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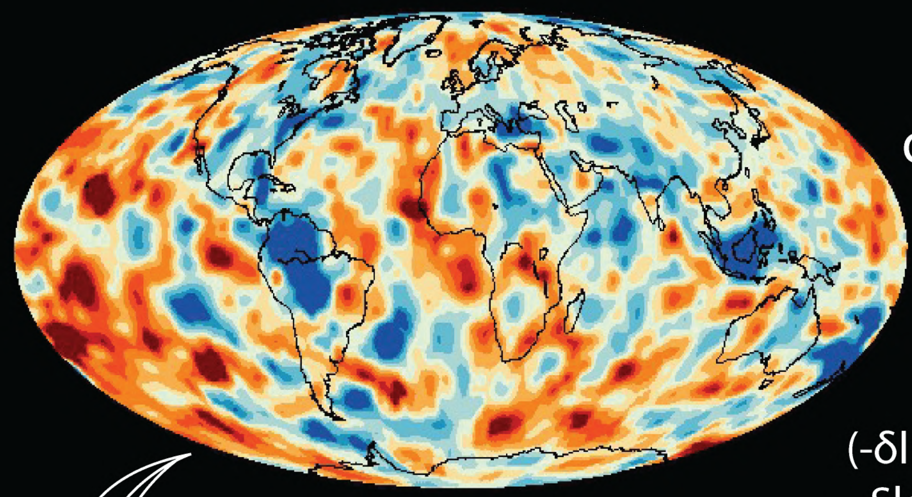
Ambient lower mantle structure and composition inferred from seismic tomography, convection models, and geochemistry

Grace E. Shephard, John Hernlund, Christine Houser, Reidar Trønnes, Fabio Crameri

What is the "ambient" mantle?

The Earth's lower mantle can be broadly divided into three domains based on amplitude and polarity of seismic wavespeed perturbations (i.e. %δlnVs, %δlnVp). These also correspond to different structural, thermo-chemical, and/or rheological regions:



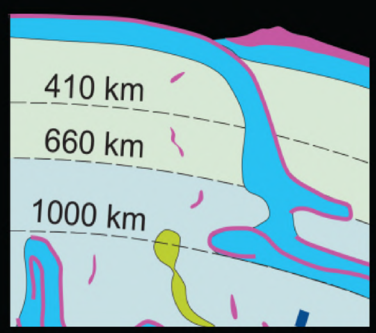
P-wave model (HMSL-P06; Houser et al., 2008) at 1000 km depth showing all anomalous wavespeed perturbations, and extracted fast and slow and ambient

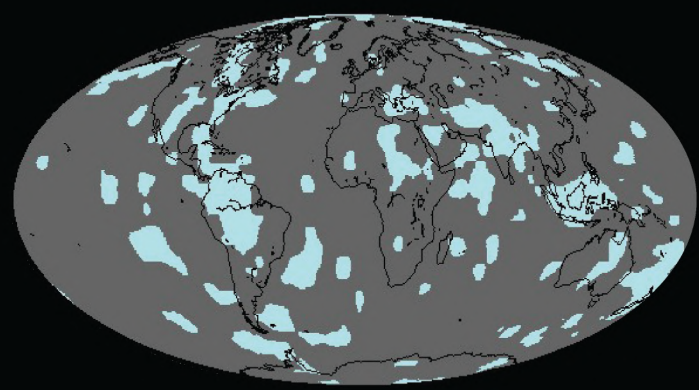
(-δlnV) Slow — 0 — (+δlnV) Fast

% or σ perturbation

1. HIGH (+δlnV)

Seismically "fast"
Denser, colder
Match palaeo-subduction
Subducted oceanic lithosphere

