# Stratified or not-stratified or somewhere in between: Multi-disciplinary study of partially stratified layers in Earth's outer core

Supervisors: Sebastian Rost (Leeds), Jon Mound (Leeds), Andrew Nowacki (Leeds)

Contact email: s.rost@leeds.ac.uk

## Background

The Earth's outer core is the source of Earth's global magnetic field, with a combination of chaotic convection and Earth's rotation producing the flow structures essential for the geodynamo process. The low viscosity of the liquid iron-nickel alloy and the fast convection (with velocities on the order of 10s km/yr) suggest that the bulk of the fluid core should be well mixed. However, evidence from seismological, geodynamic, and mineral-physics studies have indicated that the outer core close to the core-mantle boundary is not vigorously convecting and well mixed like the majority of the outer core but instead forms a stable stratified layer.

**This project aims to test whether seismological data can be used to detect and characterize the recently postulated regional stratified layers of the outer core.**

Stratified layers in the outer core have important implications for the long-term evolution of the Earth's deep interior, physical and chemical interactions between the core and mantle, and the dynamics of the outer core and the global magnetic field. Failure to properly understand core stratification will affect our ability to predict the development of the magnetic field on different time-scales; e.g., the structure of the paleomagnetic field and the mechanism by which reversals happen, and the present pattern of secular variation and hence medium-term geomagnetic forecasting for space-weather predictions.

Seismological studies of the seismic velocity structure of the outer core resolve a change in the seismic velocities compared to 1D reference models that indicate a change of either composition or temperature in this layer consistent with the existence of a stratified layer. Furthermore, structures of the Earth's magnetic field such as periodic variations in secular variations can be matched by models of waves within in a stratified layer. Several mineral physical models can explain stratification through accumulation of light material below the CMB or material flux from mantle to core.

While several lines of evidence point towards stratification in the outer core the evidence is not conclusive due to the limitations of our sampling of the outer core structure using seismology, the non-uniqueness of the interpretation of the variations of Earth's magnetic field, and our limited understanding of material properties at high pressure and temperature.

A recent study by Mound et al. (2018) proposes the possibility that the stratified layer is not global but a regional feature of the core controlled by the heat flow through the core-mantle boundary (Figure 1). A partially stratified layer will develop in regions with reduced core-mantle boundary heat-flow, e.g. beneath the lower mantle large low shear velocity provinces, while in other regions the full core from the inner core boundary to the core-mantle boundary is convecting. This scenario has so far not been considered in seismic studies. This project will use new seismic data with novel seismic analysis methods to test the hypothesis that the outer core is regionally stratified.

## Previous Work

The seismic structure of the uppermost outer core is difficult to resolve due to the depth to the core-mantle boundary (CMB), the heterogeneous structure of the mantle and the specific velocity structure of the core. Seismic velocities drop strongly across the CMB leading to a shadow zone for most seismic waves. The most common seismic phase to sample the uppermost outer core are the multiple underside reflection off the CMB of the phases *SmKS* (Figure 2), which travel as *S*-wave in the mantle and reflect as *P*-waves from the underside of the CMB. Each *SmKS* branch has *m-1* underside reflections with higher *m* sampling closer to the CMB (Figure 2). Careful study of the traveltimes of these phases allows inferences on velocity structure of the outermost core (Helffrich and Kaneshima, 2013). Although seismic evidence for outer core stratification is mounting the seismic data seems to be ambiguous (Alexandrakis and Eaton, 2010).
Stable stratification of the outer core has been postulated from studies of the Earth's magnetic field for a long time (e.g. Gubbins et al., 1982) and has been revisited many times since (e.g. Mound et al. 2018). Outer core stratification is essential for our understanding of the dynamics and evolution of the Earth's magnetic field. Several mechanisms to explain outer core stratification have been proposed including sedimentation of light elements due to inner core growth, core-mantle interaction or thermal stratification due to sub-adiabatic structure close to the CMB (Buffett, 2010).

