Deformation mechanisms in the deep mantle

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The transport of heat from the interior of the Earth drives convection in the mantle, which involves the deformation of solid rocks over billions of years. The lower mantle of the Earth is primarily composed of iron-bearing bridgmanite $MgSiO_3$ and approximately 25% volume periclase MgO (also containing some iron). Significant advancements have been made in recent years to study lower mantle assemblages under relevant pressure and temperature conditions, which have confirmed the usual view that ferropericlase is weaker than bridgmanite. However, natural strain rates are 8 to 10 orders of magnitude lower than those observed in the laboratory, and remain inaccessible to us. Once the physical mechanisms of the deformation of rocks and their constituent minerals have been identified, it is possible to overcome this limitation thanks to multiscale numerical modeling, which allows for the determination of rheological properties for inaccessible strain rates. This presentation will demonstrate how this theoretical approach can be used to describe the elementary deformation mechanisms of bridgmanite and periclase. These descriptions are compared with available experimental results in order to validate the theoretical approach. In a subsequent phase, the impact of very slow strain rates on the activation of the aforementioned mechanisms is evaluated. Our findings indicate that significant alterations in deformation mechanisms can occur in response to changes in strain rate. Consequently, we propose the necessity of developing a novel approach that integrates physics-based modeling informed by data obtained from high-pressure, high-temperature experiments.

Constraining 3-D mantle density structure combining mantle and inner-core sensitive normal mode data

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Resolving the 3-D density structure of the mantle is important to gain a better understanding of its dynamic behavior. Specifically, comparing density and velocity heterogeneities provide insight into the thermochemical structure of the mantle, as density may constrain the relative contributions of temperature and composition on seismic velocity. Long-period normal modes, i.e. whole Earth oscillations that originate after large earthquakes, are directly sensitive to the aspherical density structure and variations across the full depth range of the mantle. Normal-mode splitting functions can therefore be used to constrain the density of Large Low Shear Velocity Provinces (LLSVPs) in the lower mantle, a subject of ongoing debate. However, previous normal-mode studies often ignore the inner-core sensitive modes, despite their sensitivity to mantle structure, and only use mantle sensitive modes when making 3-D models of the mantle and LLSVP velocity and density structure.

Here, we add inner-core sensitive modes to our least-squares splitting functions inversion, to refine the 3-D density and velocity models, and to test the reliability and robustness of previous LLSVP observations. Additionally, we intend to explore the use of inner-core sensitive modes in constraining both isotropic and anisotropic structure in the inner core. Our aim is to ultimately develop a full 3-D model of seismic velocity and density structure, spanning from the Earth's mantle to inner core.

Investigation of seismic anisotropy in the D'' layer and at the CMB regarding intense magnetic flux regions

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Within the Priority Program 2404 "Reconstructing the Deep Dynamics of Planet Earth over Geologic Time" (DeepDyn, https://www.geo.lmu.de/deepdyn/en/) we investigate possible seismic signatures at magnetic high-latitude flux lobes (HLFLs). The focus is on four target regions on the Northern Hemisphere: Siberia, Canada, North Atlantic and Indonesia. While Siberia and Canada show the HLFLs, the North Atlantic should be the location of a third postulated HLFL, but this area shows no intense-flux signal in the magnetic field. The region beneath Indonesia and the Indian Ocean is characterized by an area of intense magnetic flux that changes direction and moves westwards over time. Our aim is to understand whether mineralogy and seismic structure (i.e., thermal constraints) could be responsible for the different magnetic signatures at the core mantle boundary (CMB). This is done by combining two approaches: seismic anisotropy (KIT) and seismic reflections (University of Münster) near the CMB.

To study anisotropy, we measure shear wave splitting of SKS, SKKS, and PKS (XKS) phases as well as of S and ScS phases. Thereby, we determine the splitting parameters, the fast polarization direction ϕ and the delay time δt as well as the splitting intensity SI. Especially, we search for phase pair discrepancies, e. g., between SKS and SKKS phases, as they are a clear indication for a lowermost mantle contribution to the splitting signal. For the target region underneath Siberia, we present first shear wave splitting measurements (SWSMs) on XKS phases recorded at the Finnish station KEF, including SKS-SKKS pairs.

Based on our shear wave splitting measurements, we will derive structural and mineralogical anisotropy models using the *MATLAB Seismic Anisotropy Toolbox* (Walker and Wookey 2012). To test these models, we will simulate synthetic seismograms using *AxiSEM3D* (Leng et al. 2016, 2019). Besides comparing synthetic and observed seismograms, we plan to measure the shear wave splitting of the synthetic phases and compare splitting parameters and splitting intensity to the observed values.