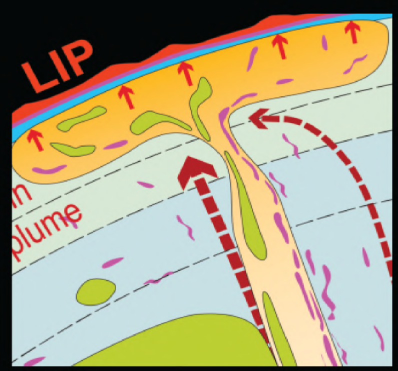


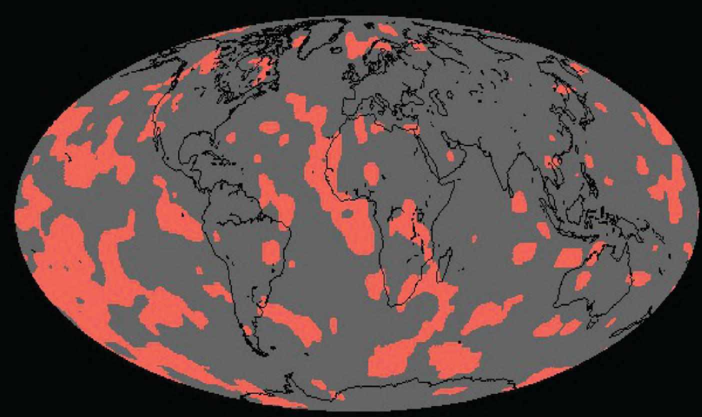


fast portion only

2. LOW (-δlnV)

Seismically "slow"
Less dense, warmer
Mantle plumes and LLSVPs

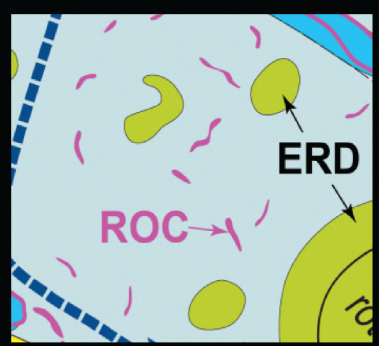


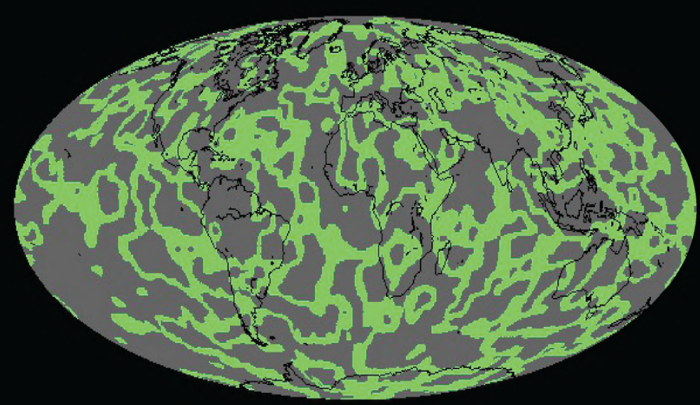


slow portion only

3. AVERAGE (±δlnV)
(or AMBIENT)

Seismically low amplitude
i.e. close to the reference model
(e.g. PREM, ak-135)





average portion only

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Are they primordial features?

We propose that these ambient domains (average velocity) may contain early refractory and bridgmantic mantle with elevated Si/(Mg+Fe) and Mg/Fe ratios. This may support the earlier proposed BEAMS model (bridgmanite-enriched ancient mantle structures; Ballmer et al., 2017).

