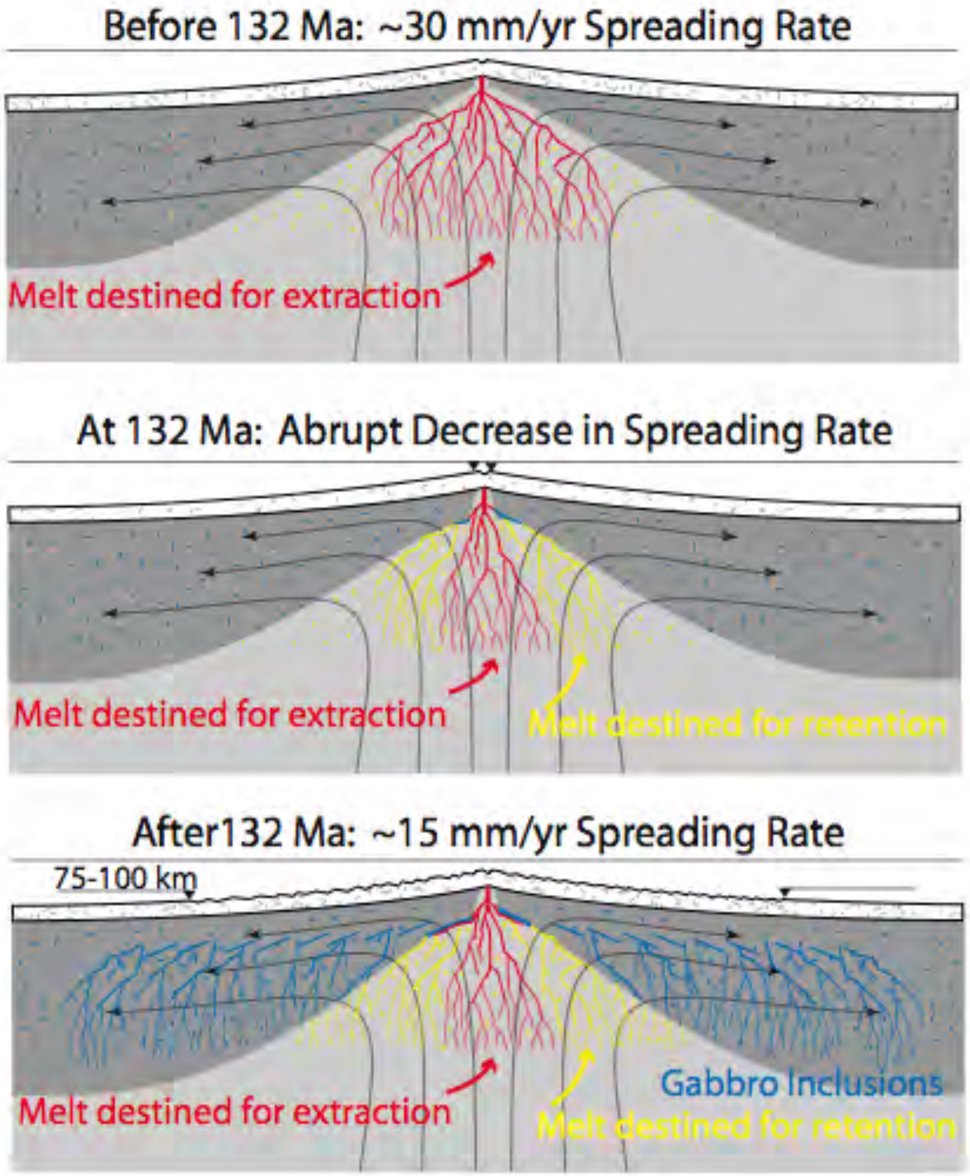
Compositional changes in the mantle – an example from oceanic lithosphere