Imaging deep subducted lithosphere beneath the Indian Ocean with source-arrays

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The D" region, located just above the core-mantle boundary (CMB), is a geologically interesting region that has been imaged using both tomographic and reflection techniques. However, reflection studies often rely on array analysis techniques, and the lack of suitable seismic arrays in the oceans has left large areas of D" unmapped. One notable area, that is currently sparsely sampled, is beneath the Indian Ocean, where ancient subducted lithosphere has been imaged near the CMB in global tomography studies. We take advantage of the long-running history of five GEOSCOPE stations located in the western Indian Ocean and Antarctica, to investigate the possibility of using source arrays to detect P-wave reflections from the discontinuity above the D" layer. Despite restricting the selected earthquakes around Indonesia to a 120 km depth range and implementing several source normalization techniques, source-array stacks (i.e., source vespagrams) were difficult to interpret. We infer that this complication arises from differing earthquake depths, violating the plane wave assumption made when constructing these stacks. Therefore, we extend our method to a source-array scatter imaging method, which we call source migration, that does not rely on travel-times calculated for a plane wave. Using this technique in conjunction with source normalization, we found clear evidence for a D" P-wave reflector at four of the six GEOSCOPE stations considered in the study. The depth of the reflector for our imaged region varies between 190 km above the CMB beneath the Great Australian Bight and 220 to 270 km beneath the Indian Ocean west of Australia. Our determined depth in the northern portion of our study area is consistent with previous studies of D" depths using S-waves. We suggest that our D" reflections are the result of the previously imaged subducted lithosphere in the region and find that this lithosphere likely thins to the southeast. Additionally, our work more broadly indicates that the long-running history of single global seismic stations combined with source array techniques may be utilized to compliment and extend previous work imaging D" using conventional receiver-array techniques.

High $P-T$ generation up to the Earth's deep lower mantle conditions by internal-resistive heated diamond anvil cell using boron-doped diamond heater

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Abstract

The deep planetary interiors are under high pressure and temperature (*P*–*T*) conditions in orders of gigapascals (GPa) and thousands of Kelvins. Some heating methods combined with a diamond anvil cell (DAC), which can generate a static high pressure, have been proposed, such as laser heating, internal-resistive heating, and external heating. However, these methods have yet to achieve stable high-temperature generation for all samples.

Boron-doped diamond (BDD) has recently attracted much attention as an electrically conductive material. Its high melting point and chemical stability make it suitable for use as an electrode and heater working at high pressures. Recent advances in synthesis methods have made it possible to synthesize thin films of BDDs suitable for thin DAC sample configurations.

We have, therefore, developed a new method of heating adjacent samples by Joule heating using a boron-doped diamond heater in the sample chamber of the DAC. As a result, we succeeded in heating the BDD compressed to 85 GPa to a temperature comparable to that of the Earth's core. We evaluated the temperature gradient inside the sample chamber by analyzing the thermal radiation profile and the recovered sample's grain size. This method enables experiments under high *P*–*T* conditions of the Earth's deep lower mantle, regardless of the electrical conductivity and transparency of the sample.

Keywords: Internal-resistive heated diamond anvil cell, Boron-doped diamond

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Investigating the D$''$ structure beneath the Indian Ocean with source- and receiver arrays

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The lowermost mantle beneath the Indian Ocean has not been extensively studied with P- and S-reflected waves from the D$''$ region but the region is thought to be adjacent to the large-low velocity province beneath Africa and it may contain ancient slab material. Mapping the D$''$ structure will help to understand processes and mineralogy in this area. To investigate seismic structure and mineralogy in this region, we collect a large number of events from Indonesia recorded at arrays in East Africa and the Middle East. We are looking for seismic waves reflected at the D$''$ discontinuity, that lies about 300 km above the CMB. These reflected waves are mainly PdP and SdS waves, but later we also want to use also PdS and SdP waves. We analyze the events using array methods (vespagram, slowness-backazimuth analysis). We find a good number of PdP waves from this area, where the PdP waves can be easily distinguished from the P and PcP waves based on different slowness. The traveltime, amplitude, polarity and slowness of the waves are then recorded. The traveltime is used to estimate the depth, and we detect differences between the observed traveltime and the expected traveltime for reflections at a depth of about 2600 km. The amplitude and polarity are used to analyze changes in velocity and density between the mantle and the D$''$ region and our data show variable polarity of the PdP waves, which may indicate anisotropy in D$''$. For a larger coverage of the Indian Ocean, a comparison with source vespagrams (several events recorded at one station) for stations in the western Indian Ocean. These data, which we process with migration methods also show a presence of a D$''$ reflector.

We find a good number of PdP waves from this area, where the PdP waves can be easily distinguished from the P and PcP waves based on different slowness. We find variable polarity of the PdP waves, which may indicate an anisotropy in D$''$. We also compare source vespagrams by using stations in the Indian Ocean, which also show the presence of a D$''$ reflector.