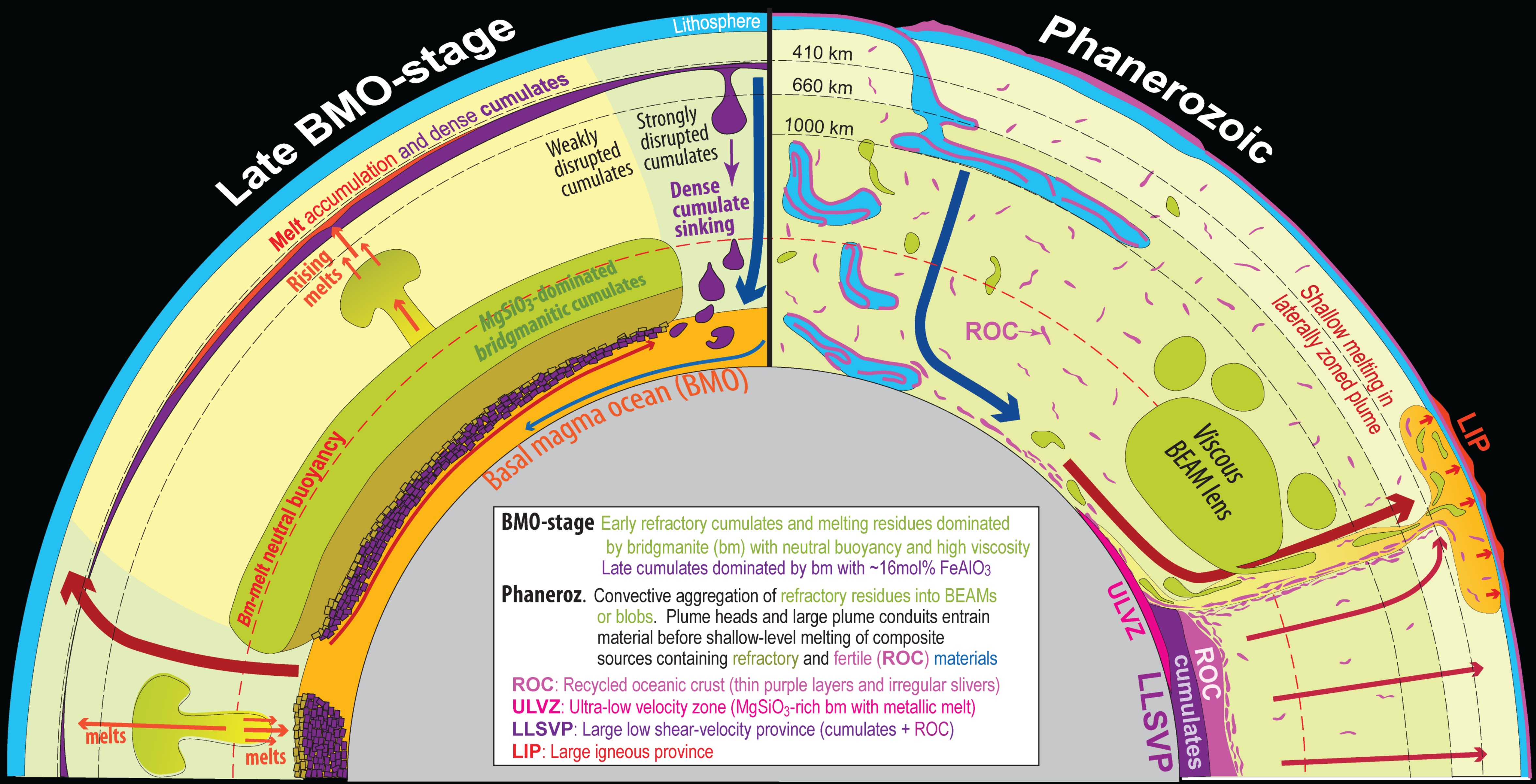

Image: Reidar Trønnes, adapted from Trønnes et al. 2019

These ambient domains could have formed by early basal magma ocean (BMO) fractionation during a period of core-BMO exchange of SiO2 (from core to BMO) and FeO (from BMO to core).

Despite its high viscosity, bridgmanitic material (possibly representing a primitive and refractory PREMA-type (prevalent mantle) reservoir with primordial-like He and Ne components), might be entrained in vigorous, deep-seated plumes.

In the upper mantle, such material will transform to less refractory pyroxenitic rocks, which can melt more easily.

