Mantle Thermochemical Variations beneath the Continental United States Through Petrologic Interpretation of Seismic Tomography

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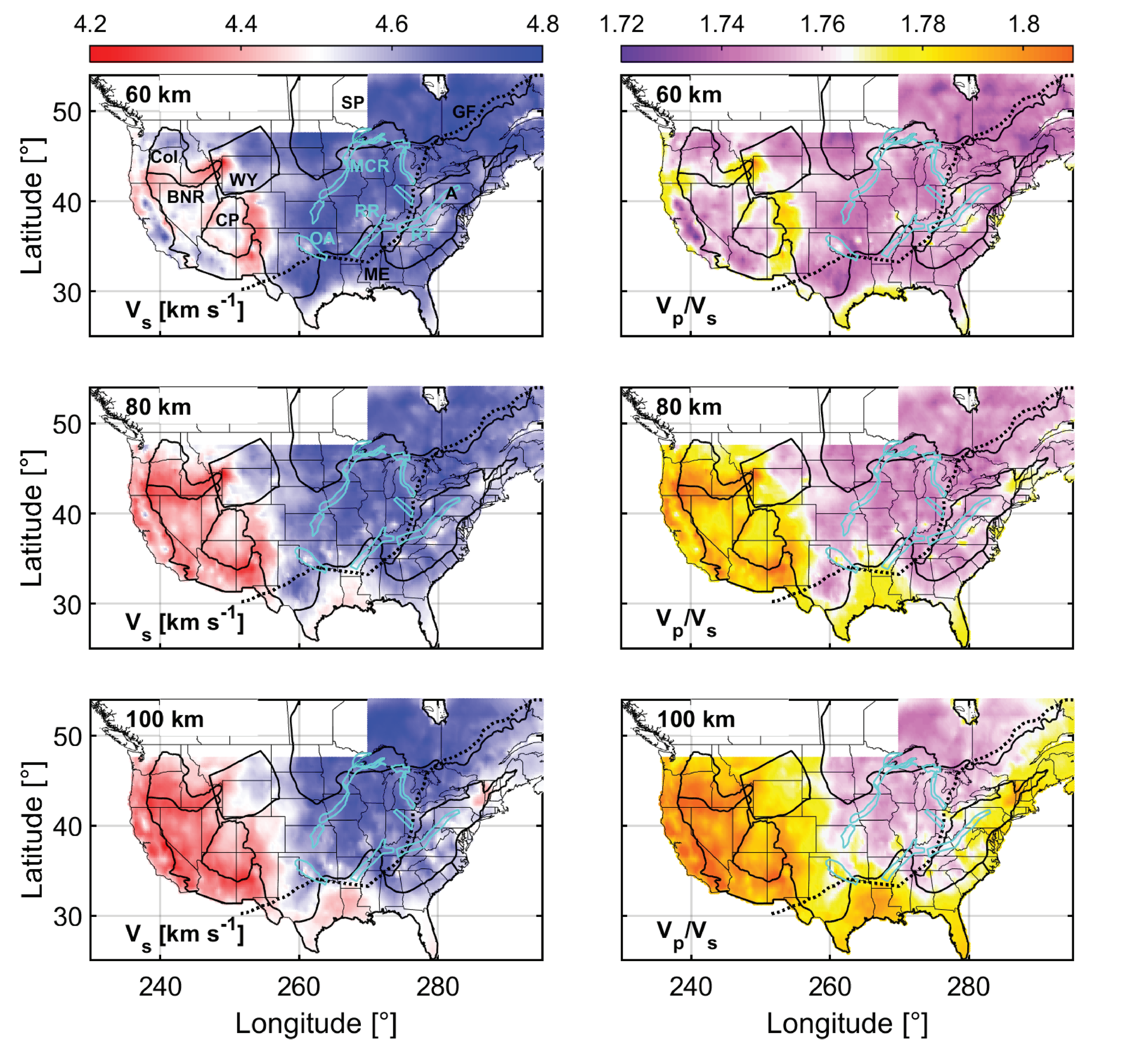
William J. Shinevar[1], Eva M. Golos[2], Oliver Jagoutz[3], Mark D. Behn[4], and Robert D. van der Hilst[3]

Overview:

