Robust tomographic proxies for phase transitions in Earth's mantle

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Overview

Convective processes, which remove heat from the Earth's deep interior, drive plate tectonics at the surface and sustain our protective magnetic field. To model these convective processes and to understand the thermal evolution of the Earth, it is crucial to have robust estimates of present-day temperatures in the Earth. Such estimates are typically obtained using observations of sharp jumps in seismic velocities, interpreted to arise due to changes in the crystal structure of mantle minerals. By combining seismic observations of such mineralogical phase transitions with expected depths based on mineral physics experiments and calculations, we obtain much-needed estimates of temperatures in the deep Earth.

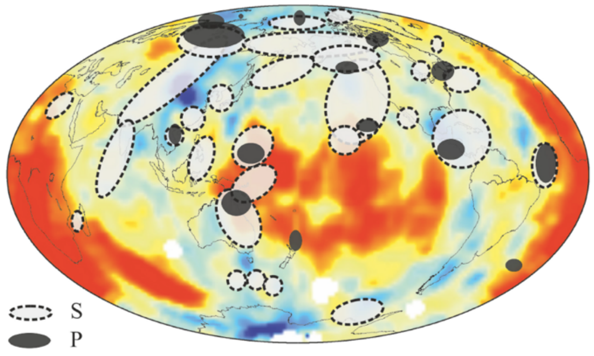

Figure 1: Locations of seismic observations of a sharp jump in velocity in the lower mantle, overlain on top of the S-wave velocity model of Grand (2002). Figure taken from Cobden et al. (2014).

Seismic observations of phase transitions are however sparse due to heterogenous seismic data coverage. This is especially the case in the deep mantle, where for example the transition of bridgmanite (Br) to post-perovskite (pPv) is inferred as explanation for jumps in seismic velocity (Figure 1). Consequently, we only have a very patchy image of where the phase boundary may occur, limiting our ability to constrain lateral variations in temperature and heat flow across the core-mantle boundary. Our interpretations are further complicated by the fact that the properties and stability field of pPv as estimated from mineral physics remains uncertain.

In this project, we aim to investigate instead to what extent global seismic tomography can be used to construct proxies for phase transitions in the mantle. Previous studies that attempted to create proxies for the presence of phase transitions and other mineralogical changes using tomographic data have generally been limited in two ways: by the selection of a single seismic proxy and by the limited seismic resolution of tomographic models as it diffuses the signal we are interested in. Here, we will address these issues by constructing optimal tomographic proxies for mineralogical changes in the mantle using a combination of geodynamic simulations, mineral physics data, seismology and simple data science methods.

Methodology

To investigate different seismological proxies, we will firstly construct high-resolution seismic models of the mantle. These will be based on available geodynamic mantle circulation models, with the temperatures converted to seismic velocities using mineral physics data for different mantle compositions, thus effectively varying which phase transitions can occur (e.g. spin transition in ferropericlase, structural changes in calcium-perovskite. Different proxies for mineralogical phase transition will then be computed based on the seismic velocities, which may include seismic velocity amplitudes, gradients in seismic velocity and relationships between seismic velocities (Koelemeijer et al., 2018; Trautner et al., 2023).

The obtained high-resolution seismic models describe mantle structure at shorter wavelengths than typically recovered in seismic tomography. To take the limited resolution of seismic tomography into account, we will employ the generalised inverse from recent tomographic inversions for shear and compressional-wave velocity variations to obtain synthetic seismic tomography models.

Subsequently, we will develop a repeatable workflow to create predictive models bespoke to existing tomography models being interpreted, trained against data from the synthetic tomography models. We will compute a suite of possible proxies in the synthetic models, which individually may only be weak indicators of a particular mineralogical change. The ultimate aim is to combine these weak proxies to obtain optimal proxies for given mineralogical changes in the mantle. By investigating both high-resolution synthetic tomography models and existing tomography models based on data, we will ascertain under which conditions different proxies work and be able to provide recommendations as to what improvements are required in seismic tomography to utilise particular proxies in practice.

Timeline

Year 1: Doctoral training courses, literature review, familiarising with mineral physics data, geodynamic models and seismic tomography.

Years 2 and 3: Development of workflow for different proxies, testing of proxies in high-resolution synthetic tomography models, tomographic filtering high-resolution models, development of predictive model.

Year 4: Extension to multiple proxies and models, thesis completion, writing of papers for international journals and presentation of results at international conferences.

Training & Skills

The supervisory team in Oxford are leaders in global seismic tomography, multi-disciplinary interpretations of mantle structure and experimental mineral physics. The successful candidate will join the vibrant seismology group at the University of Oxford, and benefit from interactions with existing PhD students, postdocs and faculty who work on similar topics.

In this multidisciplinary project, the PhD student will receive training in analysis and compilations of mineral physics data, geodynamic simulations and global tomographic inversions of seismic data. 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

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