What is the temperature and composition at the bottom of Earth's mantle?

Supervisory Team	• **Dr Andrew Walker (https://www.earth.ox.ac.uk/people/andrew-walker/)** • **Dr Paula Koelemeijer (https://cube.rhul.ac.uk/~paulak/index.html)**

In May 2022 Paula Koelemeijer will join the Department of Earth Sciences as an Associate Professor in Geophysics

Key Words	**Deep Earth, seismology, mineral physics, mantle dynamics**

Overview

The thermochemical structure of the lowermost mantle remains poorly known yet plays a crucial role in the whole Earth system that underpins the behaviour of both the core and mantle. Seismology tells us that Earth's lowermost mantle is a complex place. Tomographic images include two continent-sized anomalies sat on the core under Africa and the Pacific with debated origin. These anomalies, called large low velocity provinces (LLVPs), could be hot regions where mantle plumes are concentrated, or they could be chemically distinct dense structures sat stably on the core-mantle boundary (CMB) and sculpted by convection of the surrounding mantle. Particularly, their density and viscosity remain unconstrained.

Furthermore, detailed analyses of the waveforms of seismic phases passing close to the core reveal the presence of small bodies with very low seismic velocities. These ultra-low velocity zones (ULVZs) may be partially molten or could be highly enriched in iron. Hypotheses for their origin include the idea that they are remnants of a global magma ocean that existed early in Earth's history, and that they slowly formed over time by chemical reactions between the silicate mantle and the iron core. Figure 1 shows one interpretation of the structure and dynamics of the Earth highlighting the critical importance of the lowermost mantle for our understanding of the dynamics of the Earth, including coupling between the mantle and core.

One key unknown property of the lowermost mantle is the distribution of post-perovskite, a high-pressure mineral phase thought to form in the lowermost few hundred km of the mantle just above the CMB. If the LLVPs are chemically distinct from the rest of the mantle, the pressure and temperature stability field of post-perovskite will be different inside and outside the LLVPs. Accounting for this variability is key for correct interpretations of seismic velocity and density observations and to resolve the effect of the lowermost mantle on planetary scale processes.

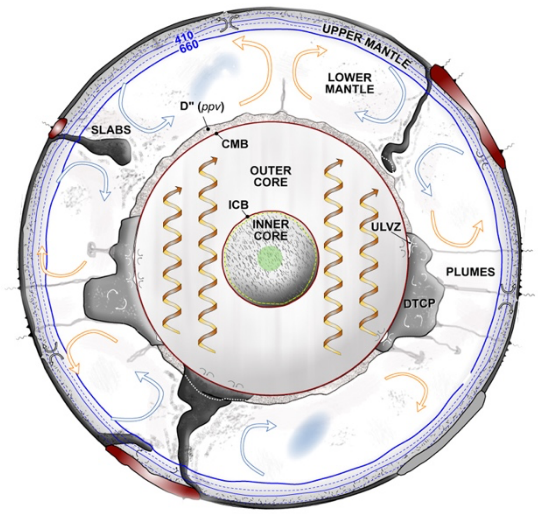
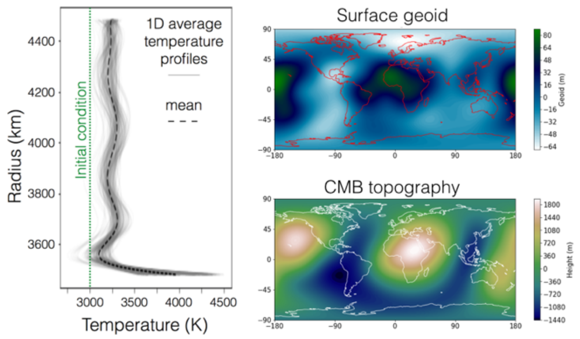


Figure 1: Cartoon showing the dynamics of the Earth's interior. Convection in the mantle drives plate tectonics at the surface and cools the outer core to drive the generation of the magnetic field. The lowermost mantle, immediately above the outer core, includes complex structures on many scales that control and reveal the dynamics of the interior. Image from Ed Garnero (http://garnero.asu.edu/). CMB: core-mantle boundary; ICB: inner core boundary; DTCP: dense thermochemical pile; ULVZ: ultra-low velocity zone; D'': a seismic reflector ~200 km above the CMB; ppv: region where post-perovskite may be thermodynamically stable.