- Drop in spreading rate
- Decrease in crustal thickness
  - Retained gabbro

Compositional changes in the mantle – an example from oceanic lithosphere

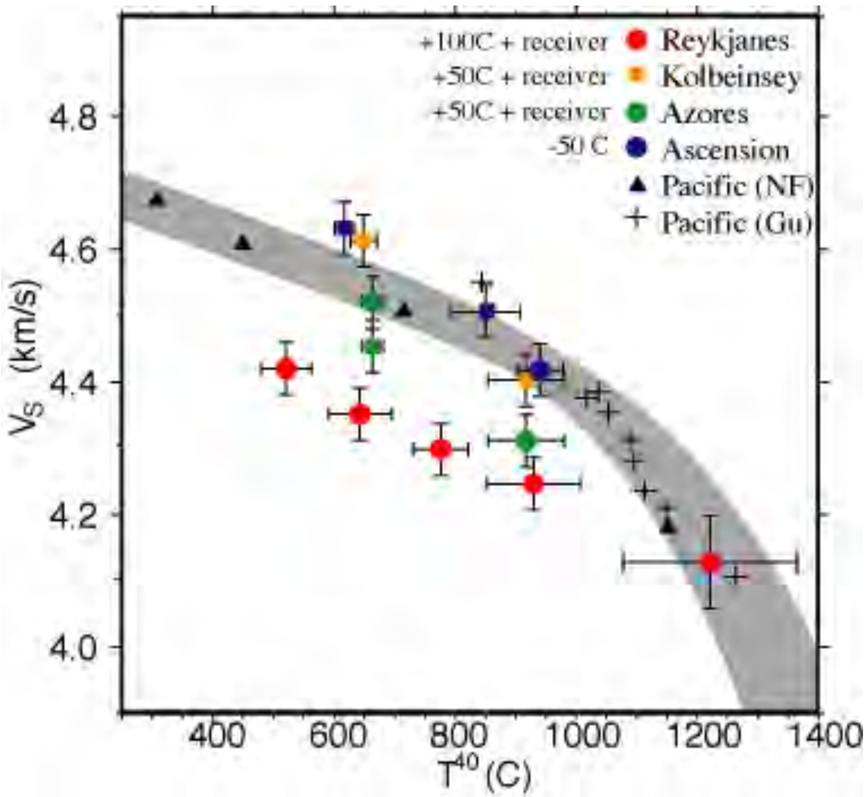


Efficiency of melt **extraction** controls gradient: retained gabbro

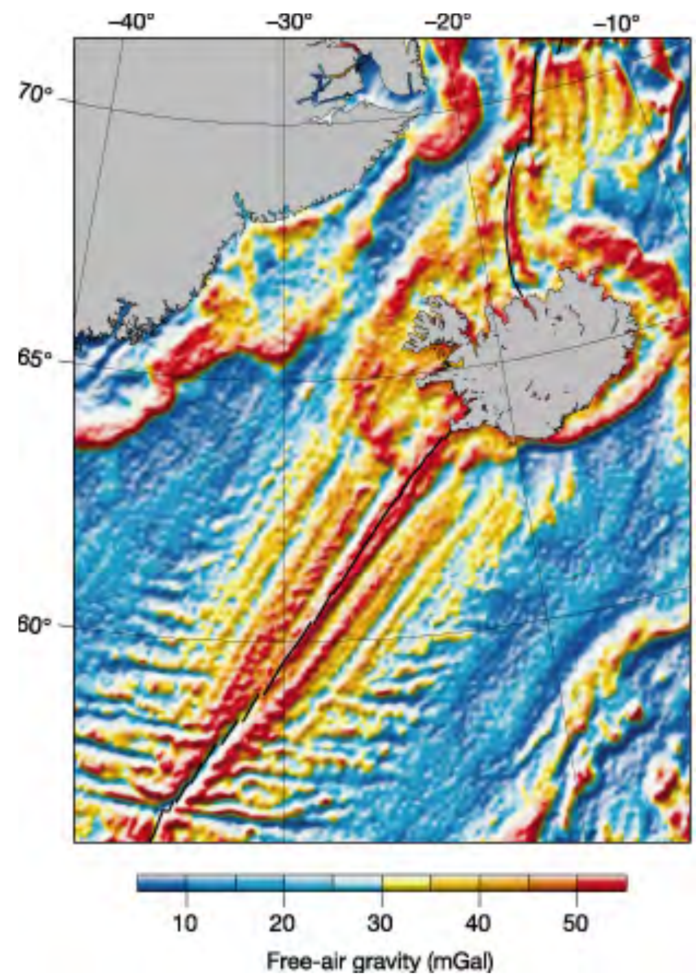
- Approximate balance between missing crust and sub-Moho gabbro suggests that production unchanged
- Consistent with geochemistry observed at slow spreading rates
- Likely important in rift settings where extraction pathways are highly variable

Lizarralde, Gaherty, Collins, Hirth, and Kim, ***Nature***, 2004.

Compositional changes in the mantle – an example from oceanic lithosphere



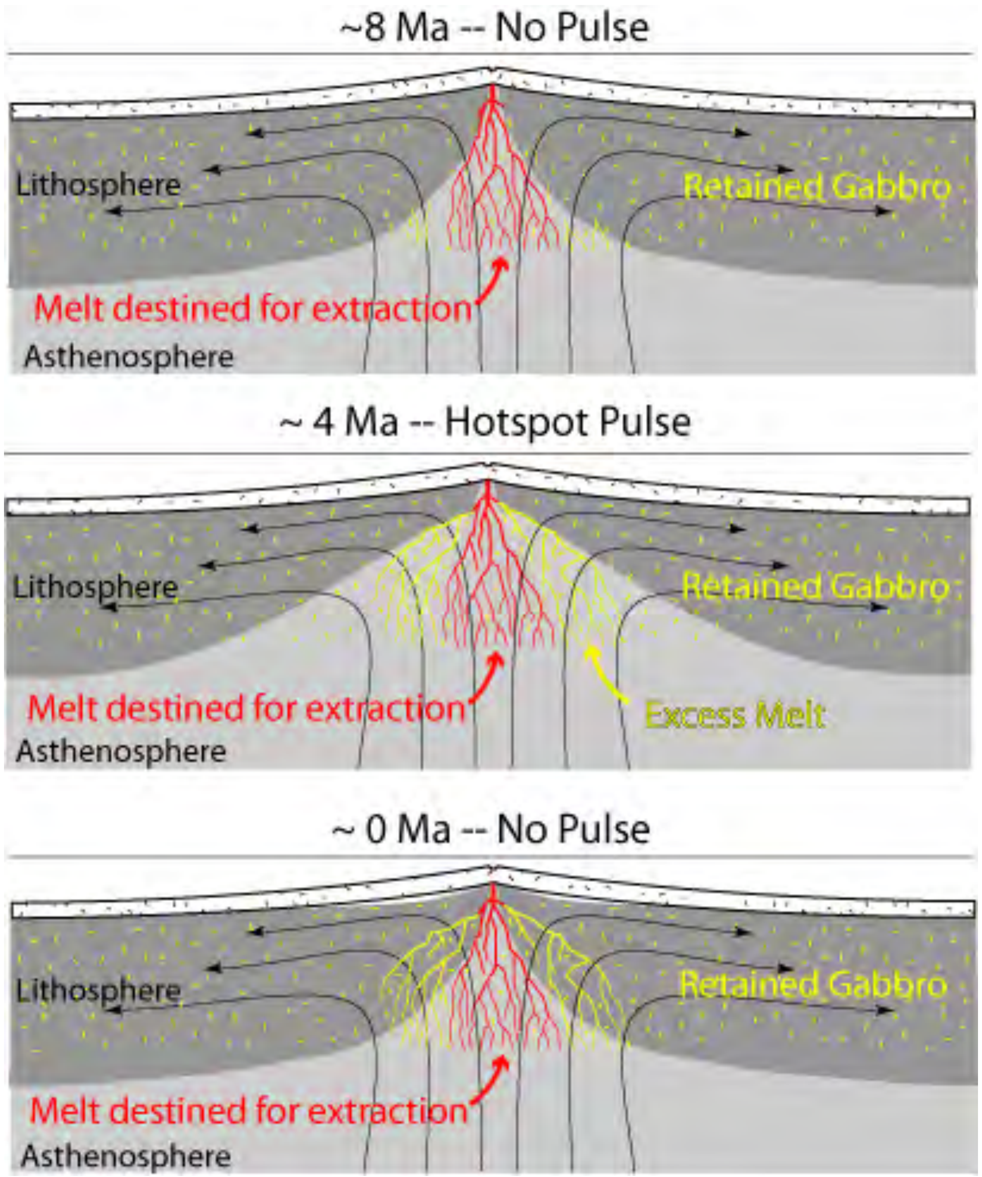
Pacific (Gu): *Gu, Webb, Lerner-Lam, Gaherty* (2005).
Pacific (NF): *Nishimura and Forsyth* (1989).



