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Transdimensional seismic tomography of the inner core using body wave and normal mode data

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The Inner Core

The inner core is seismically anisotropic, with seismic P-waves travelling faster in a north-south direction (Polar) than in an east-west direction (Equatorial). We distinguish between polar and equatorial data with the angle, ζ, between a raypath and Earth's axis of rotation (see Figure 1).

We want to image anisotropy as it can inform us on the orientation of the iron crystals responsible for the anisotropy and provide invaluable insight into inner core dynamics and structure.

To achieve this we use both seismic body waves (see Figure 2) and normal modes to produce models of inner core elastic structure and utilise a Bayesian methodology to recover the uncertainties in these elastic parameters. The body waves constrain P-wave anisotropy while the normal modes are in principle also sensitive to S-wave anisotropy.

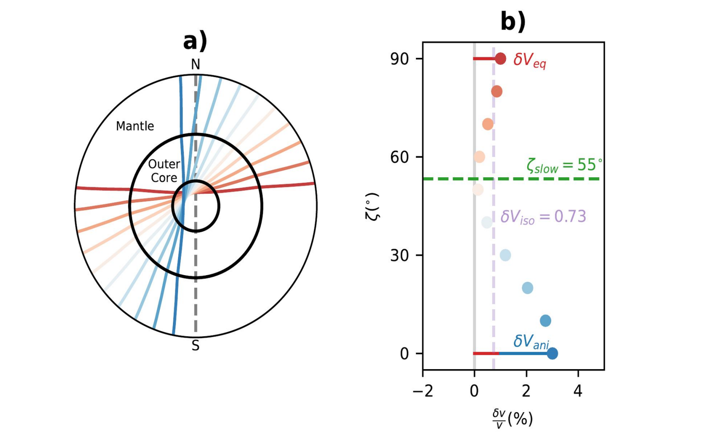

Figure 1. Left: Example raypaths travelling through the Earth, with colours corresponding to the angle ζ. Right:A typical anisotropy curve; with the four model parameters we are most interested in; δV_{ani}, δV_{ani}, δV_{ani}, and ζ_{slow}

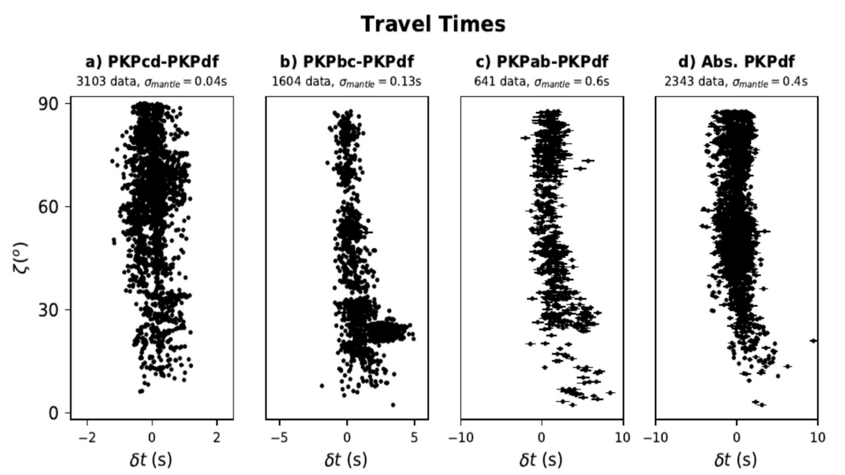

Figure 2. Our body wave dataset, showing the differential travel time of individual raypaths relative to their angle ζ for each type of differential travel time.

3D Transdimensional Seismic Tomography with Body Waves

We conduct 3D transdimensional seismic tomography using our body wave data. Transdimensional Markov Chain Monte Carlo (MCMC) is a Bayesian method where many millions of models are created which are each a small perturbation on a previous model. Most importantly, in a transdimensional inversion, the parameterisation of the model space is a part of the inversion. Effectively the data defines how to parameterise itself with a given basis function (in our case Voronoi Cells). We ran 20 chains for 4,000,000 iterations resulting in a collection of 533,380 models.

