Reconciling seismic and thermo-chemical models of cratonic lithosphere

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Abstract

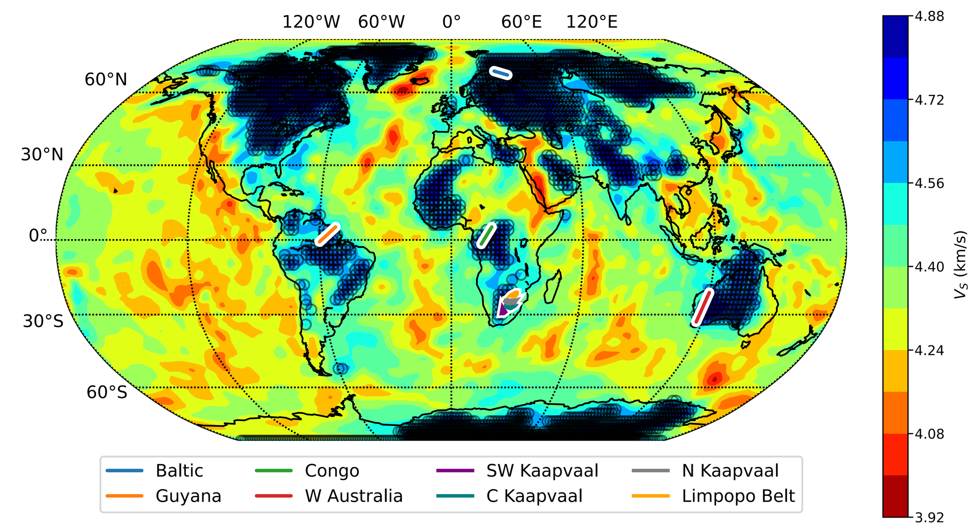
Most published shear-wave (V_S) velocity models of cratons include a V_S increase with depth below the Moho, with a maximum at 100-150 km depth. This feature is seen in regional and global 3D tomography models and in regional 1D V_S profiles. Taken at face value, it implies an oscillatory geotherm, with a ubiquitous temperature decrease below the Moho, which is implausible. The V_S increase with depth has thus been attributed to strong compositional layering in the lithosphere. One recent model postulated widespread hydration and metasomatism in the uppermost cratonic mantle, decreasing V_S just below the Moho. An alternative model suggested a strong enrichment of the lower cratonic lithosphere in eclogite and diamond, increasing V_S but implying an unusual lithospheric composition.

Here, we assemble a representative dataset of phase-velocity curves of Rayleigh and Love surface waves for cratons globally, including the all-craton averages, averages over regions in southern Africa, and interstation measurements elsewhere. We perform both thermodynamic and purely seismic inversions and show that the sub-Moho V_S increase is not required by the data. Models with equilibrium, conductive lithospheric geotherms and ordinary, depleted-peridotite compositions fit the surface-wave data fully. A model-space mapping quantifies the strong trade-off between seismic velocities just below the Moho and at 100-150 km depth, which is the cause of the ambiguity. The reason why most seismic models contain a V_S increase with depth below the Moho is regularization that penalizes deviations from global average reference models, which are much slower than cratonic V_S profiles.

Data and Background

We define our cratons as the fastest region from the six clusters produced by K-means clustering analysis of velocity profiles from tomographic model SL2013sv. The borders of our identified cratons correspond well to those identified using other methods, such as lithospheric thickness or the presence of Archaean basement rock.

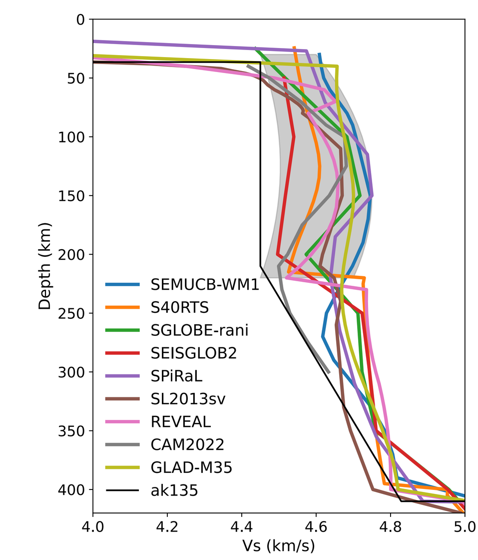
We invert a global average set of dispersion curves across all cratonic nodes in our regionalisation, as well as interstation dispersion curves across four cratons, and regionally averaged dispersion curves for four sub-regions of the Kalahari craton.



