How hot is the bottom of Earth's mantle?

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Can you combine geophysics, fluid dynamics and mineralogy to construct a deep-Earth thermometer and better constrain Earth's energy budget?

Convection in Earth's rocky mantle controls the long-term evolution of the planet, drives surface tectonics and is intimately linked to planetary habitability. It also permits magnetic field generation by cooling the liquid iron outer core. At first sight the fluid dynamics of mantle convection appears quite simple as the high viscosity implies that flow is not turbulent, although it is chaotic. The rich and complex dynamics exhibited by Earth, and the other terrestrial planets, arise because the physical properties that characterise mantle materials, and in particular the rheology, are enormously sensitive to small changes in temperature, pressure and composition. The complex feedbacks between mantle physical properties and mantle flow are most prevalent in the uppermost and lowermost boundary layers of the mantle, and it is the rheology in these regions that is largely responsible for the diversity of planetary behaviour and evolution. In this project you will make use of a range of geophysical observations and models to constrain the thickness, lateral variability and temperature of the lower boundary layer of the mantle. You will then use this information to probe the evolution of the planet.

Earth's lowermost mantle

The thermal structure of the lowermost mantle is a poorly known yet crucial property of 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 [1]. Tomographic images include two continent-sized anomalies sat on the core under Africa and the Pacific with debated origin. These anomalies, called large low shear velocity provinces (LLSVPs), could be hot regions where mantle plumes are concentrated [2], or they could be chemically distinct dense piles of material sat on the core-mantle boundary and sculpted by convection of the surrounding mantle [3,4]. Existing methods using geodynamics and seismic anisotropy have not been able to distinguish these two cases [5-8]. Furthermore, detailed analysis of the waveforms of seismic phases passing close to the core reveal the presence of small bodies with very low seismic velocities [9]. These ultra-low velocity zones (ULVZs) may be partially molten, could be highly enriched in iron, and hypothesis for their origin include the idea that they are a remnant of a global magma ocean that existed early in Earth's history, and that they slowly form over time by chemical reactions between the silicate mantle and the iron core [10]. Figure 1 shows one interpretation of the structure and dynamics of the Earth highlighting the critical importance of the lowermost mantle to our understanding of the dynamics of the Earth including coupling between the mantle and core.

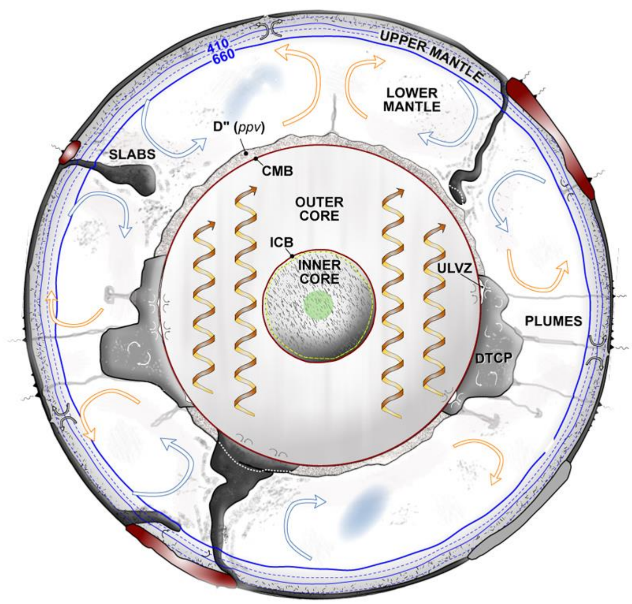

Figure 1: cartoon showing the dynamics of the Earth's interior. Convection in the mantle drives plate tectonics at the surface and cools the outer core to drive the generation of the magnetic field. The lowermost mantle, immediately above the outer core, includes complex structures on many scales which 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 ~100 km above the CMB; ppv: region where post-perovskite may be thermodynamically stable.