From these models we calculate the mean and standard deviations of compressional equatorial velocity (δV_{eq}, velocity of raypaths at ζ=90°), anisotropy (δV_{ani}, the difference between raypaths with ζ=0° and ζ=90°) the isotropic velocity (δV_{iso}, the average velocity across all ζ) and the angle of slowest direction (ζ_{slow}) (see Figure 1). With this methodology and dataset we are able to resolve features in the inner core in greater detail than before and constrain their uncertainties.

Main Findings:

1. **Strong anisotropy is isolated to a zone within the western hemisphere. The anisotropy is strongest north of the equator and weakens to virtually no anisotropy near the south pole (Figure 3e & Figure 4).**
2. **The inner most inner core (IMIC with ζ_{slow} = 55° ± 16°) is located primarily in the eastern hemisphere at a radius less than 700 km with a centre offset from the centre of the inner core by 400 km (Figure 3g).**
3. **Equatorial and isotropic velocity anomalies are separated into two hemispheres, with a slow western hemisphere and a fast eastern hemisphere in the top 60-170 km of the inner core (Figure 3a).**

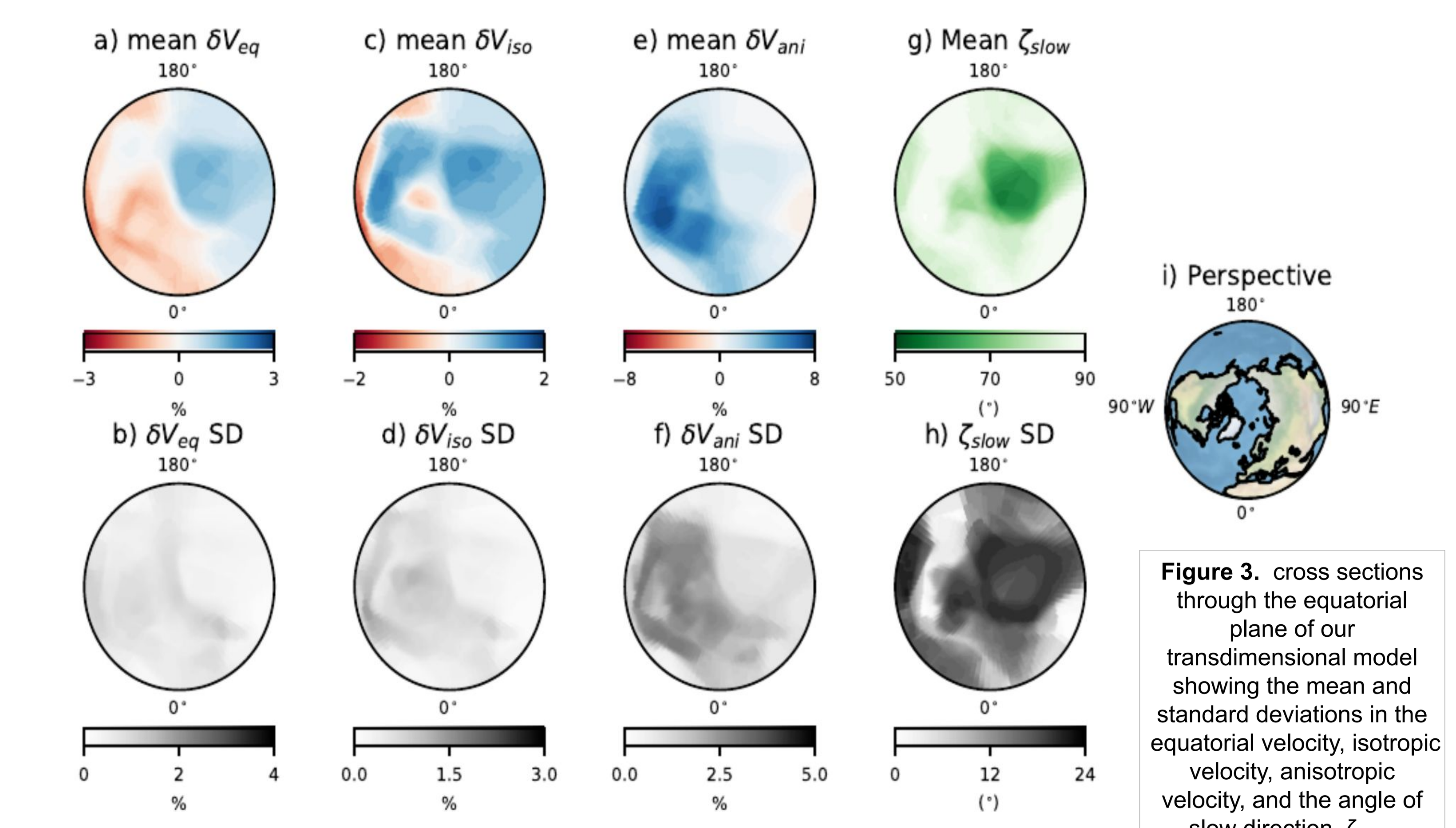

Figure 3. cross sections through the equatorial plane of our transdimensional model showing the mean and standard deviations in the equatorial velocity, isotropic velocity, anisotropic velocity, and the angle of slow direction, ζ_{slow}.

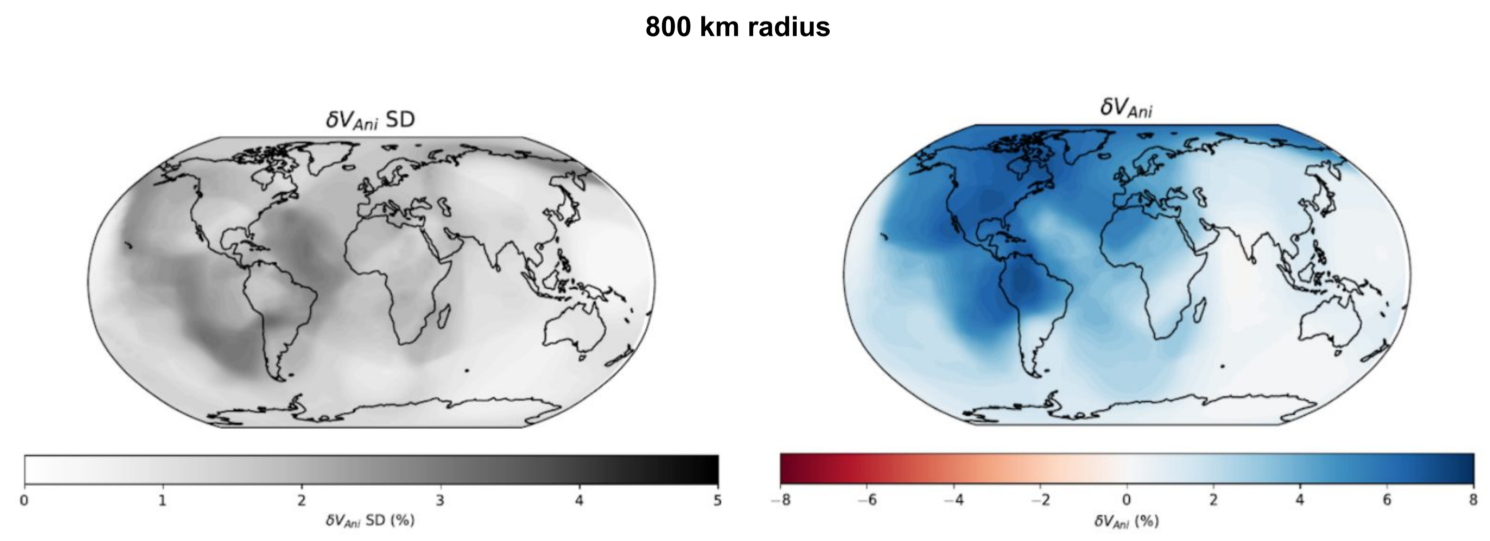

Figure 4. Right: a map of the anisotropy and its uncertainty at 800 km radius

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Earth and Planetary Science Letters, 2022