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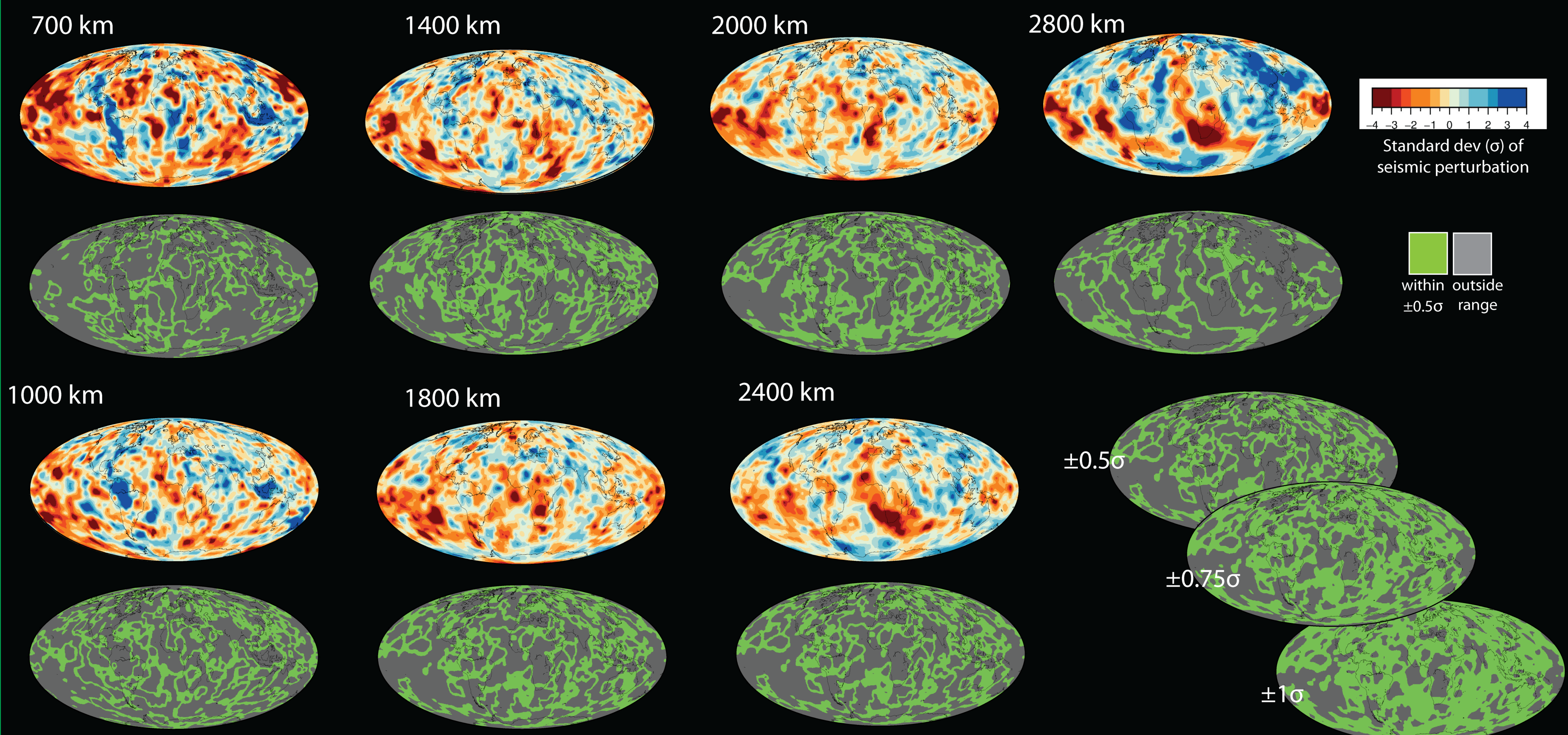
What does the ambient look like for a given tomography model?

Below is a comparison of the P-wave tomography model of HMSL-06 (Houser et al., 2008) at different lower mantle depths for the original model (top panels) and the extracted ambient mantle within 0.5± standard deviations (sigma) from the average i.e. the ambient portion (below panels).
Also compared in bottom right for alternative sigma thresholds (±0.5σ, ±0.75σ and ±1σ)