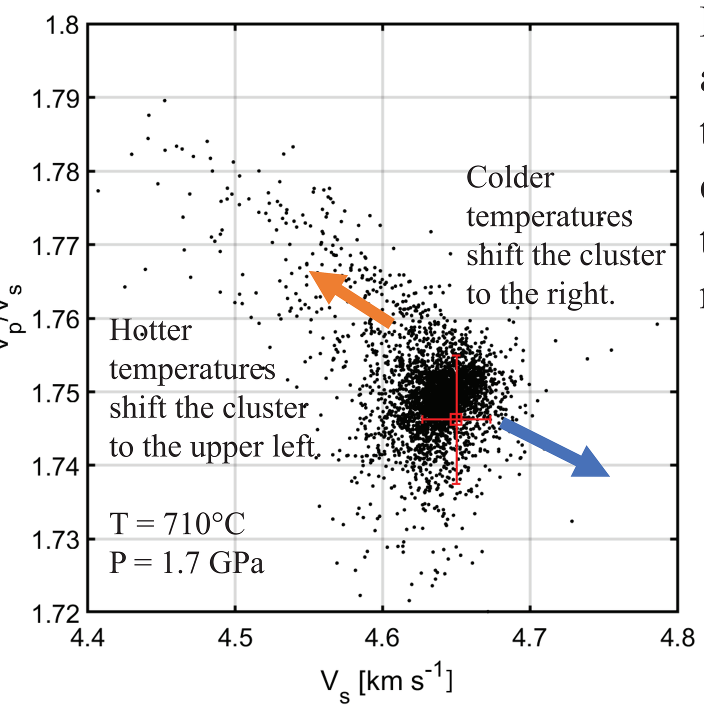
Understanding the thermomechanical state of the mantle beneath the continental United States is vital to understand the current mantle flow and force balance, as buoyancy forces drive plate tectonics. To estimate this state between 60 –100 km depth, we interpret a recent seismic tomographic model (MITPS_20, Golos et al. 2020, figure below) with forward model estimates of ultramafic seismic wave speeds (WISTFUL, Shinevar et al., in rev.).

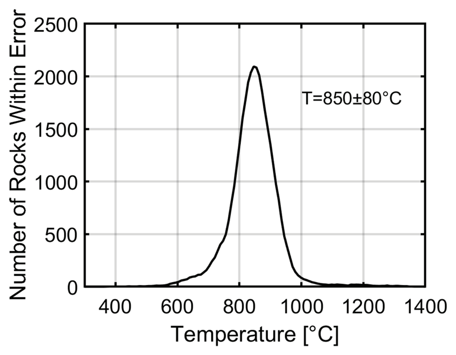


Black boundaries represent tectonic provinces (A: Appalachian Mountains, BNR: Basin and Range, Col: Columbia Plateau/Snake River Plain, CP: Colorado Plateau, SP: Superior Craton, WY: Wyoming Craton). The dotted line represents the Grenville Front (GF), and the blue boundaries represent rifted regions (MCR: Mid-Continent Rift, OA: Oklahoma Aulacogen, RR: Reelfoot Rift, RT: Rome Trough).

Methodology:

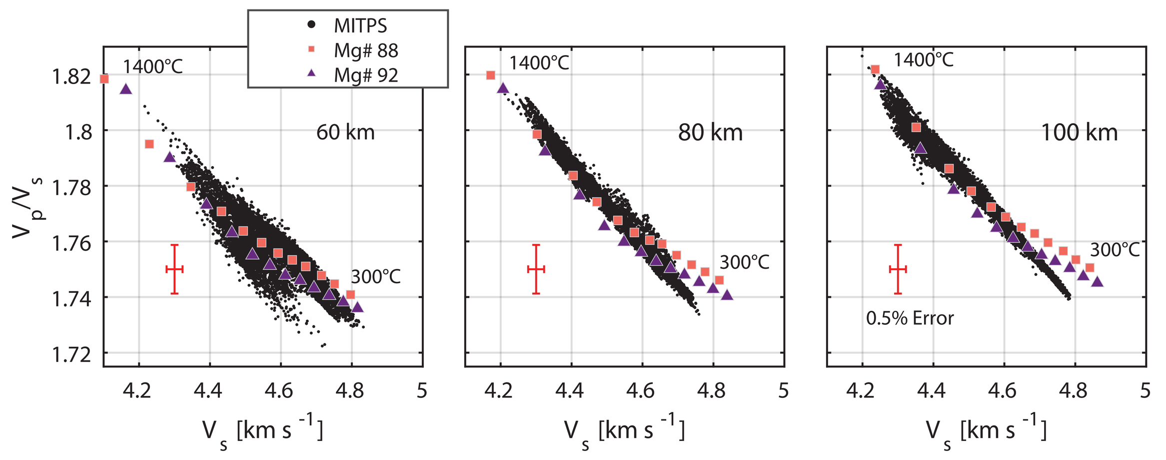
WISTFUL (Whole-rock Intperative Seismic Toolbox for Ultramafic Lithologies) incorporates an up-to-date integration of laboratory elastic moduli measurements with Perple_X (Connolly, 2009) using new thermodynamic solution models (Holland et al., 2018) chosen to best-fit mineral modes of well-studied mantle xenoliths. Here we use the Behn et al. (2009) power-law anelasticity model. The left figure shows estimates of wave speed for >4000 peridotite compositions. To calculate a best-fit temperature for a given wave speed (red square with 0.5% error), we count the number of compositions within the expected error at each temperature (right figure). Best-fit temperature is defined as the mean of the distribution, uncertainty is defined as the standard deviation.