Regionalisation from Schaeffer & Lebedev (2015); background model SL2013sv (Schaeffer & Lebedev, 2013)

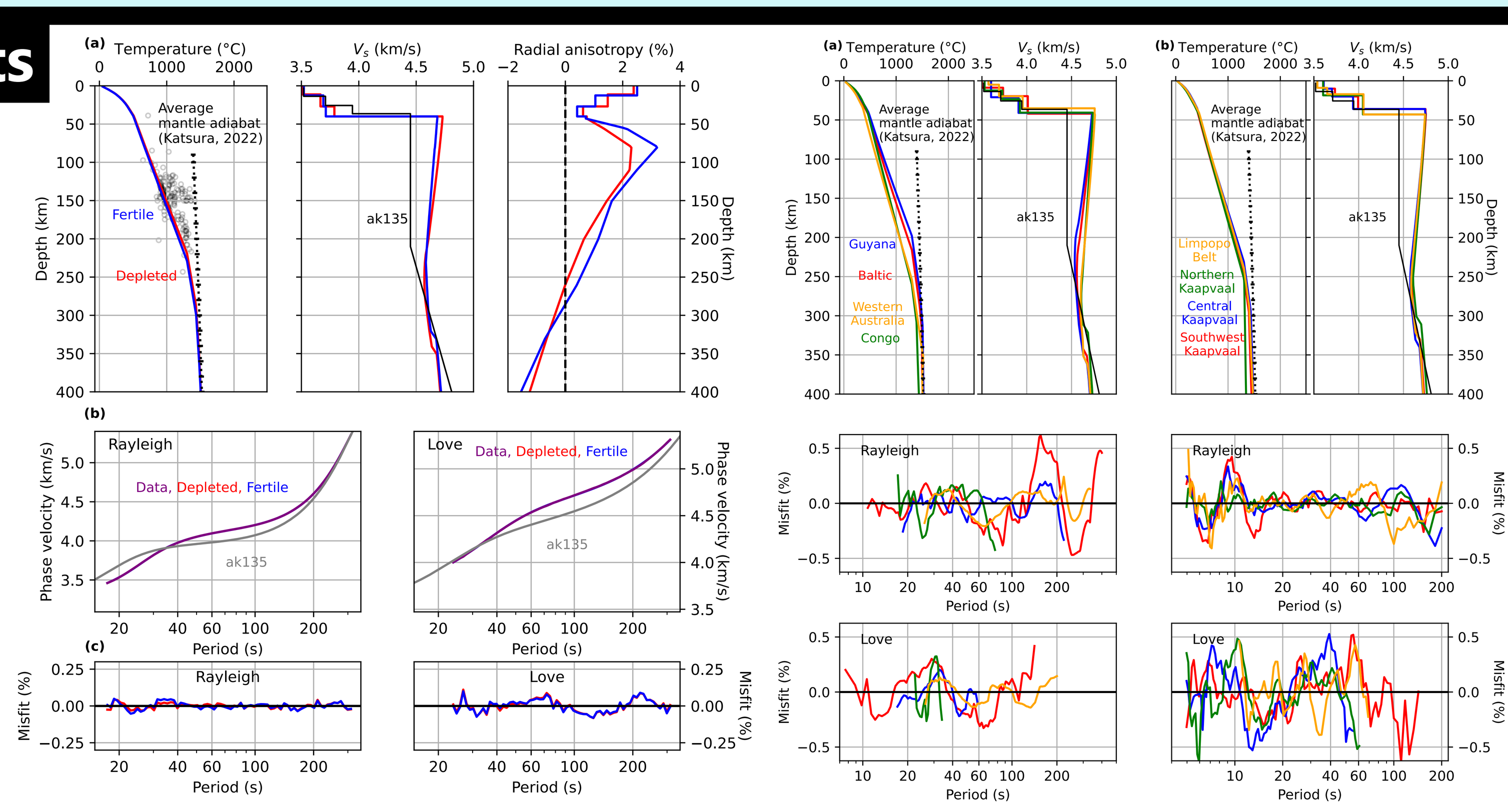
Prior tomographic models, produced using a wide range of techiques, consistently show a velocity maximum at around 150 km depth, entirely within the lithosphere, shown here in the average 1D velocity profiles from each model through the same regionalisation we use to define cratons. This would require temperature to decrease, or layered compositional variation to exist, pervasively across cratons.

As these models span a range of different treatments of anisotropy, crustal structure, and forward calculation methods, either, as previously interpreted, this velocity increase must reflect real, and unusual, structure, or, as we identify, it can be produced due to a bias common across all these methods.



Inversion and Results

- Composition (weight % of Mg, Fe, Ca, Al, Si oxides) + temperature
- Equilibrium geotherm calculated, factoring in stratified radiogenic heat production in the crust
- Phase equilibria computed at each depth from temperature and pressure (W. Xu et al., 2008)
- Elastic parameters calculated for those equilibria and conditions with Perple_X (Connolly, 2011)
- Those elastic parameters taken together with attenuation to produce V_P, V_{SV}, and V_{SH} profiles
- Phase velocity dispersion curves calculated from those, and their fit to data minimised in inversion.