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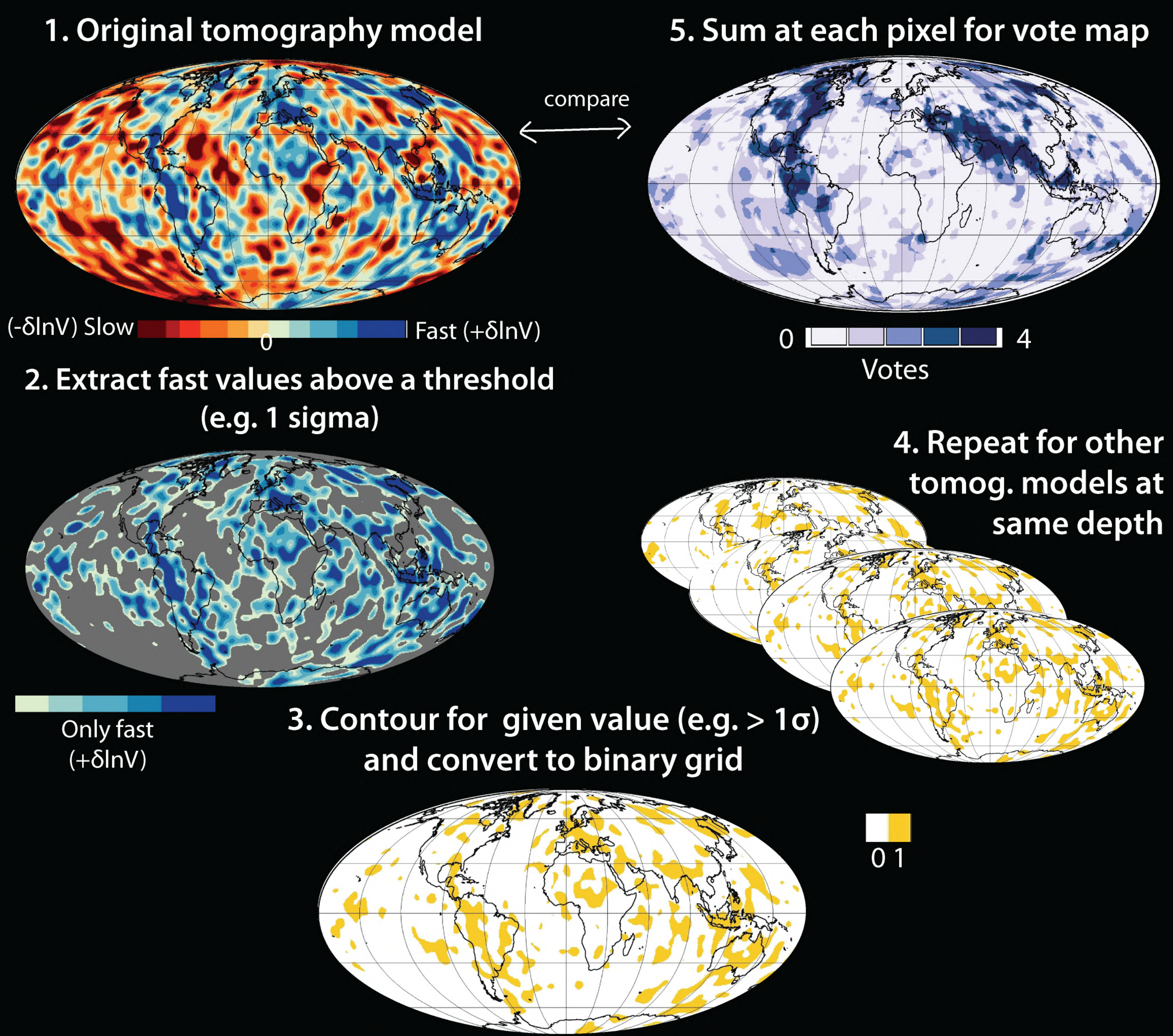
Which tomography model to choose?