Methodology

Your project will involve the use and further development of a numerical toolkit for modelling the lower mantle called LEMA. This collection of tools allows simulation of the properties and dynamics of the lower mantle based on proposed models of its temperature and composition. LEMA makes use of self-consistent mineral physics to translate these input parameters into descriptions of the mantle's elasticity and density. These can be compared with models derived from seismic tomography, and with other constraints such as observations of the long-wavelength surface gravity field and the shape of the core-mantle boundary.



One of the major advantages of this toolkit is its high performance: an Earth model can be created and compared to the full gamut of observations in less than a third of a second. This leads to the ability to make use of LEMA in a Bayesian approach where very large numbers of models are randomly constructed and compared with observations. This way we generate a statistical view of the range of possible temperature and composition distributions in the lower mantle that are consistent with observations, and with what is known of the physical properties of mantle minerals (Figure 2).

Timeline

Year 1: An initial project will involve testing hypotheses for the stability of post-perovskite in realistic models of lowermost mantle temperature from high resolution geodynamics. Varying the thermodynamic parameters that define the stability of post-perovskite will lead to changes in the distribution of density anomalies as well as seismic velocities. This project will thus involve exercising the full range of capabilities of LEMA (which span mineral physics, geodynamics and seismology), where different hypotheses are expected to lead to different levels of agreement with long-wavelength seismic tomography, CMB topography, surface gravity, and normal mode splitting.

Years 2 and 3: After completing the initial project, you will have some choice on the direction for further study. One option is to attempt inverting for the temperature distribution in the lowermost mantle accounting for lateral variations in composition (an approach that will require the implementation of advanced inversion methods). Another option would be to make closer links with seismic observations and to use LEMA to define the advancements that are required in tomographic models to robustly constrain the dynamics of the lowermost mantle. A third option is to attempt to resolve the viscosity profile in the lowermost mantle in a way that is consistent with the properties of the constituent minerals and geophysical observations.

Year 4: Whatever approach is taken in years 2 and 3, you will have become an expert in a range of methods used for studying the lowermost mantle. We expect that some time towards the end of the project will be dedicated to integrating these results with a wider view on the dynamics of the Earth.

Training & Skills

You will receive training in skills tailored to the project, which are also useful to help secure a future career as a research scientist in academia or elsewhere. To allow you to complete the project you will learn a range of numerical and computational methods as well as develop a understanding of the properties and dynamics of Earth's interior. You will also learn how to confidently develop software for the analysis of results and to use large-scale high performance computing resources. Alongside transferable skills such as oral and written communication and project and time management skills this will open a wide range of career pathways.

Funding for the studentship can be sought from https://www.environmental-research.ox.ac.uk/, Oxford's NERC doctoral training partnership (DTP) in Environmental Research, or other sources. The DTP provides an additional programme of training in research and wider skills over the first six months, and offers continuing support for the full 4-year duration of the project.

References & Further Reading

D.R. Davies, S. Goes, J.H. Davies, B.S.A. Schuberth, H.-P. Bunge, and J. Ritsema. Reconciling dynamic and seismic models of Earth's lower mantle: The dominant role of thermal heterogeneity. Earth and Planetary Science Letters, 353-354:253 – 269, 2012.

E.J. Garnero, A.K. McNamara, and S.-H. Shim. Continent-sized anomalous zones with low seismic velocity at the base of Earth's mantle. Nature Geoscience, 9:481 – 489, 2016.

J.W. Hernlund and A.K. McNamara. The core–mantle boundary region. In Treatise on Geophysics, chapter 7.11. Elsevier, second edition, 2015.

P. Koelemeijer, B.S.A. Schuberth, D.R. Davies, A, Deuss, ans J. Ritsema.'Constraints on the presence of post-perovskite in Earth's lowermost mantle from tomographic-geodynamic model comparisons, Earth and Planetary Science Letters, 494:226-238, 2-18.

G. Schubert, G. Masters, P. Olson, and P. Tackley. Superplumes or plume clusters? Physics of the Earth and Planetary Interiors, 146:147 – 162, 2004.

Further Information: Contact Andrew Walker (andrew.walker@earth.ox.ac.uk) or Paula Koelemeijer (paula.koelemeijer@rhul.ac.uk)