Gaherty and Dunn, *G^3*, 2007.

Ito, *Nature*, 2001.

Compositional changes in the mantle – an example from oceanic lithosphere

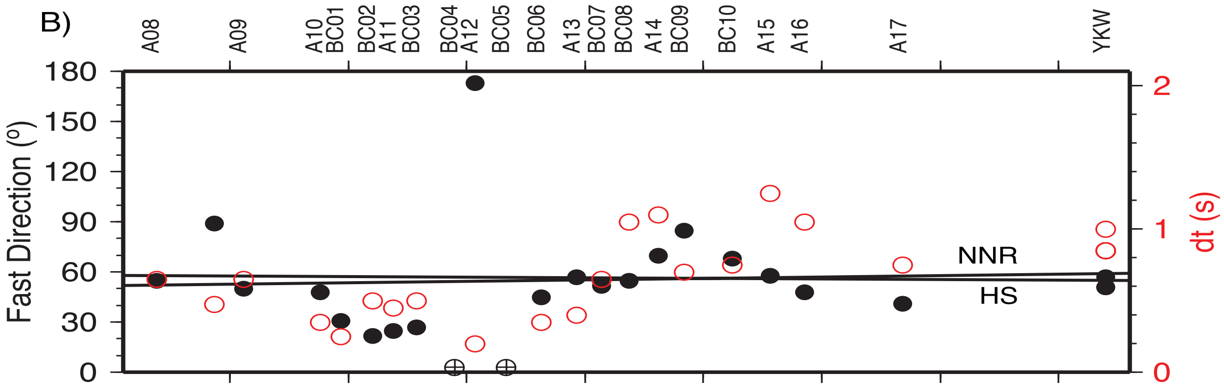


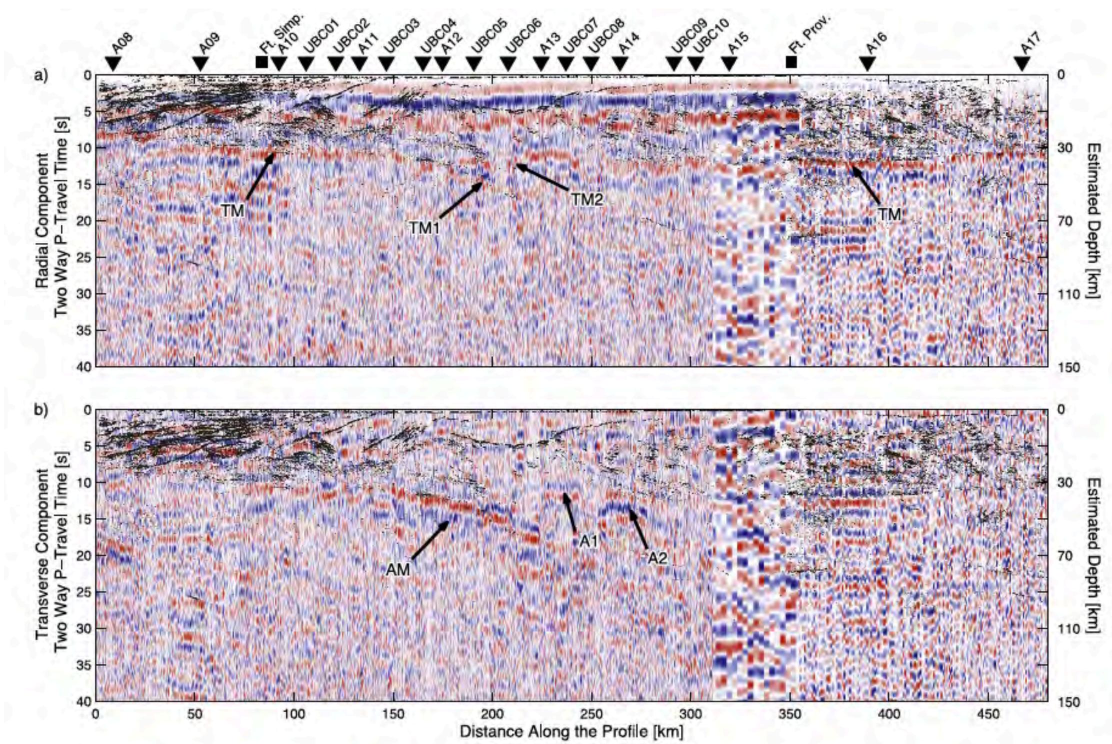
Efficiency of melt **production** controls shear velocity: retained gabbro