## Objectives

This project is novel since it will test the recently proposed hypothesis that the outer core may be only partially stratified, a model that has not been considered so far. This project will aim to better understand the possibility of partially stratified layers at the top of the outer core by using a combination of new seismic data analysis, geodynamic modelling and synthetic seismic wave propagation. This project is now possible due to the global distribution of high-quality broadband seismometers that allow regional rather than global analysis of the seismic wavefield, improvements of our understanding of core dynamics and material properties at high-temperature and pressure.
The project will consist of different objectives each forming a sub-project, which can be varied dependent on the interests of the student:

- We will start by using new seismic data from globally distributed seismic networks and array processing techniques to identify and characterize the different *SmKS* branches.
- We will test the influence of the seismic 3D mantle structure on the seismic measurements of core phases using synthetic seismic wave propagation through complex 3D velocity fields.
- Potential velocity structures of the outer core can be translated into thermal or chemical stratification models using mineralphysical approaches.
- Their influences on the outer core dynamics and their geomagnetic signatures can be tested using forward modelling of geomagnetic core convection models.

## Impact of Research and Publications

The project is designed to test recent hypotheses on outer core structure and to develop a better understanding of the structure and dynamics of the outer core in a multi-disciplinary approach. It will use new data and combine several processing techniques to test these hypotheses using the expertise of the supervisors from a variety of disciplines. It will be structured into several work packages with each package aiming for publications in high impact journals. The work will be presented at national and international workshops and conferences.

## Fieldwork

This project will mainly use existing datasets held at international data centres. Opportunities for active fieldwork participation might arise as part of other fieldwork-oriented projects within the School of Earth and Environment

## An excellent Training and Research Environment

The Deep Earth Research Group (http://www.see.leeds.ac.uk/research/igt/deep-earth-research) at the University of Leeds consists of researchers in seismology, core dynamics, magneto-hydrodynamics and high-pressure mineral-physics. The group is one of the largest concentration of scientists interested in deep Earth structure and dynamics in the world. The research group is part of the Institute of Geophysics and Tectonics (IGT) with about 25 permanent staff working in a wide variety of solid Earth geoscience disciplines including Tectonophysics, Geodynamics, Petrology, Structural Geology, Seismology, Petrology, Mineral-Physics, Remote Sensing and Geochemistry (http://www.see.leeds.ac.uk/research/igt/). The successful candidate will have the opportunity to interact with internationally leading specialists in these areas and will have the opportunity to present the research work at national and international workshops and conferences.

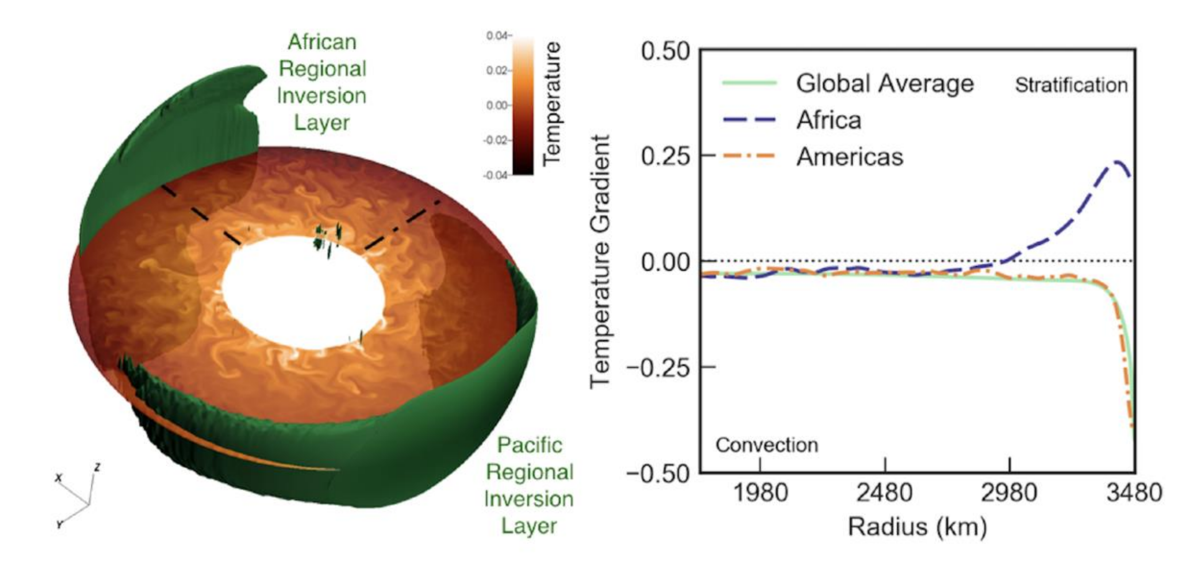


Figure 1: (left) core structure with tomographic core-mantle boundary heat-flux beneath the large-low shear velocity provinces (LLSVPs). Stratified layers (green) form beneath the LLSVP due to the low heat-flux in these areas. Strong convection and radial motion can be seen in the equatorial cross section through a core convection model. (right) Time-averaged profiles of dT/dr in the top half of the outer core. Regional profiles for Africa (black dashed) indicating a stratified region beneath the LLSVP and the Americas (dot-dashed red) indicating a non-stratified region are shown. Global average shown as green. Global averages might show convection, non-stratified regions.