We invert directly for composition and temperature with depth, following the methodology of Fullea et al. (2021), updated by Y. Xu et al. (2023).

Both globally and regionally, direct inversion for temperature and composition produces models without this bump. Where regional dispersion data was limited to <100 s maximum period, velocity profiles have been truncated at 250 km depth.

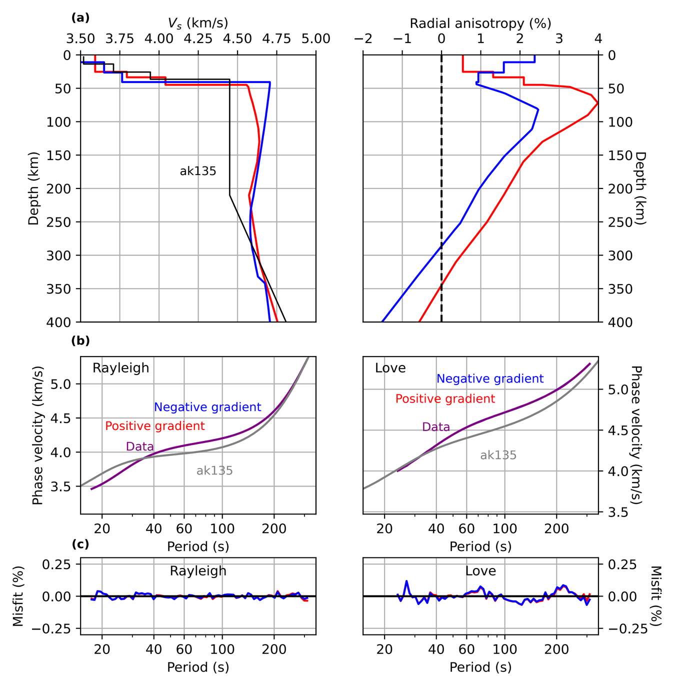
The fit to data is as good or better compared to fits from purely seismic inversions.

Why the Bump?

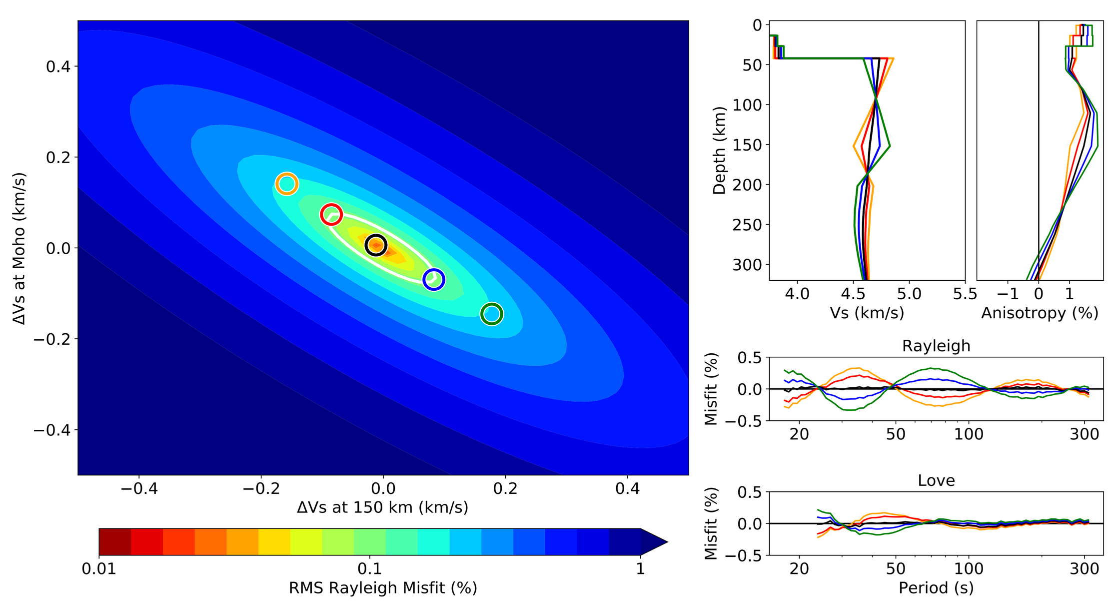
Seismic inversions can produce the same result as our thermodynamic inversion, given the right choice of background model. Models which more closely fit a cratonic average velocity, such as our output model, a smoothed version of SL2013sv, or ak135 with the lithosphere made 350 m/s faster all produce models without the bump.

Models made using a faster background model do lack the bump, including TX2011, TX2019slab, and GyPSuM.

The two possibilities - bump and no bump - can both fit the data within 0.1% misfit at all periods for a global average dataset.



In model space, average velocity from the sub-Moho to 150 km is well constrained, but the two trade off strongly.



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