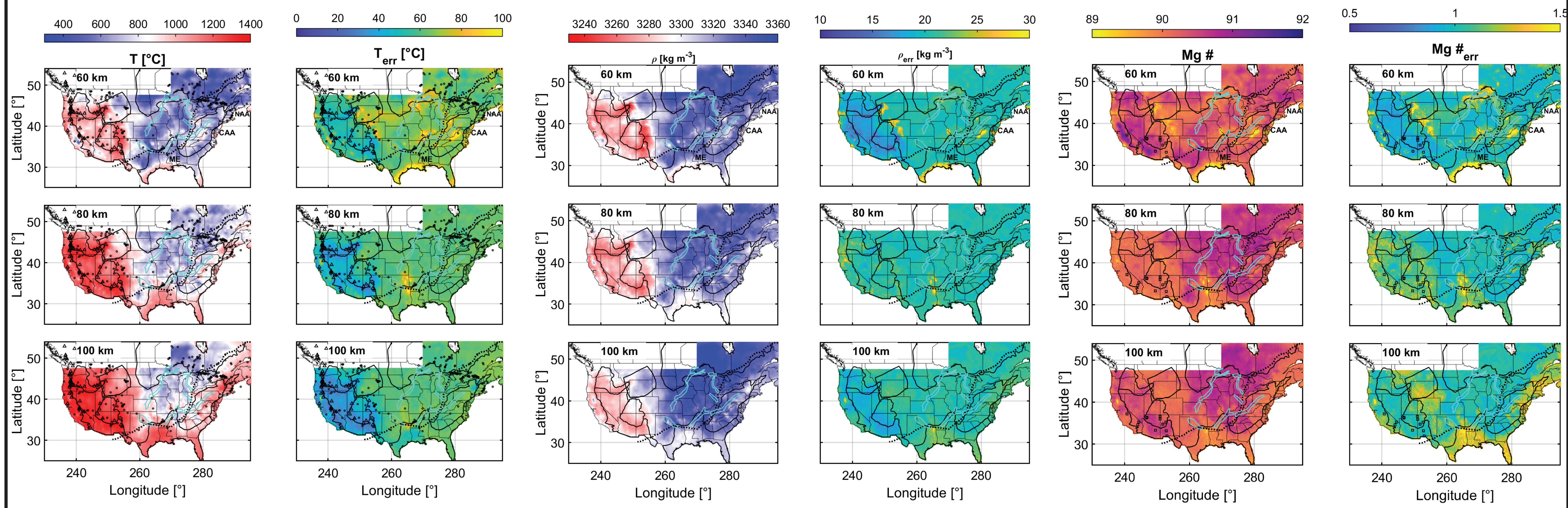


Best-fit composition/density and uncertainty is defined as the mean or std. of all acceptable rocks at the best-fit temperature weighted by misfit.

Below shows a schematic figure of the MITPS_20 wave speed values (black dots) compared with the average values of Mg # 88 (pink squares) and Mg #92 (purple triangles) from 300–1400°C.