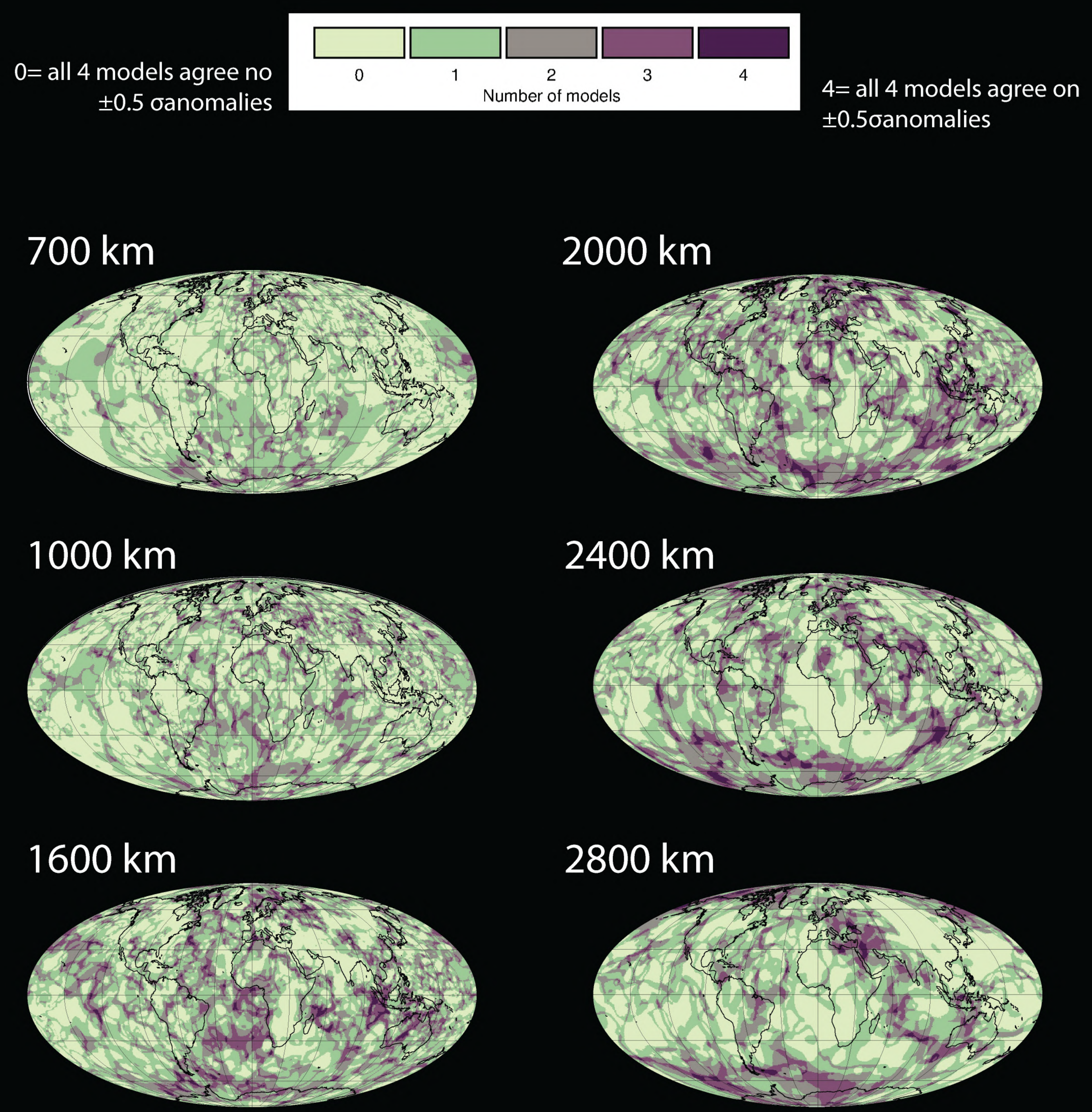
There exist numerous seismic tomography models; each image the Earth in slightly different ways. To quickly survey where different models agree, and therefore provide an insight into what are likely the most robust features, a "vote map" methodology can be used (e.g. Lekic et al., 2016; Shephard et al., 2017). <u>This method does not add anything new to the mantle structure - it just culls the features that differ between the models!</u>

Below is adapted from Shephard et al. (2017); the slabs are identified from the faster anomalies (e.g. >+1σ). This process can also be applied to slow or a selected range, such as the ambient domains.



What do 'ambient' vote maps look like?

Here are vote maps contoured for ±0.5 sigma for 4 P-wave models. A vote of 4 (darkest purple) means all models agree that there is a anomaly at this location of between ±0.5 sigma. Whereas 0 or low votes (greens) mean there are fast or slow anomalies that are outside this range i.e. slabs, plumes, or LLSVPs.



The 4 P-wave models included here:
DETOX; HMSL-P06; GAP-P4; MITP-2011. See reference list.