Measuring Inner Core Sensitive Normal Modes

Normal modes are whole Earth oscillations, which we observe by looking at the frequency spectra of days long seismograms. Modes are sensitive to 3D variations in velocity, anisotropy, density and attenuation (alongside rotation and ellipticity) and since Woodhouse et al. (1986) anomalous splitting has been observed for inner core sensitive modes. This splitting is most obvious when looking at the c_{20} and c_{40} spherical harmonic parameters, which for inner core sensitive modes are anomalously large. This is significant as this strongly suggests some form of cylindrical anisotropy with the symmetry axis approximately parallel to Earth's axis of rotation, in broad agreement with the body waves.

However, measuring normal modes is a complicated task and it has also been observed that when measuring inner core sensitive normal modes using a splitting function approximation the final measurement depends on the starting values of c_{20} and c_{40} used to measure the modes (Megnin and Romanowicz 1995, Durek and Romanowicz 1999). To overcome this we conduct a grid search for 18 self coupled splitting functions with an up to date catalogue of spectra, starting many thousands of measurements from different values of c_{20} and c_{40} (Figure 5).

From these grid searches we find both the best fitting measurement to the spectra and estimate the uncertainty of that measurement (Figure 6), which we will then use later when modelling inner core anisotropy.

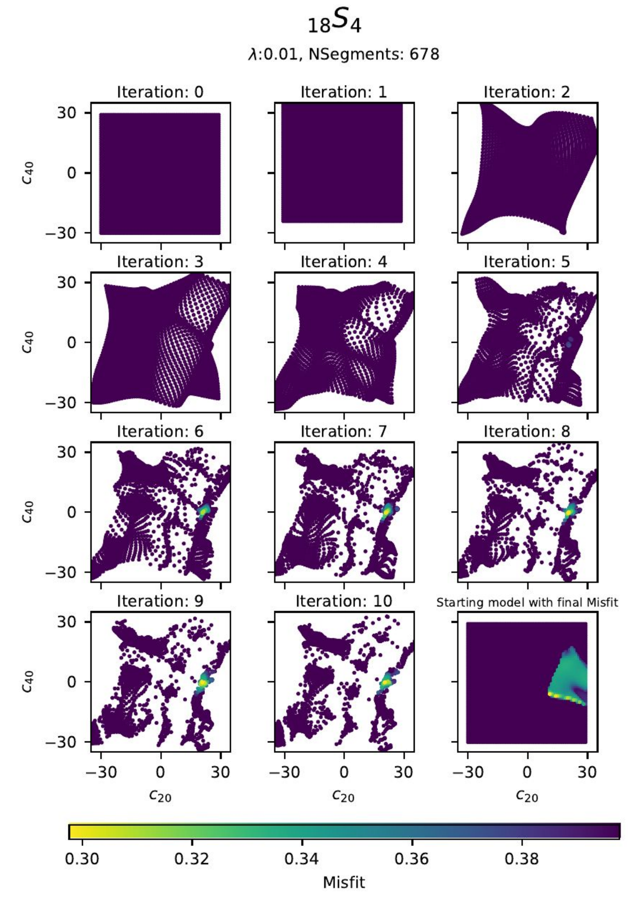

Figure 5. c_{20} and c_{40} values and their corresponding misfit for mode $_{18}S_4$ where each point is the c_{20} and c_{40} combination found in a splitting function measurement for 10 iterations. The colour shows the misfit.

