High bulk modulus structures in the lower mantle from dynamic Earth models with paleogeography

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1. Tethyan subduction history is a dominant influence on the location and morphology of the African LLSVP
2. Depth-dependence of the coefficient of thermal expansion controls the development of LLSVPs and the propagation of slabs to the deep Earth
3. Depth-dependent material properties are required to satisify geodynamic, mineral physics, and seismological constraints on the LLSVP
4. Lithosphere and slab assimilation ensures that global heat flux and thermal buoyancy in the upper mantle are consistent with plate motion and geological history

Model Setup

- 3-D spherical Boussinesq and Extended Boussinesq (EBA) using CitcomS
- High resolution (129 x 129 x 65 x 12 = 13 million nodes)
- Rayleigh number = 2.1E8
- Kinematic surface boundary condition (Figure 2)
- Realistic slab behaviour captured through 'slab assimilation' (Figure 3)
- Global heat flux constrained by 'lithosphere assimilation' (Figure 3)
- Temperature- and pressure-dependent rheology (approx 10^3 variation)
- PREM-like depth-dependent properties (for EBA models)
- Internal and basal heating
- Factor of 5 decrease in thermal expansion coefficient from surface to CMB (EBA) motivated by Birch (1952) and Chopelas and B1oehler (1992) (for EBA models)
- Assumption that LLSVPs existed prior to 250 Ma. Initial condition: Two 'mesas' initially emplaced at 0 degrees (African LLSVP) and 180 degrees (Pacific LLSVP) that rise 900 kilometers above the CMB. In most cases, slabs are initially prescribed in just the upper mantle
- Model proceeds from 250 Ma to present day assimilating data at every time step