A key unknown property of the lowermost mantle is its temperature and the variation of temperature with lateral position and height above the core-mantle boundary. There is almost certainly some kind of thermal boundary layer at the base of the mantle reflecting the conduction of heat from the hot core to the relatively cooler interior of the convecting mantle [11]. Instabilities in this boundary layer are probably the origin of mantle plumes, which lead to oceanic islands such as Hawaii and the Canaries. Knowledge of the thickness and temperature drop across the thermal boundary layer would resolve a number of important geophysical questions: we would be in a position to estimate the cooling rate of the core (and thus establish the energy budget of the geodynamo), we would be able to distinguish between models of the nature of LLSVPs and ULVZs, we would be better able to establish the vigour of mantle convection, and we would be in a position to constrain the composition and dynamics of the lower mantle. Although it is not possible to directly measure the temperature of the lower mantle, temperature does indirectly influence many geophysical observables. In this project you will take advantage of these indirect effects to better establish the three-dimensional temperature structure of the mantle immediately above the core-mantle boundary.

The project

In this project you will make use of two complimentary approaches designed to constrain the temperature of the lowermost few hundred kilometres of the mantle. The first will involve the further development and use of a new low-resolution model of the lower mantle, which we call LEMA (Leeds Earth Modelling Approach). This Earth model is designed to simulate the properties and dynamics of the lower mantle based on proposed models of its temperature and composition making 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 of the shape of the core-mantle boundary. One of the major advantages of our approach 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 in order to generate a statistical view of the range of possible temperature distributions in the lower mantle that are consistent with the observations, and with what is known of the physical properties of mantle minerals.

LEMA is capable of placing robust constraints on the radial structure of the thermal boundary layer at the base of the mantle (Figure 2), but further work remains to examine lateral variability in this layer taking results from 1D to 3D. For example, our current implementation uses the propagator matrix approach as a semi-analytic dynamical core of the code to compute the pattern of mantle flow from its density [12,13]. While this yields the long-wavelength topography of the core mantle boundary, we currently only make use of the core ellipticity to constrain our models. New observations of CMB topography [14] should be incorporated. It is also necessary to fully probe the effect of incorporating uncertainty on the parameters describing the behaviour of mantle minerals. These parameters are known [15], but their incorporation will increase the dimensionality of the inverse problem.

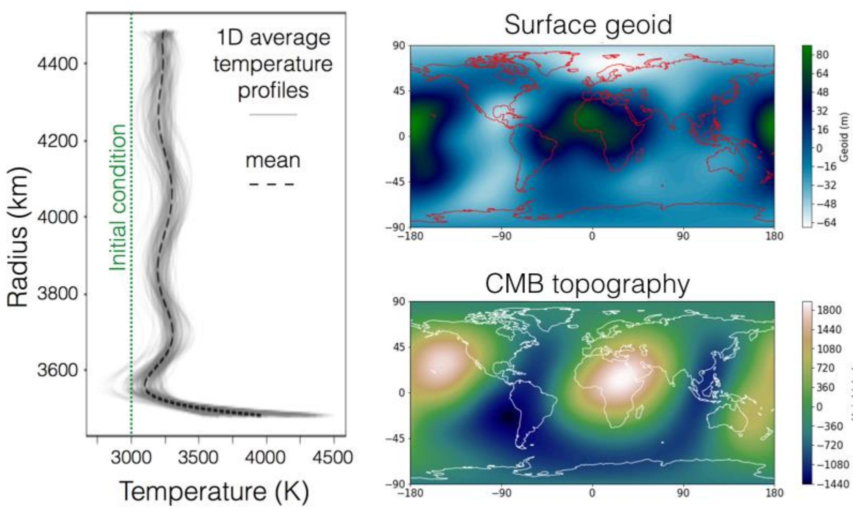

Figure 2: Example output from LEMA. Left: Radial temperature averages of the 10% of models that best fit geophysical observations reveal the presence of a thermal boundary layer at radii less that 3600 km. Right: Best fitting models for the geoid and CMB topography derived from this run.