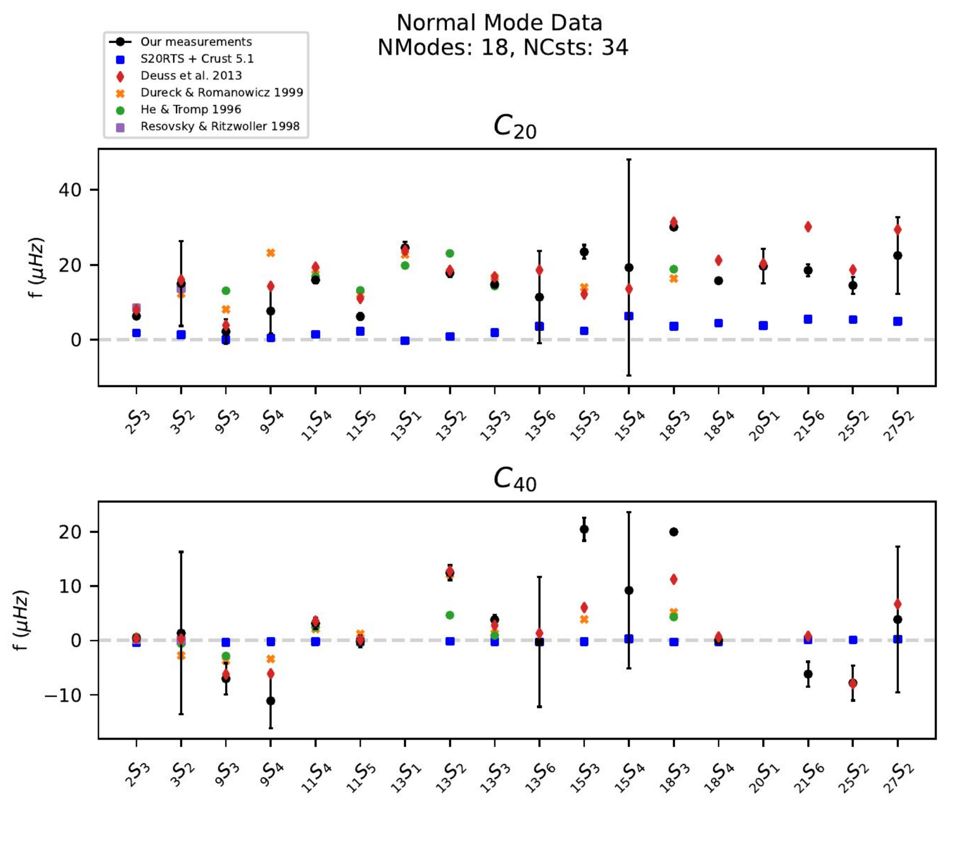

Figure 6. Our measured c_{20} and c_{40} values compared to previous measurements and predictions from S20RTS and Crust 5.0

3D Transdimensional Seismic Tomography with Body Waves & Normal Modes (Preliminary)

Incorporating normal mode and body wave data in a single tomographic model is an interesting inverse problem as the normal modes and body waves have overlapping but different sensitivity to inner core seismic structure. The body waves provide us with regional 3D sensitivity to P-wave anisotropy, while the normal modes provide information on 1D S-wave and P-wave anisotropy. The challenge is in extracting as much information from both types of data without introducing too much null space or trade-offs.

We run a 3D transdimensional inversion with Voronoi cell basis functions for 1,000,000 iterations solving for P-wave anisotropy, and P-wave velocity in the Equatorial direction using our body wave dataset and a subset of 13 of our splitting functions. We assume cylindrical anisotropy with the fast direction parallel to Earth's axis of rotation and we use a 1D background S-wave anisotropy model to reduce trade-offs. With these assumptions we can fit both data types, reducing misfit by 45% in both the body waves and the normal modes. In future work we wish to incorporate more modes and move away from the assumption of a fixed anisotropy symmetry axis and a constant S-wave anisotropy model.

This is the first time that normal modes and body waves have been combined in a transdimensional inversion. Our preliminary model has similar P-wave velocity anomalies as our body wave only model (Figure 7). We find a fast eastern hemisphere and slow western hemisphere in the upper inner core, with an anisotropic zone isolated in the northern hemisphere in the west, starting at ~100 km below the ICB. There is also a region with a particularly strong ζ_{slow} anomaly in the east of the inner core, but it is not consistently located near the centre of the inner core. This anomaly requires further study. Our model is only preliminary, but we are confident that with the right approach it should be possible to reconcile the two ζ_{slow} anomalies as seen by the body wave and normal mode data.