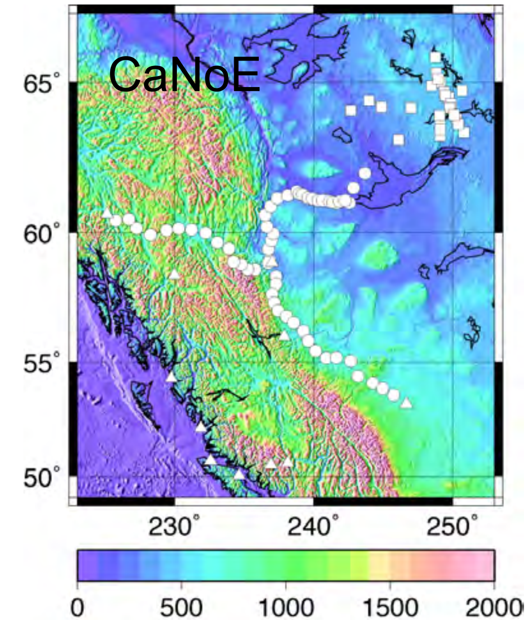
- Connection between melt production and basaltic crust is provided by a complex 3D network of melt channels
- Sensitive to abrupt changes in melt productivity
- Likely important in rift settings where variable mantle temperature influences productivity

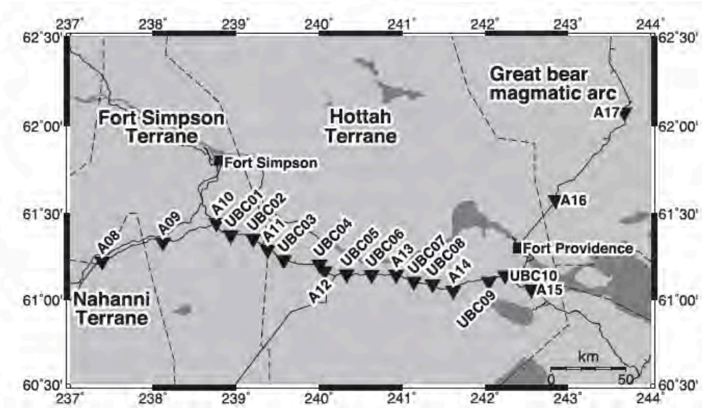
Gaherty and Dunn, *G*[3], 2007.

Record of ancient deformation in the mantle – an example of heterogeneous lithospheric anisotropy



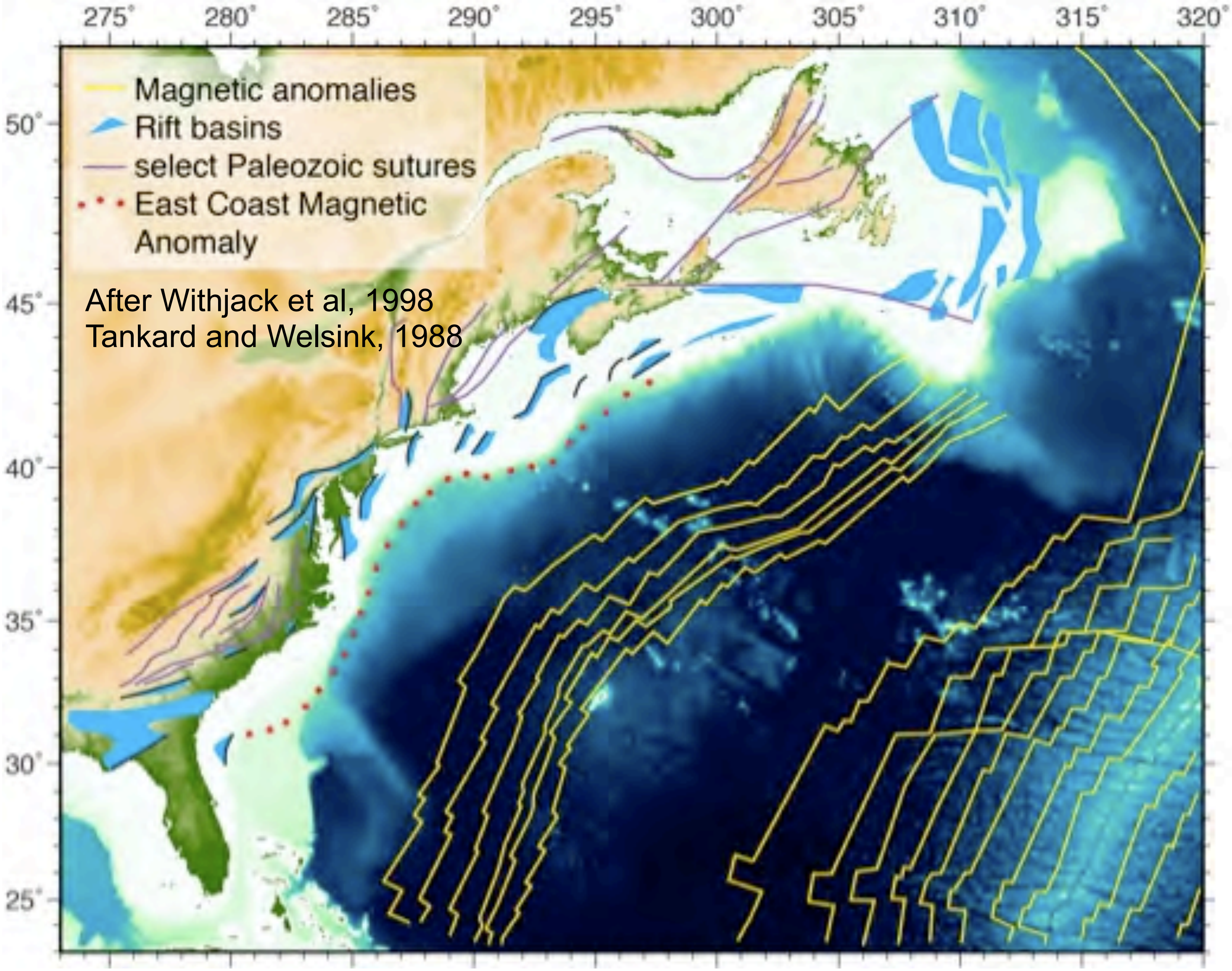






Mercier et al, *JGR*, 2008;
Courtier et al., *Geology*, 2010.

Can we see such structures along East Coast North America margin?