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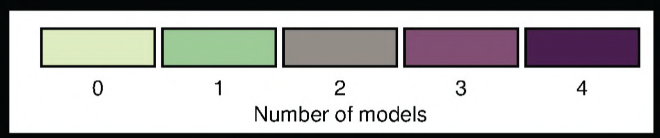
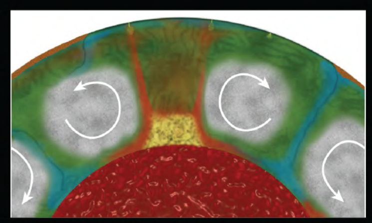
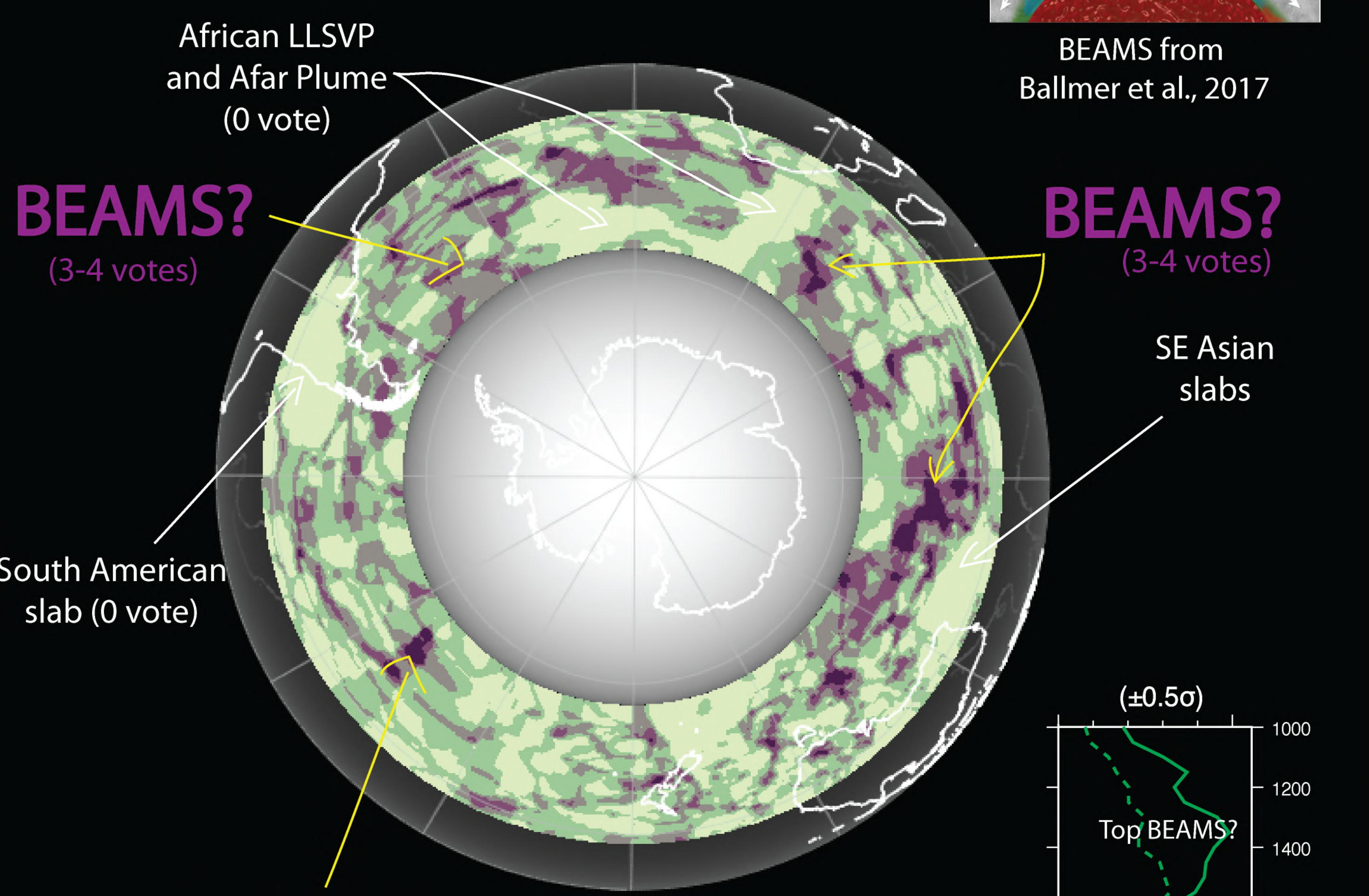
Any depth-dependent trends?

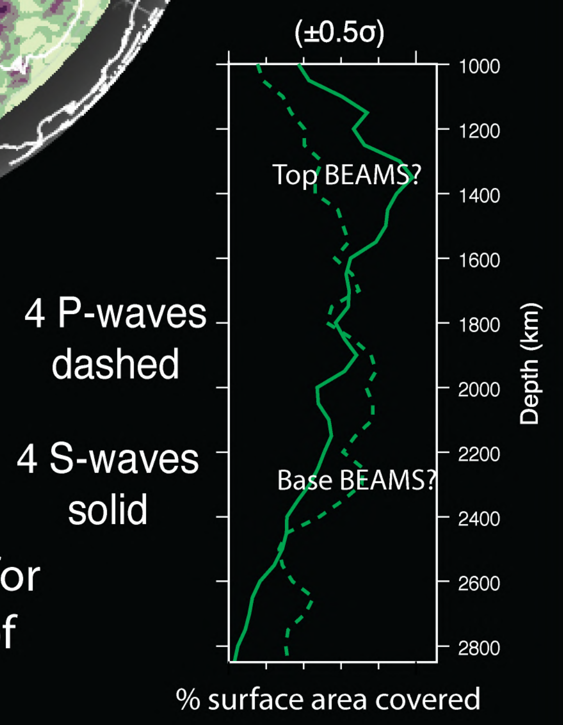
Below is a vertical section through the lower mantle around the equator as viewed from the South Pole. The purples are the "most" ambient domains according to the four models used here.