Seismic Observations

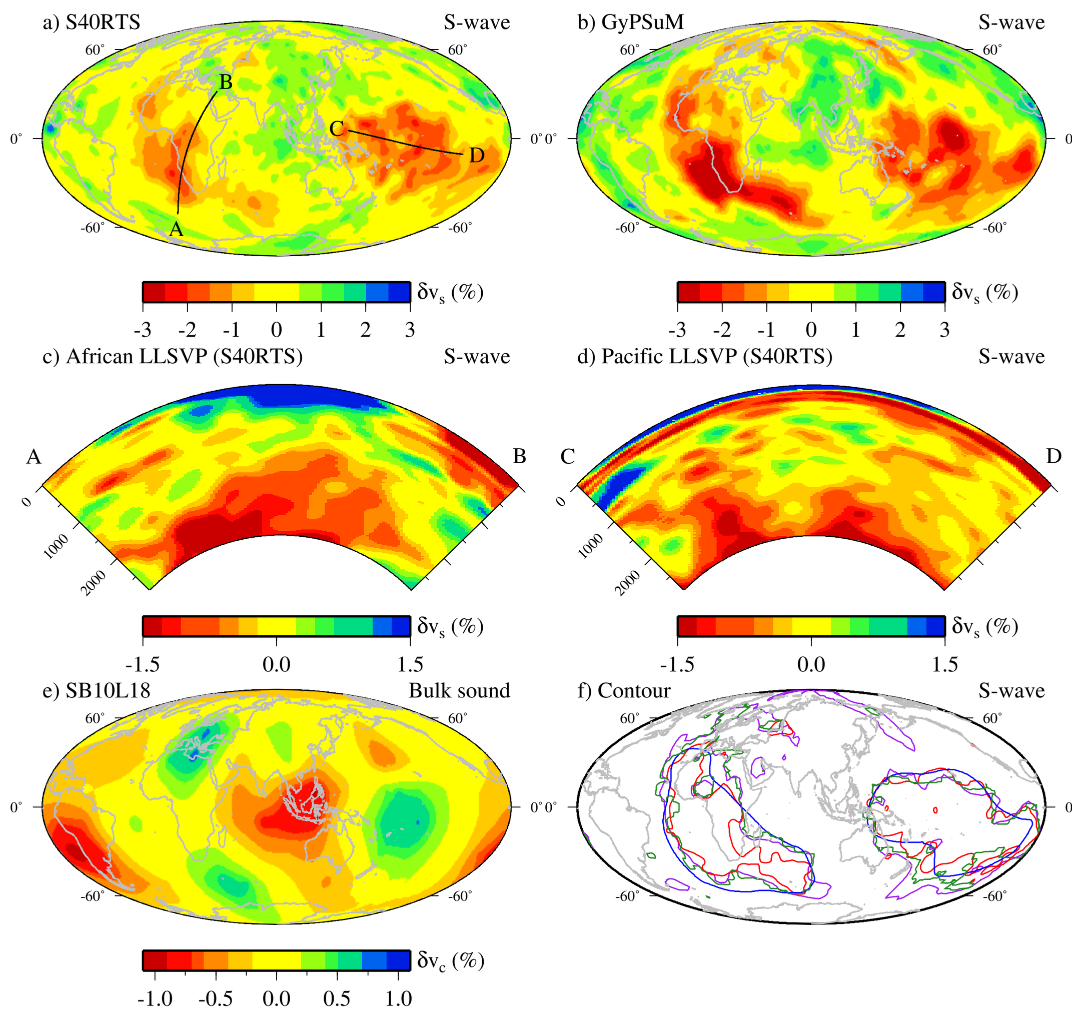


Figure 1. (a) and (b) Shear velocity tomography models at 2800 km depth. (a) S40RTS (Ritsema et al., 2011), (b) GyPSuM (Simmons et al., 2010). (c) and (d) Cross-section through the African (c) and Pacific (d) LLSVPs. The color scale is saturated to highlight mid-mantle structure. Location of cross-sections are marked on (a). (e) Bulk sound speed from SB10L18 (Masters et al., 2000) at 2800 km depth. Note anticorrelation with shear velocity. (f) -0.6% shear velocity contours from several tomography models at 2800 km depth show remarkable consistency: S40RTS (red), GyPSuM (purple), TXBW (Grand, 2002) (green), SB10L18 (blue).