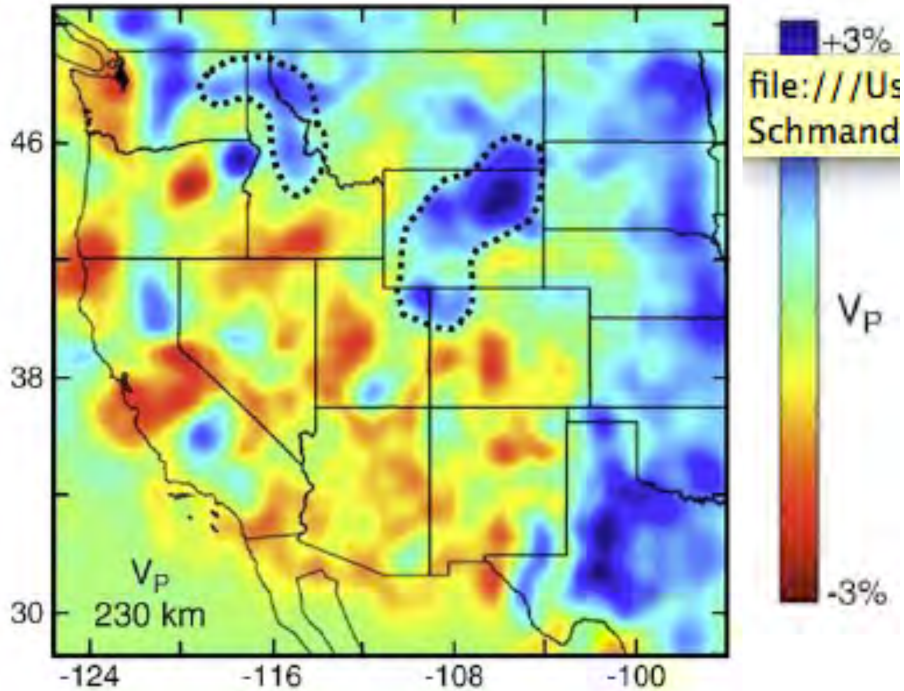
Can we see such structures along East Coast North America margin?

Key ingredients:

- Integrated active + passive source
  - *P, S,* anisotropy, discontinuities
- Span onshore sutures to seafloor spreading
  - Pre-breakup geological structures
  - Relationship to seafloor-spreading segmentation
- Length scales of 10's-100's km
- 3D!

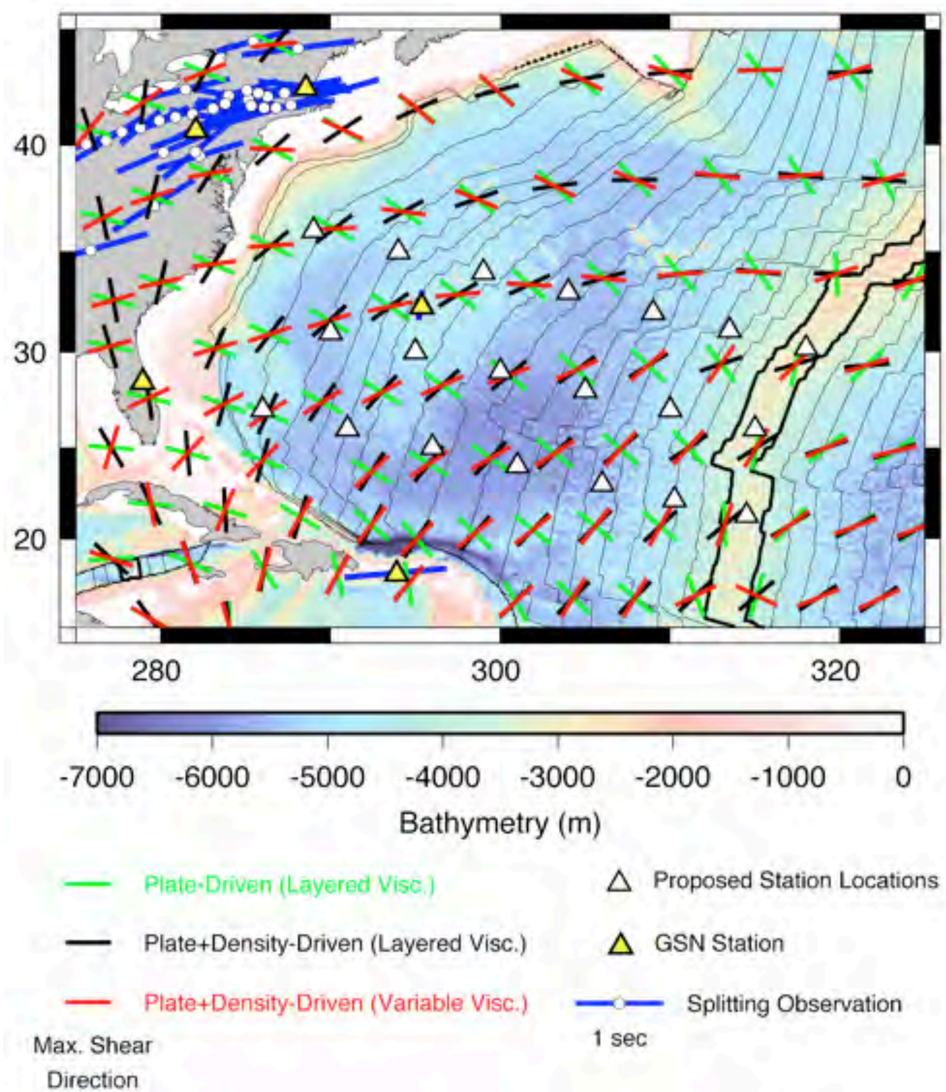
Thanks to D. Shillington, D. Lizarralde, K. Keranen, B. Holtzman