BEAMS from Ballmer et al., 2017





It is possible to sum up the percentage that each of the votes cover (4 votes to the right) for a given depth slice . This gives an indication of depth-dependent variations
(e.g. Shephard et al., 2017; Shephard et al., in submission).

Can we compare these to geodynamic models?

The high viscosity of bridgmanitic material will promote its convective aggregation, not be readily-mixed, and stabilise the large-scale, degree-2 convection pattern. The primordial features may also be neutrally buoyant in the mid lower-mantle. Models testing scenarios with high viscosity domains (thus resisting entrainment), and for long timescales including since BMO conditions, are under development (see also Gülcher et al., 2020).

Below are schematic StagYY models through an equitorial slice showing temperature (regional and global residual) and dynamic flow fields (e.g. Crameri, 2018) .

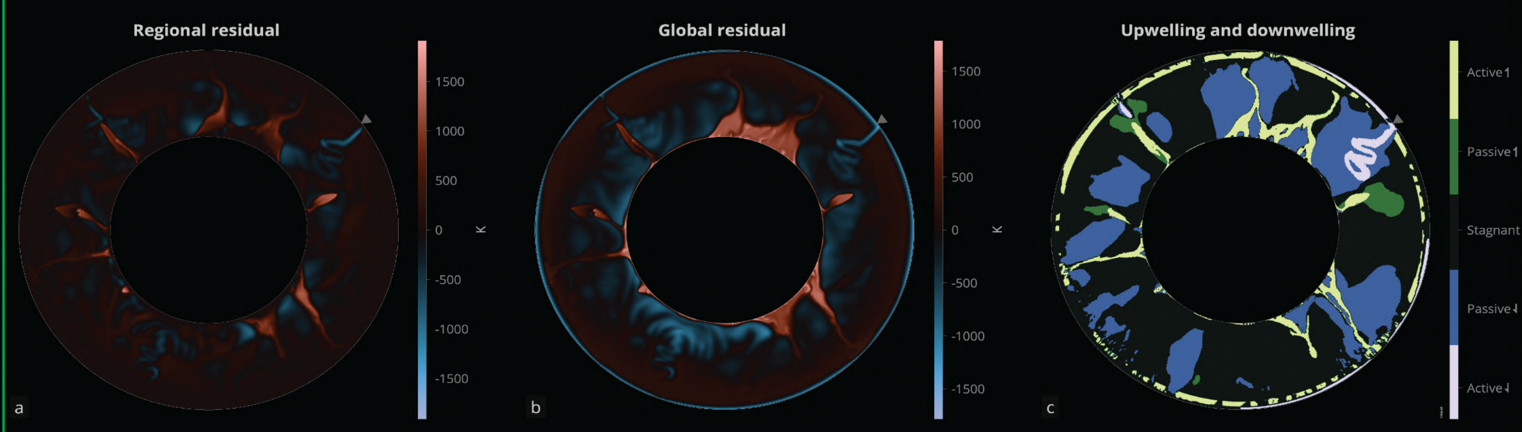


Image: Fabio Crameri/StagLab

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GAP-P4=Obayashi, M. et al. Finite frequency whole mantle P wave tomography: Improvement of subducted slab images. Geophys. Res. Lett. 40, 5652–5657 (2013).

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Trønnes, R.G et al. Core formation, mantle differentiation and core-mantle interaction within Earth and the terrestrial planets. Tectonophysics v.760 (2019)

Also check out: Hosseini et al. (2018)
www.earth.ox.ac.uk/~smachine/

SubMachine

Scientific Colour Maps

Crameri (2018)
www.fabiocrameri.ch/colourmaps

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