Plate History Model

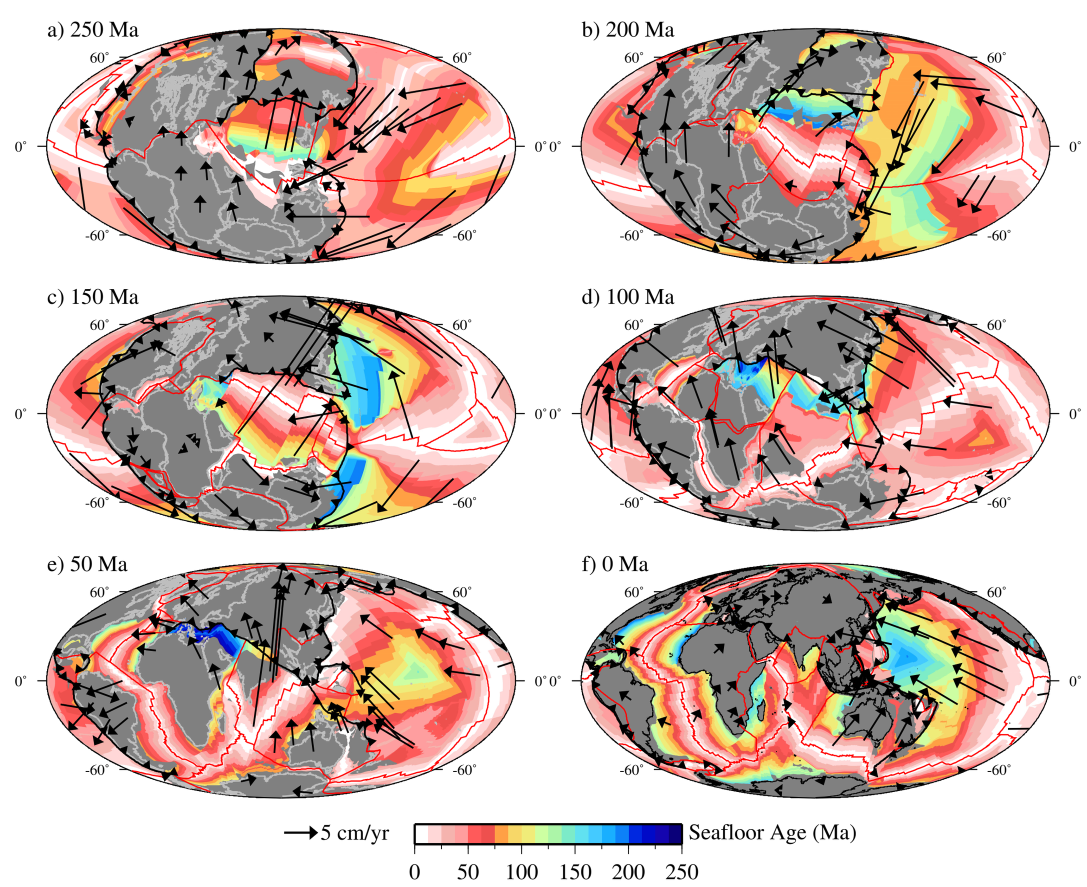


Figure 2. Snapshots of the plate history model (Seton et al., 2011) (a) 250 Ma, (b) 200 Ma, (c) 150 Ma, (d) 100 Ma, (e) 50 Ma, (f) present day. Ridges and transform faults are represented by red lines and subduction zones are represented by black lines with sawteeth to show the polarity. Non-oceanic regions are dark grey and reconstructed continents are outlined in light grey (except black for the present day).

