Optimal seismological proxies for phase transitions in the mantle

Primary supervisor:	Prof Paula Koelemeijer: https://users.earth.ox.ac.uk/~univ4152
Co supervisor(s):	Prof Hauke Marquardt: https://www.earth.ox.ac.uk/people/hauke-marquardt Prof Andrew Walker: https://www.earth.ox.ac.uk/people/andrew-walker
Key words:	Deep Earth, Data Science, Seismology, Mineral physics, Phase transitions
Research theme(s):	• Geophysics and Geodynamics • Planetary Evolution and Materials
Eligible courses for this project:	• MSc by Research in Earth Sciences (2-3 years) • DPhil in Earth Sciences (3-4 years) • Interdisciplinary Life and Environmental Science Landscape Award (ILESLA) • Intelligent Earth (UKRI CDT)

Overview

Earth's mid mantle appears unremarkable at first, but in fact conceals significant changes in mineralogy and viscosity that affect mantle convection. In the mid mantle, the short-scale, tectonic features that we find near Earth's surface disappear and give way to a long-wavelength structure that dominates the lower mantle. Constraining where, why and how this profound change occurs is vital for understanding global mantle flow and determining how deep the influence of the surface reaches into our planet.

Seismological imaging provides important observational constraints on mid mantle structure and dynamics, but to interpret seismic tomography models we also need to understand how different physical parameters affect seismic velocities. Particularly, abrupt changes in mineralogy due to the increase in pressure in the Earth, often lead to strong changes in seismic velocities, while they also influence mantle low patterns. However, it is not clear how phase transitions manifest themselves in seismic images. The presence of abrupt phase transitions may in turn be inferred from seismic tomography (Sidorin et al., 1999; Koelemeijer et al., 2018). Knowledge of where these phase transitions occur provides important information on composition and temperature inside the Earth.

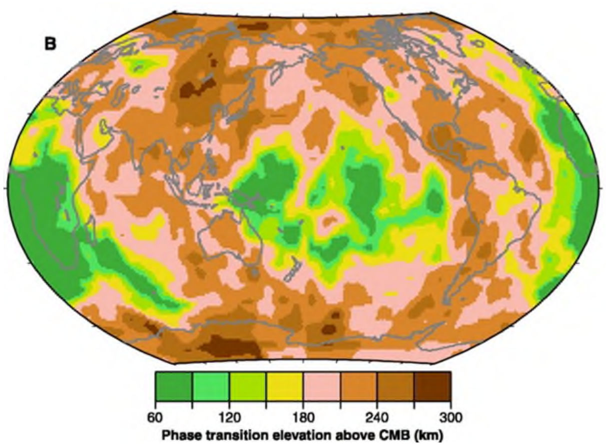

Fig. 1. Prediction of phase boundary above the core-mantle boundary based on seismic tomography, before post-perovskite was discovered (taken from Sidorin et al., 1999).

Various seismic observables (e.g. traveltime anomaly in Vs and Vp and ratio between them), are only weakly sensitive to phase transitions (Trautner et al., 2023; Leung et al., 2024; Trautner et al., 2025). This is further complicated by the dominant effect of temperature on seismic velocities as well as trade-offs with compositional variations. Consequently, it remains difficult to develop seismological proxies for phase transitions in the mantle.

Methodology

We aim to (1) investigate the influence of phase transitions on seismic observables, (2) to develop optimal seismological proxies for phase transitions in the mantle and (3) to apply these proxies to data-based tomographic models.

(1) We can study the effect of phase transitions on seismic observables by combining mineral physics data (e.g. Stixrude & Lithgow-Bertelloni, 2024) with temperature distributions from geodynamic simulations (e.g. Davies et al., 2025) to develop high-resolution seismic models of the mantle. These can also be used in forward solvers to predict different seismic observables (traveltime anomalies, waveform amplitudes, etc). We will vary various input parameters in the simulations (composition, viscosity, etc), thus effectively varying which phase transitions may occur (e.g. spin transition in ferropericlase, structural changes in calcium-perovskite) and analyse the changes in the seismic observables.

(2) The sensitivity of individual seismic observables to phase transitions is likely weak, and it can be difficult to find optimal combinations of observables that uniquely point to a given phase transition. We will therefore employ simple machine-learned predictors (e.g. random forest) to derive optimal proxies. These ML schemes will initially be trained on the high-resolution seismic tomography models along with key information such as depth of the phase transition. As data-based tomography models are often based on few parameters (leading to damping of structures), we will also develop optimal proxies based on "tomographically filtered" seismic models (Ritsema et al., 2007; Koelemeijer et al., 2016), where we account for the limited resolution in seismic tomography. This allows us to develop proxies for realistic tomography models.

(3) The newly developed optimal proxy predictors will be applied to recent mantle models, developed using Backus-Gilbert inferences, to map out different phase transitions in Earth's mantle.

Timeline

Year 1: Literature review, familiarising with geodynamic model simulations, mineral physics data and forward modelling of seismic observables.

Years 2 and 3: Workflow development for phase transition proxy determination using the geodynamic models and machine learning approaches. Writing of papers and presentation of results at international conferences.

Year 4: Application of optimal proxies on data-based models, thesis completion, writing of papers for international journals and presentation of results at international conferences.

Training & Skills

The successful candidate will join the vibrant seismology group at the University of Oxford, and benefit from interactions with existing PhD students and postdocs who work on similar topics.

The PhD student will receive training in computational methods, mineral physics data, the processing and inversion of seismic data and geodynamic modelling. In addition, they will be mentored on how to prepare scientific results at (inter)national conferences, how to write manuscripts for publication in international journals and how to communicate their science to a general audience.

In addition to the training in these transferable skills and research skills, the student will be provided with advice on funding applications and career support.

References & Further Reading

Davies, J.H., J. Panton, (…), **P. Koelemeijer**, F. Lattalerie et al. (2025). How to assess similarities and differences between mantle circulation models and Earth using disparate independent observations. *Proc. Roy. Soc. A.,* vol. 481(2315), doi:10.1098/rspa.2024.0827.

Koelemeijer, P., B.S.A. Schuberth, D.R. Davies, A. Deuss & J. Ritsema (2018). Constraints on the presence of post-perovskite in Earth's lowermost mantle from tomographic-geodynamic model comparisons. *Earth Planet. Sci. Lett.*, Vol. 494, 226-238, doi:10.1016/j.epsl.2018.04.056.

Leung, J., A.M. Walker, **P. Koelemeijer**, F. Restelli & D.R. Davies. Quantitative assessment of tomographic proxies for lowermost mantle composition and mineralogy (2025). *PEPI (SEDI special isssue)*, doi:10.1016/j.pepi.2025.107423.

Trautner, V.E., S. Stackhouse, A. Turner, **P. Koelemeijer**, D.R. Davies, A.S.J. Mendez, N. Satta, A. Kurnosov, H.-P. Liermann & **H. Marquardt** (2023). Compressibility of ferropericlase at high-temperature: evidence for the iron spin crossover in seismic tomography. *Earth Planet. Sci. Lett.*, vol. 618, 119296, doi: 10.1016/j.epsl.2023.118296.

Trautner, V.E., **P. Koelemeijer**, J. Ritsema & **H. Marquardt** (2025). Seismic signal of the iron spin crossover in travel-time data. *Under consideration at Geophys. Res. Lett.*

Further Information

Contact: Paula Koelemeijer (paula.koelemeijer@earth.ox.ac.uk)