Post Rift Evolution – Influence of Mantle Dynamics



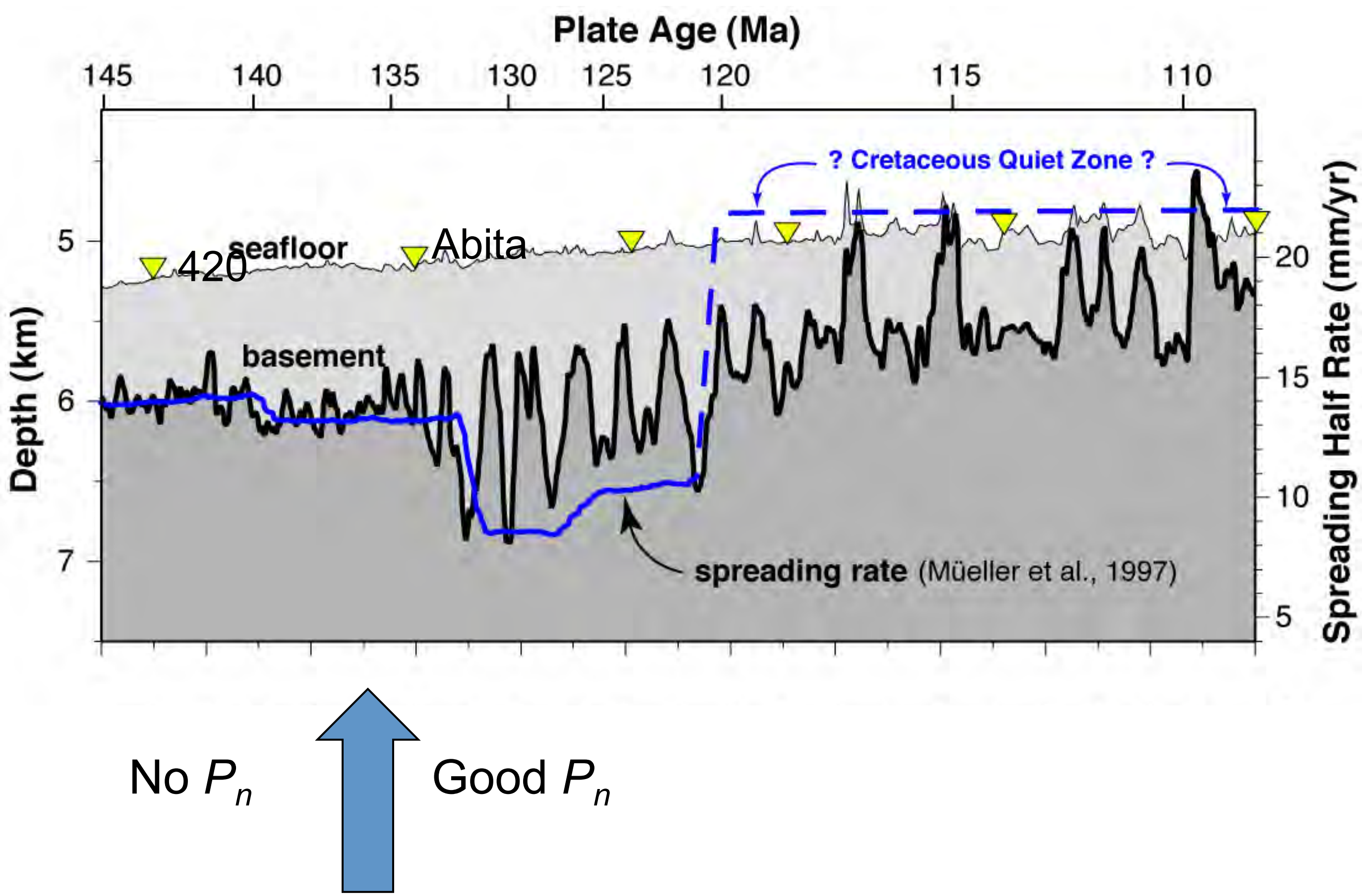
Significant velocity (and thus density) variations in the asthenosphere

Schmandt and Humphreys, 2010



Behn and Conrad

Seismic observations in ocean basins
2) lid gradients too strongly positive



Change in mantle *P* propagation coincides with:

•Drop in spreading rate (~13 to 8 mm/yr)