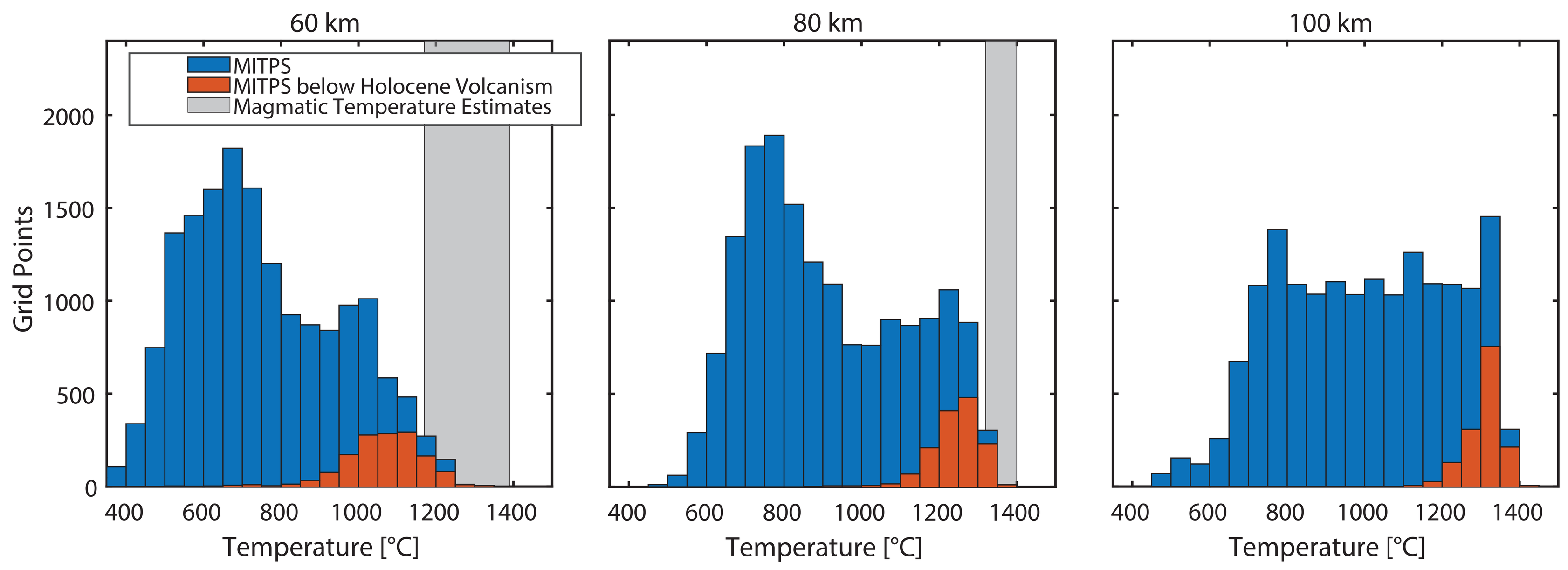


Results:



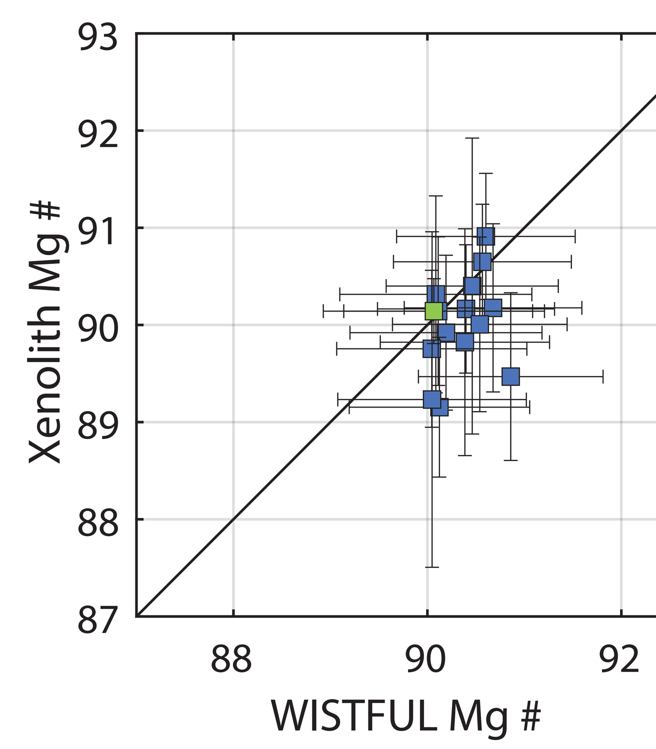
Above: Temperature, density, and Mg # with respective uncertainties. Geological outlines are the same as the seismic figure. Circles show locations of alkaline-carbonatite magmatism. Triangles show locations of Holocene volcanism (Venzke, 2013). Squares show location of young (<10 Ma) xenolith suites.