The second approach will involve a more detailed analysis of the behaviour of the fluid dynamics of mantle-like dynamical systems (Figure 3). Although the influence of depth-dependent material properties has been extensively analysed in models of 2D mantle convection, the way that rheological complexity, itself caused by temperature variation, alters this idealisation of mantle convection has not been subject to significant study. This part of the project will involve an analysis of the properties and behaviour of complex mantle-like systems. Starting with simplified 2D models, you will explore convection in models with increasingly complex material properties using a combination of theoretical and numerical tools. This understanding will permit a numerical study of the 3D case where statistical measures of boundary layer behaviour can be compared with observations of the Earth [16], and boundary layer heat-flux can be used to explore the long-term evolution of the terrestrial planets.

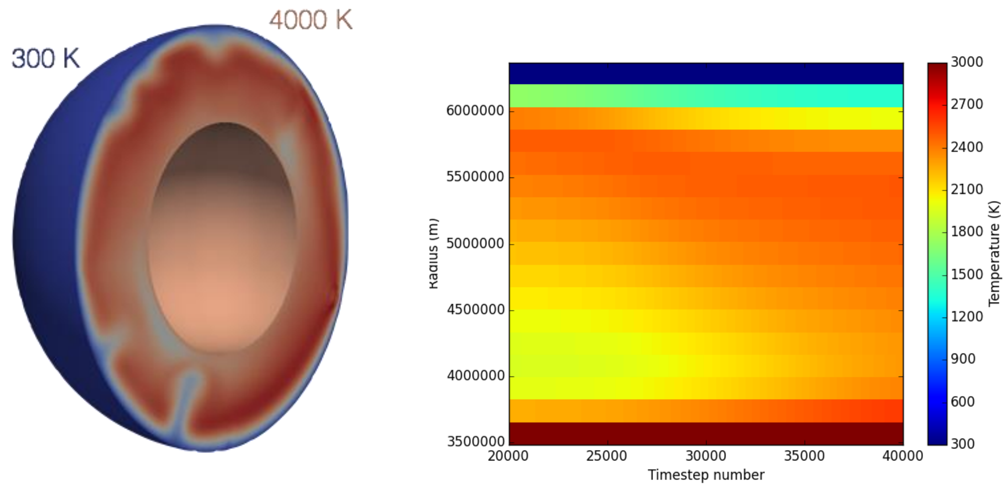

Figure 3: Example simulation using the TERRA code [17,18] with imposed surface plate motions and a simple viscosity model. The snapshot of the temperature field on the left shows focussing of the subduction of cold material from convergent plate boundaries. The histogram of average radial temperature profiles on the right illustrates how the upper and lower thermal boundary layers persist in this simulation.

As well as providing important information on boundary layer behaviour, the high-resolution 3D simulations of mantle convection can feed back into the low-resolution LEMA-based inversion of mantle temperature in several ways. Most simply the simulations can be used to validate aspects of the output of LEMA and establish if the use of a simplified low-resolution model introduces important artefacts that would need correction when making comparisons with observations. It should also be possible to replace the semi-analytic dynamical core of LEMA with a more accurate finite-element model of mantle convection, although this would need careful benchmarking and may prove to be computationally challenging. A third possibility would be to use the 3D simulations of mantle convection to develop energetic constraints, which could then be incorporated into LEMA to better constrain the inversion.

Training environment

You will receive training in skills tailored to the project but 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 developing an understanding of the properties of the 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, including those at the University of Leeds (Figure 4). Alongside the transferable skills in communication and management this can open a wide range of career pathways. These skills will be developed by a mixture of hands on experience, attending external training courses, and by participating in the Leeds–York NERC doctoral training partnership.

Figure 4: University of Leeds hosted tier 2 high performance computing facility of the N8 HPC consortium (http://n8.hpc.org.uk), one of the supercomputers that can be used in this project.

Student profile

Overall this project offers significant flexibility depending on the interests and experience of the candidate. A focus fluid dynamics and numerical simulation may be most appropriate for somebody with a background in mathematics or mathematical physics; a comparison between multiple geophysical observations and models of the mantle may be more attractive for somebody with a background in geophysics. Whatever the candidate's background the development of strong programming skills will form an important part of the project.

References and further reading

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