Lithosphere and Slab Assimilation

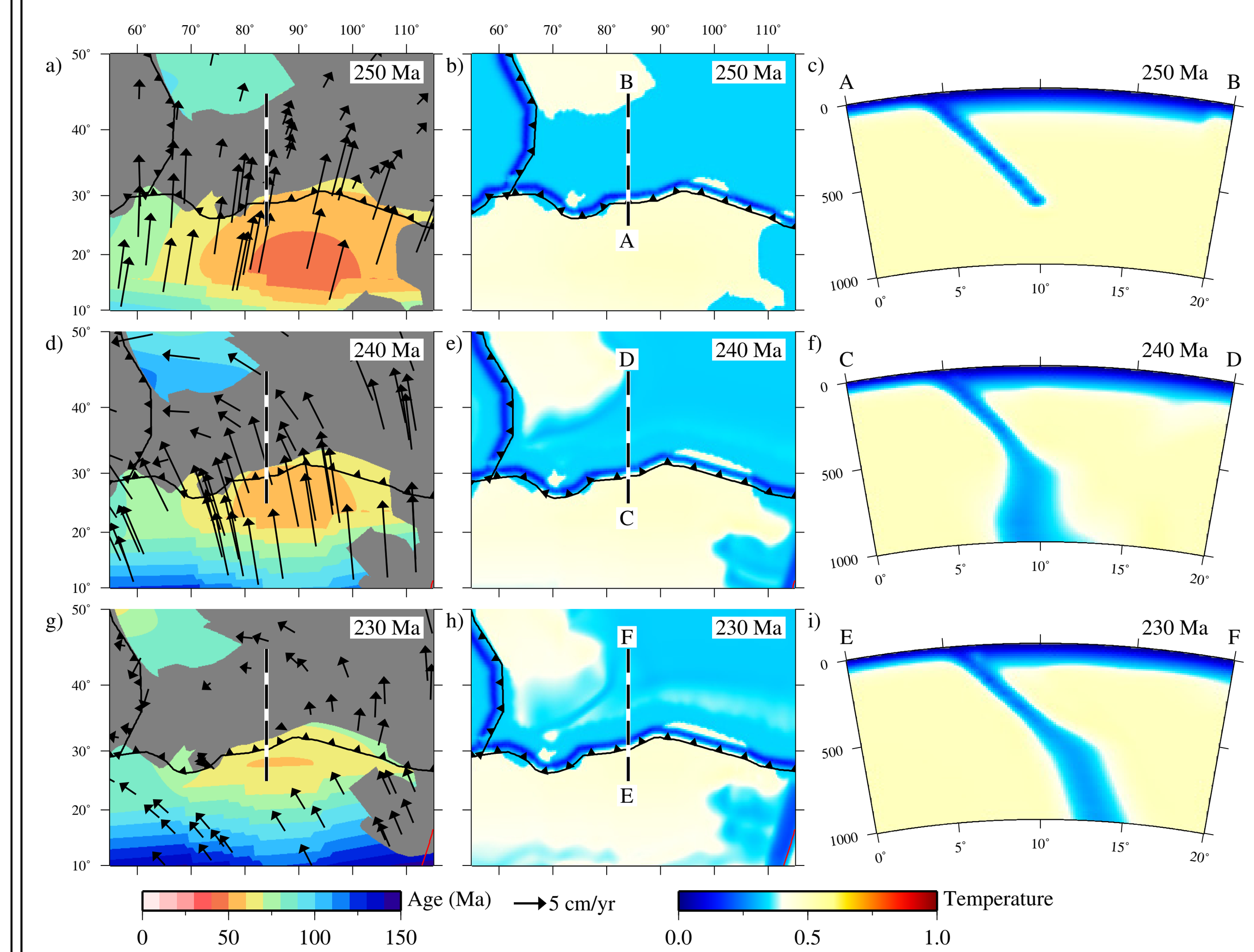
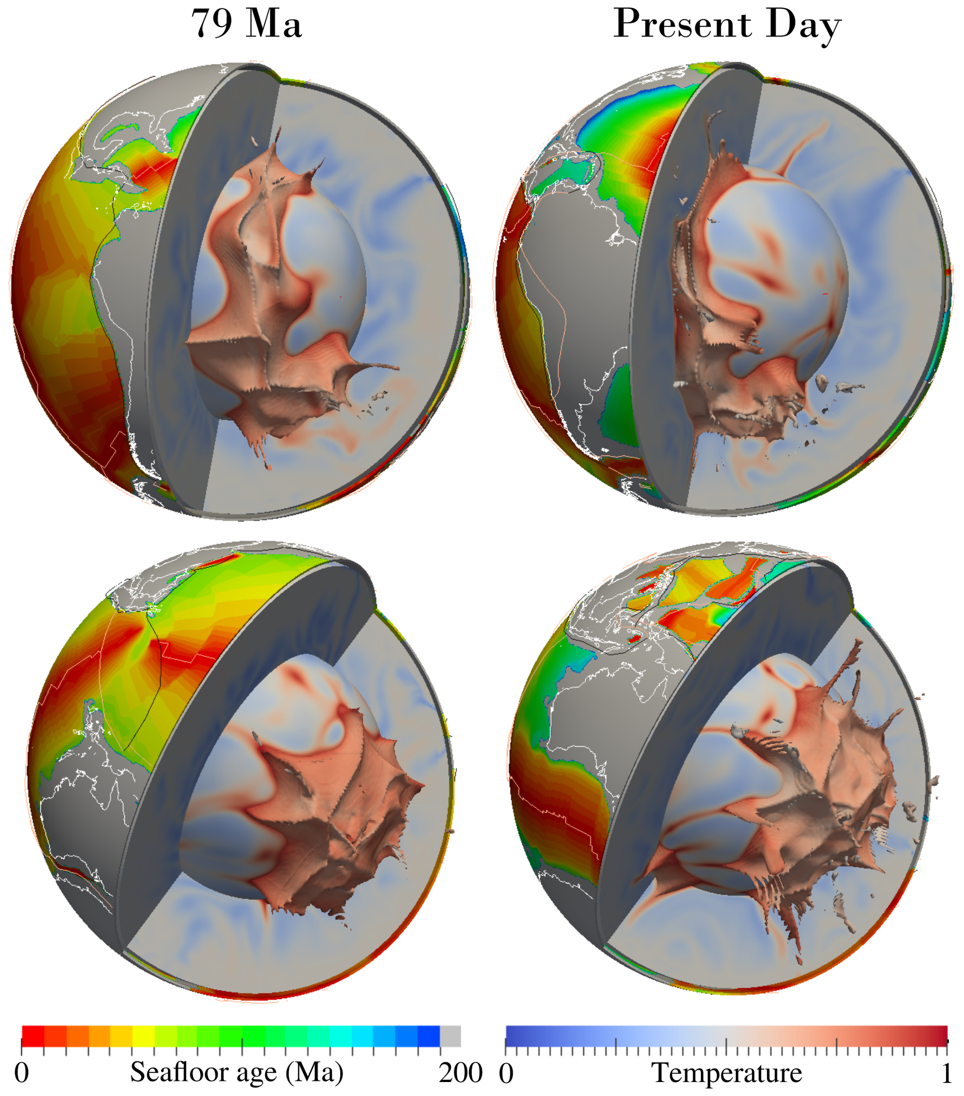


Figure 3. Example of lithosphere and slab assimilation for the convergence of the Paleo-Tethys Ocean and Laurussia. Plate history model (a) 250 Ma, (d) 240 Ma, (g) 230 Ma. Temperature field at 110 km depth (b) 250 Ma, (e) 240 Ma, (h) 230 Ma. Cross-section of slab (c) profile A-B, 250 Ma, (f) profile C-D, 240 Ma, (i) profile E-F, 230 Ma. Ridges and transform faults are represented by red lines and subduction zones are represented by black lines with sawteeth to show the polarity. Non-oceanic regions are dark grey.