The mantle west of the Rocky Mountains is slightly more enriched (Mg# 89–90) than the cratonic mantle (Mg# 91–92). This difference causes a compositional density difference of ~20–30 kg m^{-3}. Still, the colder cratonic mantle is ~80 kg m^{-3} denser than the hotter mantle.

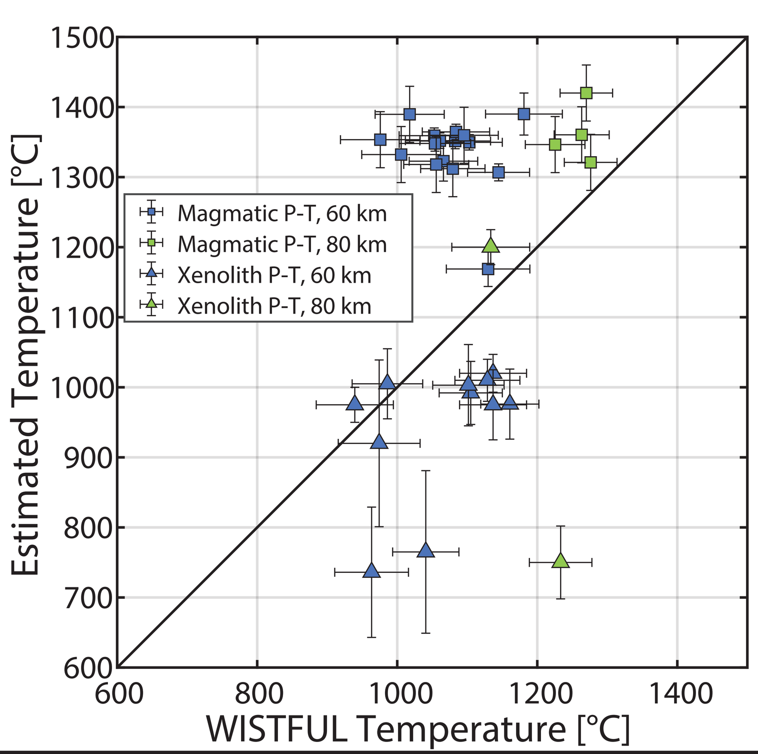


Left: Temperature results plotted as histograms for each depth (blue) with temperatures within 0.5° of Holocene volcanoes plotted in orange. Temperature variations of 800–900°C exist between the cratonic US and the mantle west of the Rocky Mountains.

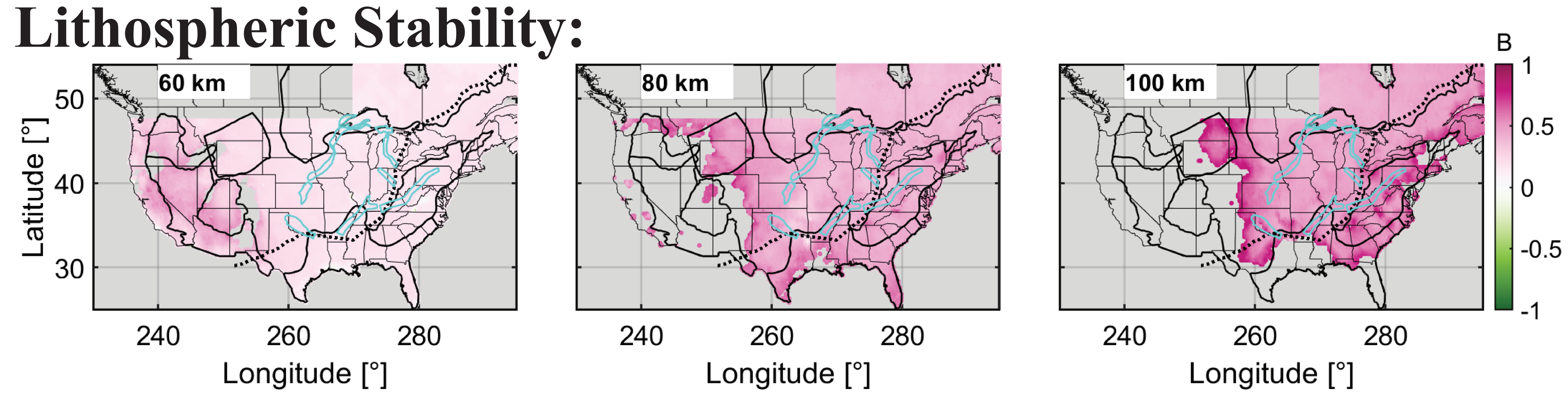
Comparison with Geology:



Our results predict young (<10 Ma) xenolith compositions well (figure above) and spinel xenolith thermometry (triangles below), but underpredict primary magma thermobarometry (squares below), likely due to difference in measurement scale.