•Increase in basement roughness

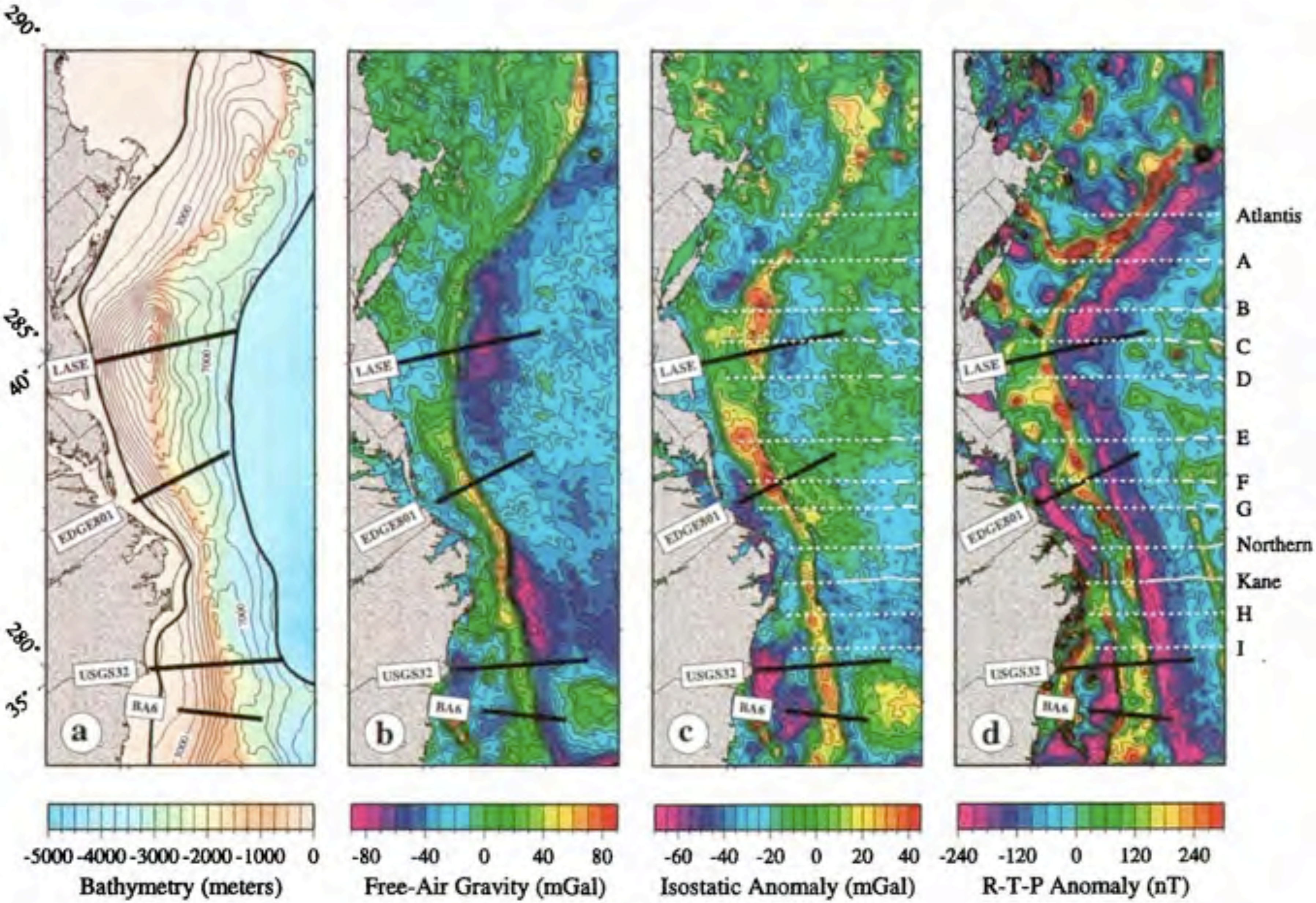
•Decrease in crustal thickness

Retained gabbro

Crustal thickness
~7 km

Crustal thickness
~5.5 km

Is Rift Segmentation Related to MOR Segmentation?



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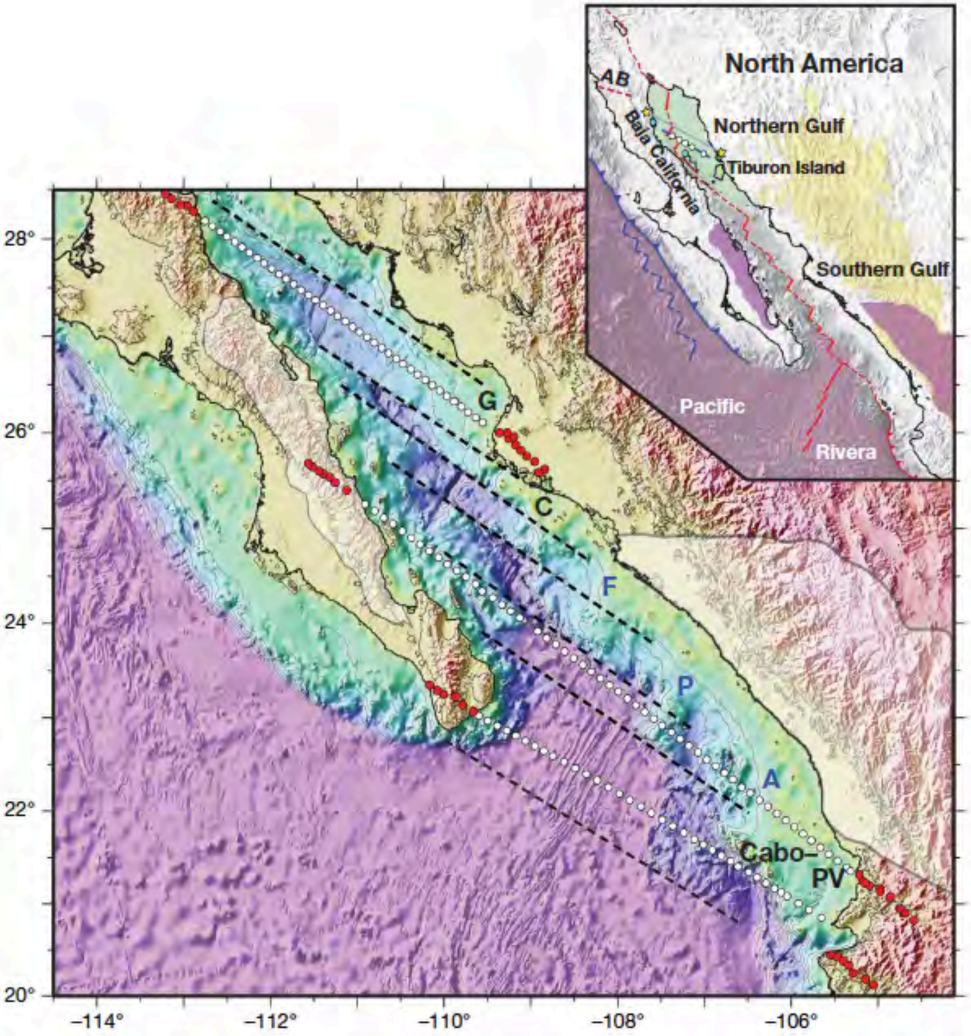