Results 1: Benchmark Boussinesq Case



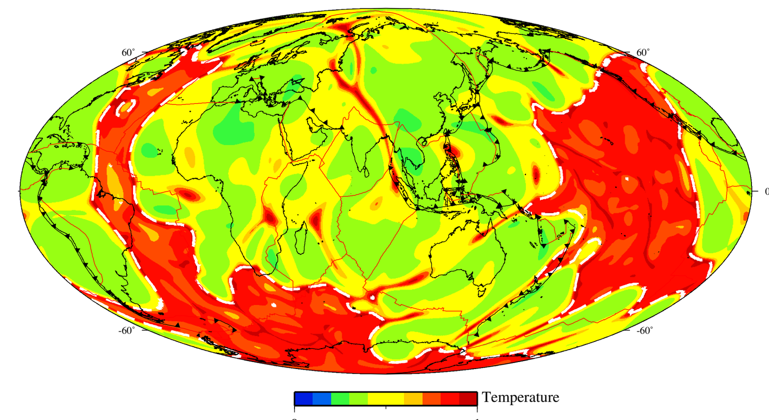


Figure 4. Present day temperature at 2776 km depth. Ridges and transform faults are represented by red lines and subduction zones are represented by black lines with sawteeth to show the polarity.

- Uniform chemical density anomaly with pressure (buoyancy no. = 0.5)
- Model captures the general morphology at depth: a ridge for the African LLSVP and a rounded pile for the Pacific LLSVP
- Location of African LLSVP does not correlate well with tomography: Tethyan subduction history introduces slabs that push the structure further to the west
- Vertical extent of LLSVPs does not correspond well with tomography or waveform modeling
- Plumes develop on ridge crests and not at the edges of the structures ('Plume generation zones')

Results 2: Present Day Temperature at 2776 km Depth

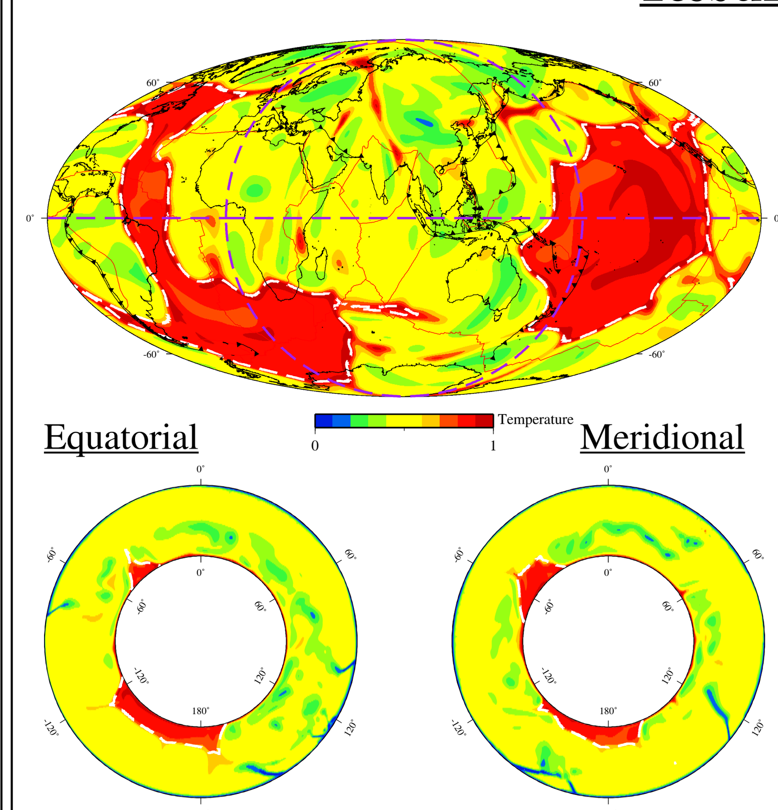


Figure 5. High bulk modulus structure model with lithosphere and slab assimilation. In this case the slab buoyancy is over-estimated. Ordinarily, slabs only have enough buoyancy to reach the uppermost lower mantle and do not influence the development of the LLSVPs.