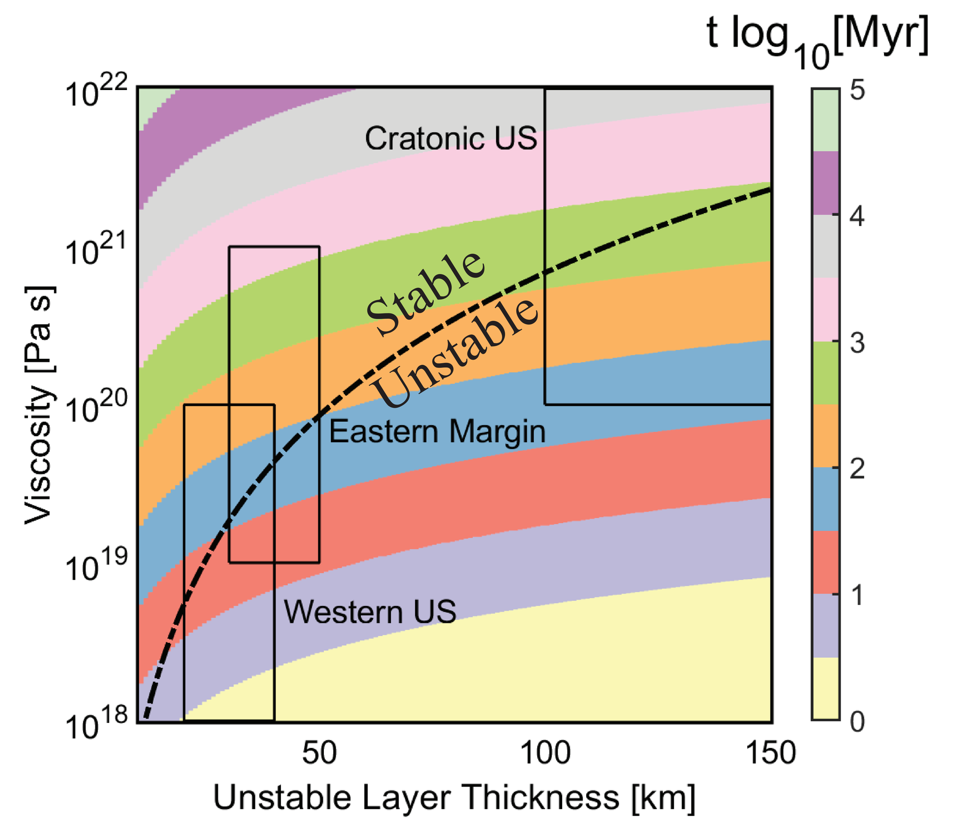


Lithospheric Stability:



Above: The buoyancy number, B, the ratio of the compositional and thermal buoyancies compared to an idealized mantle composition (DMM), $\frac{\Delta\rho_c}{\Delta\rho_T}$. A B value of 0 implies no compositional buoyancy. A B value of 1 implies that the compositional and thermal effects are equal (the isopycnic hypothesis). We estimate B~0.4 for mantle beneath the continental US.

Below: Instability periods and stability regimes using Rayleigh-Taylor instability analysis (Jaupart et al., 2007). Black boxes estimate the unstable layer thicknesses (ductile, T>800°C, to LAB) for the western US, eastern margin, and cratonic US. If unstable, the lithosphere is predicted to undergo oscillatory convection, the alternation between cooling, densifying, and sinking of a chemically buoyant layer with reheating and rising once the layer has reheated.



Conclusions:

1. Cratonic mantle beneath the continental US is significantly colder than the mantle to the west of the Rocky Mountains (temperature variations of 800–900°C).
2. Due to these variations, the cratonic mantle is ~80 kg m^{-3} denser than mantle beneath the western US despite roughly ~20 kg m^{-3} compositional buoyancy.
3. Using Rayleigh-Taylor instability analysis predicts that if the mantle is on the lower end of viscosity estimates, oscillatory convection would occur on timescales of 1–100 Myr for the western US, 10–100 Myr for the eastern US, and 100–1000 Myr for cratonic regions.