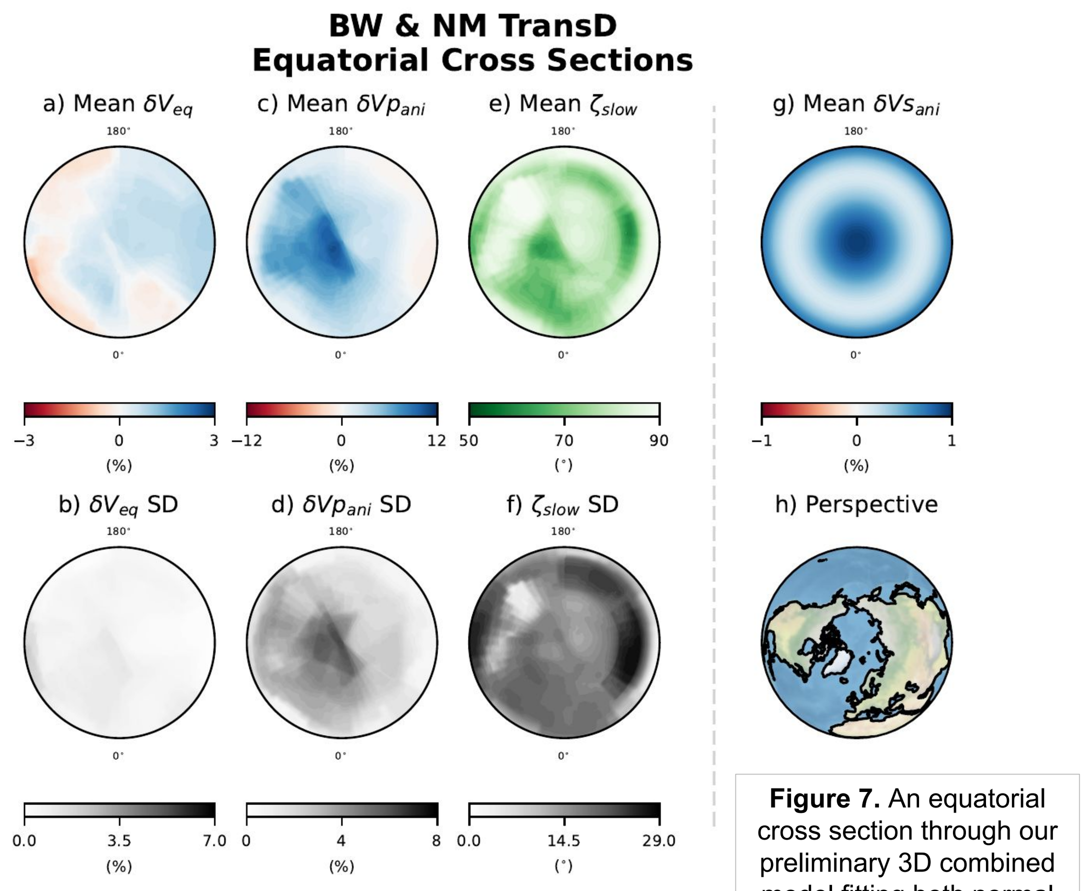

Figure 7. An equatorial cross section through our preliminary 3D combined model fitting both normal modes and body wave data

Acknowledgements and References

This research was supported by the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation programme (grant agreement No 681535 - ATUNE) and a Vici award number 016.160.310/526 from the Netherlands organization for scientific research (NWO). LW acknowledges support from a Discovery Early Career Research Award (project number DE170100329), funded by the Australian Government. We thank the International Federation of Digital Seismograph Networks (FDSN) who stored and provided the data. Data processing was done using the Obspy and Scipy python packages while the code to conduct the inversion was written in the Julia programming language using multiple external libraries, the most important being `QHULL' written by Barber, C.B, Dobkin, D.P., and Huhdanpaa, H.T.

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