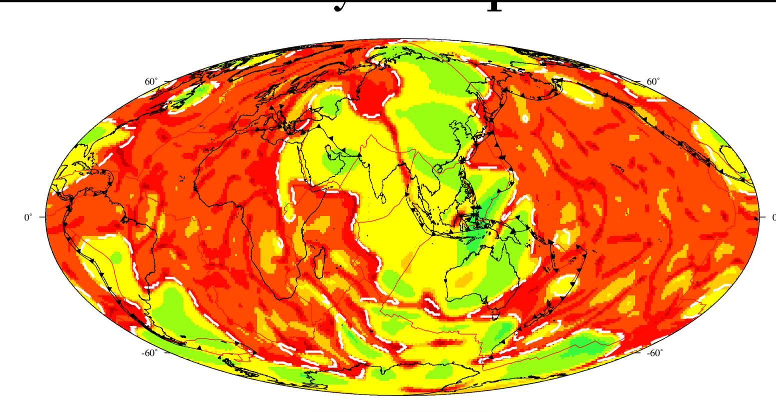


Figure 6. Boussinesq model without lithosphere and slab assimilation. Slab material in the deep Earth is notably less.

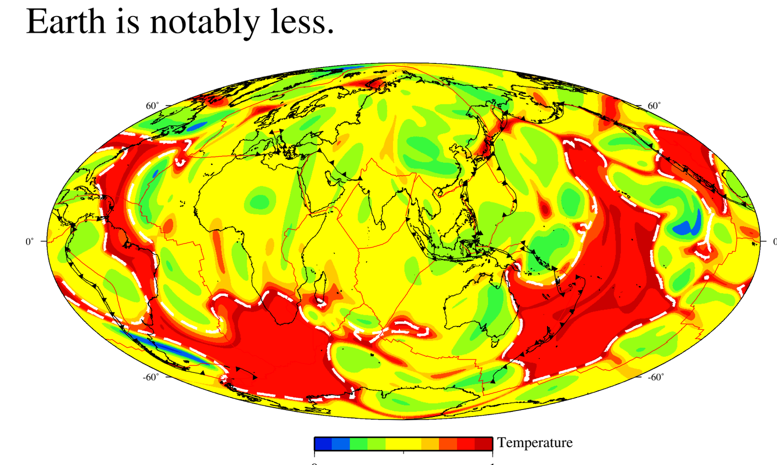


Figure 7. High bulk modulus structure model with slabs initially prescribed to the CMB.

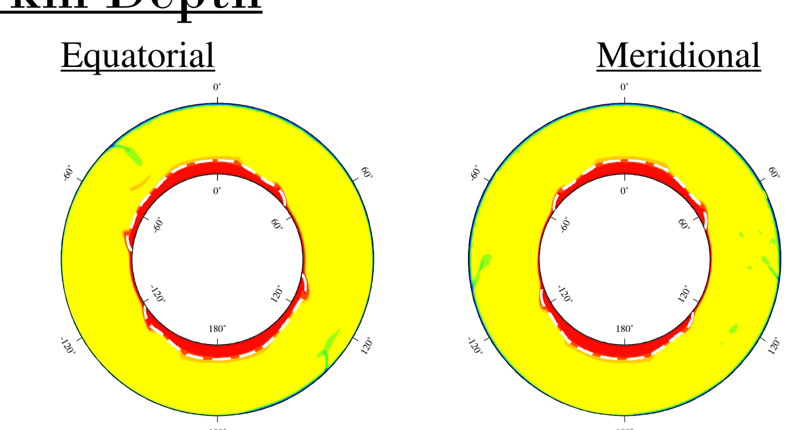


Figure 8. Slabs stall in the upper lower mantle because of the reduction in the thermal expansion coefficient with pressure. Additionally, the high bulk modulus structure is intrinsically too dense and fails to develop into a neutrally buoyant structure.

Next steps

1. Understand Tethyan subduction history and review the plate history model
2. Reduce change in thermal expansion coefficient across the mantle