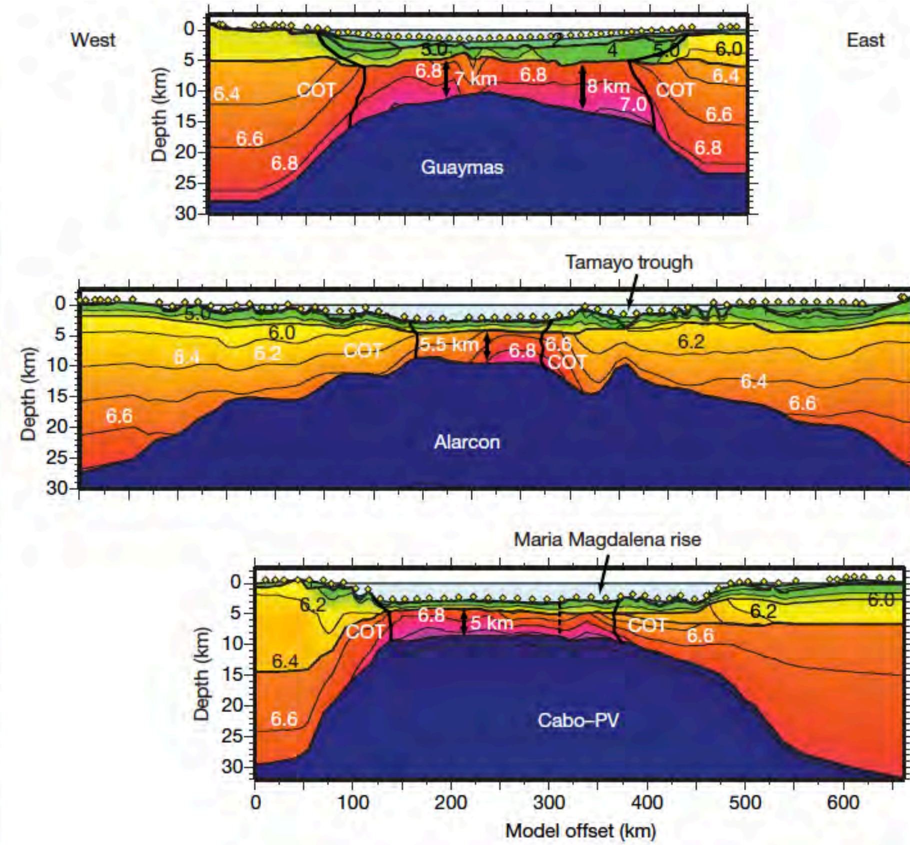

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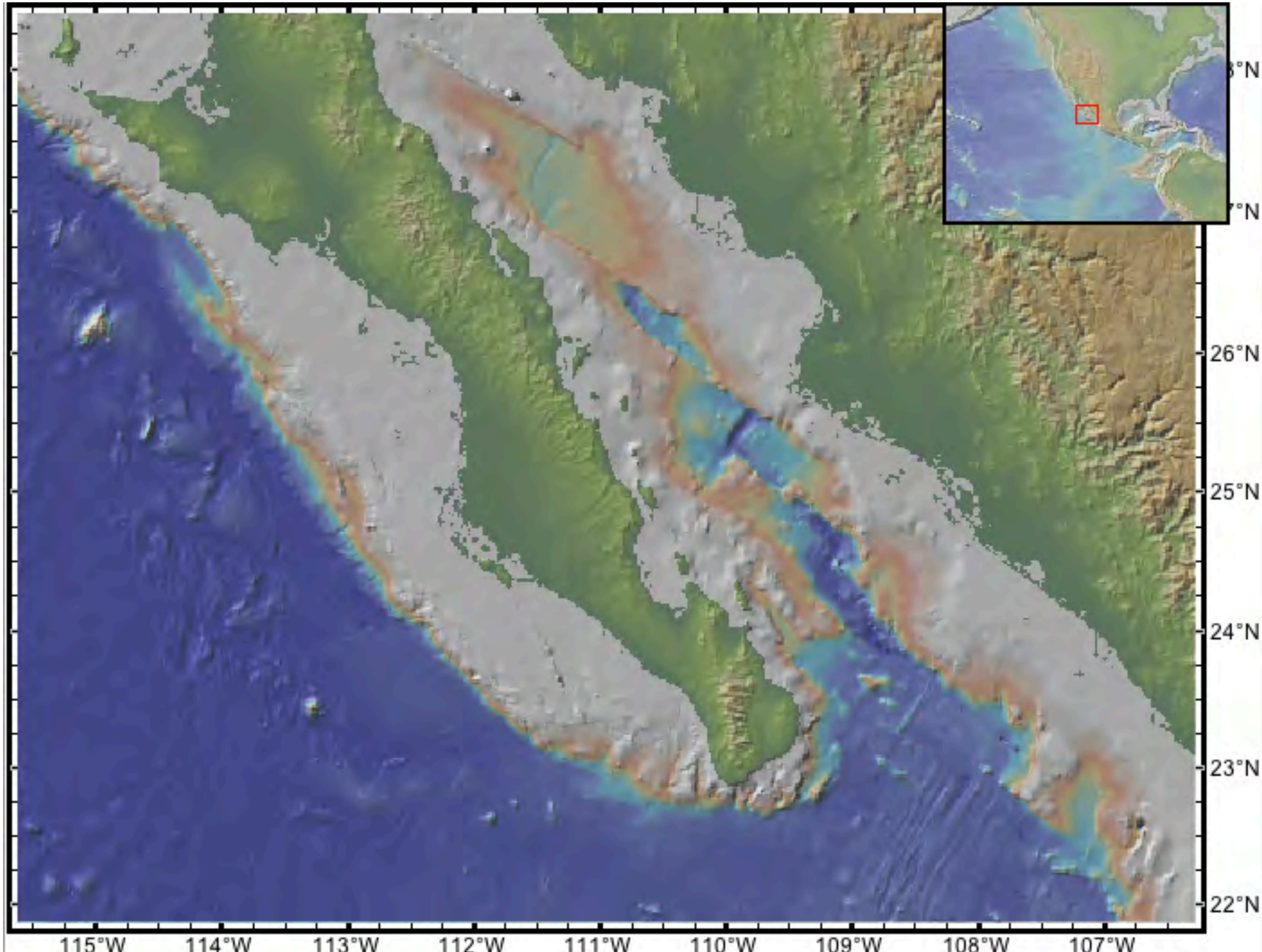

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