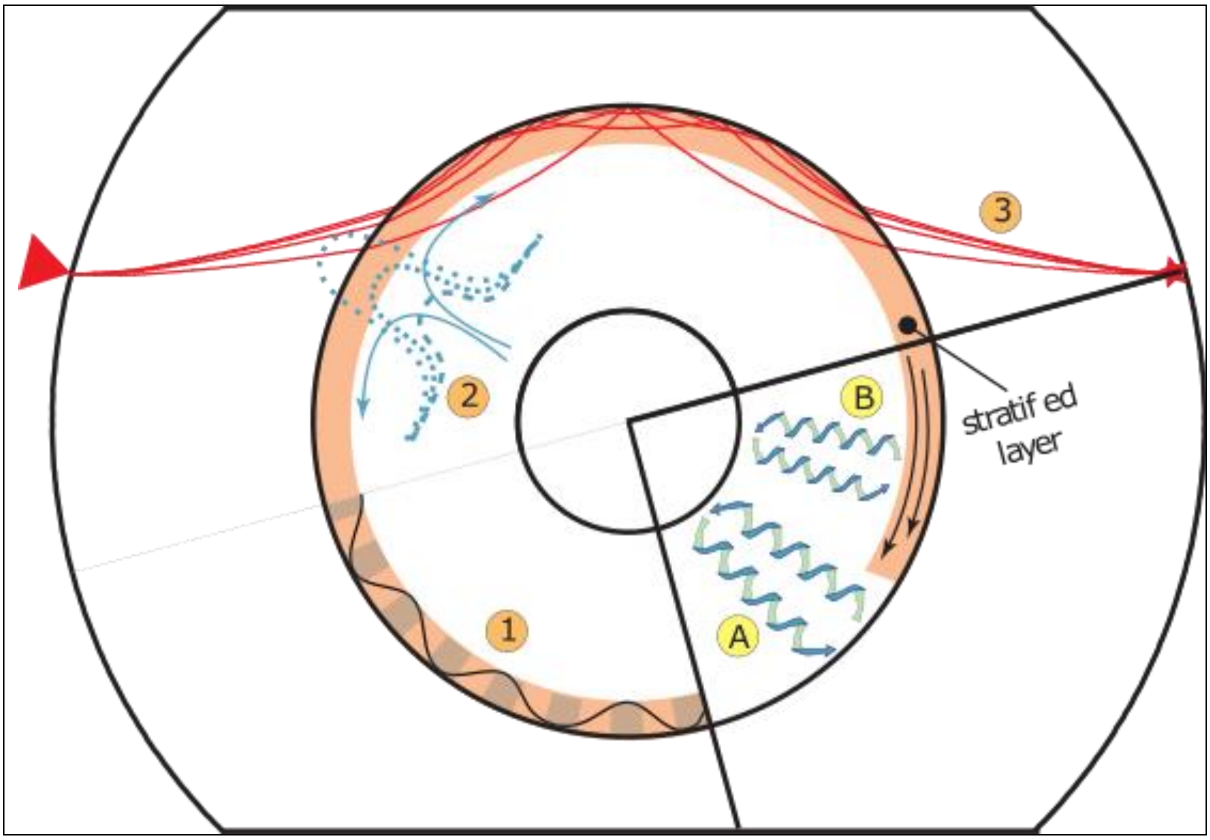

Figure 2: Cartoon showing the effect of a stratified layer (A-B) and imaging methods (1-3). A stratified layer (orange) screens the core's interior: motion inferred for the outermost core is not indicative of the bulk core (B), whereas it is in (A).
The geophysical methods that are used to constrain the stratified layer properties are (1) geomagnetic waves, (2) geomagnetic flux expulsion and (3) seismic travel time analysis. This project will focus on a combination of geophysical methods and mainly rely on seismic data.

## References/Further Reading:


Alexandrakis, C., & Eaton, D. W. (2010). Precise seismic-wave velocity atop Earth's core: No evidence for outer-core stratification. *Physics of the Earth and Planetary Interiors*, *180*(1–2), 59–65.

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