Tomographic evidence of the co-occurrence of Bridgmanite and post-perovskite in the lowermost mantle

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In the Earth's lowermost mantle, increased ratios of shear-wave (V_S) velocity to compressional wave velocity (V_P) anomalies and negative correlations between shear-wave and bulk-sound velocity (V_C) anomalies are observed, both inside and outside the large low-velocity provinces (LLVPs), which dominate lower mantle structure. While these signatures are often explained by chemical heterogeneity in the LLVPs, the phase transition from Bridgmanite to post-Perovskite also exhibits such seismic signatures. However, due to large uncertainties in mineral physics, and the non-linear sensitivity of seismic wave speeds to pressure, temperature, composition and phase, the details of this phase transition and thus its ability to explain the seismic observations remain uncertain. Robust constraints on the origin of these lowermost mantle seismic structures would provide further insight into dynamic processes at the lower boundary of the mantle and on the influence of subducting plates on lowermost mantle structure and composition. This has implications for how the deep mantle impacts Earth's surface.

Few studies have examined the combination of both chemical heterogeneity and phase transitions to explain lowermost mantle seismic signatures. Here, we use LEMA (Walker et al., 2018; AGU abstract) —a numerical toolkit developed for lower mantle modelling— to investigate the tomographic signatures expected from a range of scenarios for the stability of post-perovskite within models of different lowermost mantle temperatures and compositions. We calculate synthetic V_S and V_P fields from existing temperature and compositional fields as predicted by geodynamic simulations and recent thermodynamic data. These are filtered to account for the limited resolution of seismic tomography, allowing us to quantitatively compare predicted and observed seismic tomography models. By rejecting synthetic velocity models that do not fit within the uncertainties of the Backus-Gilbert based model of Restelli et al. (2024; EPSL), we can obtain optimal compositional and thermodynamic parameters for the lowermost mantle. We find that a co-occurrence of Bridgmanite and post-Perovskite across a wide depth interval is required to explain lowermost mantle seismic signatures. This implies that the effects of post-Perovskite need to be taken into account when modelling dynamic processes in the deep mantle.

Slabs in D": implications for the dynamo

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Earth's convective system is largely driven by the negative buoyancy of oceanic lithosphere produced at mid-ocean ridges, where partial melting forms a basaltic crust overlaying a depleted mantle. As the oceanic lithosphere ages, it becomes denser than the underlying mantle and eventually recycles all its thermal and chemical heterogeneity into the mantle at subduction zones as slabs. Many slabs fully traverse the mantle eventually reaching D" and the core-mantle boundary (CMB), where they can accumulate, survive for millions of years without thermal assimilation, and insulate the core. We have updated the successful kinematic model of the fate of slabs from Lithgow-Bertelloni and Richards (1998), updating it with the most recent tectonic reconstructions (e.g. Müller et al., 2019) for the last 200 My of Earth's history, the role of major phase transitions on their trajectories, and radial viscosity structures. We treat slabs in their fluid dynamical limit as Stokes bloblets whose terminal velocity is the convergent velocity normal to the trench. Slablets either sink vertically or at an imposed dip angle. Their density contrast with respect to the surrounding mantle depends on the age of the slab at the time of subduction and diminishes as the slab ages inside the mantle. Slablets can be deflected at the 660 km discontinuity and do not sink into the lower mantle until they are warm enough for the bridgmanite forming reactions to occur. The terminal velocity is modified by a factor proportional to the natural log of the viscosity contrast at a given depth and nominal upper mantle. We determine the optimal factor by computing Earth's geoid anomalies. We accumulate the slablets that reach the CMB in D". We validate the slab model with comparisons to the most recent tomographic models, by calculating Earth's geoid anomalies and Cenozoic plate motions. We calculate the effects of the accumulation of slabs on present-day CMB heat flow and its evolution throughout the Cenozoic. We speculate on the consequences for Earth's geomagnetic field, including reversal frequency.

Thermodynamics of mantle minerals – III: the role of iron

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Iron and oxygen are the two most abundant elements in Earth, and the interaction between them sets the first order separation of our planet into core and mantle. The mantle contains 14 % of Earth's iron by mass, where it exists predominantly in the two common valence states of the iron cation (ferrous and ferric) and has an important influence on physical properties and geochemical processes. Iron is unique among the major elements in exhibiting multiple valence and spin states in natural systems.

We have completed a major update to our thermodynamic code HeFESTo, which captures for the first time the rich behavior of iron. To accommodate the multi-valent nature of iron, we add oxygen as a linearly independent component. We have added several new end-members containing ferric iron, including a magnetite end-member of ferropericlase, and several ferric iron end-members of bridgmanite to encompass the possibility of ferric iron incorporation on multiple sites and the dependence of ferric iron incorporation on Al content. We demonstrate good agreement with the well-known behavior of fundamental systems, such as the Fe-O, and Fe-O-SiO_2 phase diagrams, and the properties of native iron to over 200 GPa, and thousands of K, as well as more recent data in many systems, including Mg-Si-Fe-Al bridgmanite. The addition of the high-spin to low-spin transition permits a much more careful examination of the thermodynamics of deep mantle than was possible in previous versions of HeFESTo, including iron partitioning in the lower mantle, and the bridgmanite to post-perovskite transition.

We apply our update of HeFESTo to explore the significance of multi-valent iron for our understanding of the oxidation state of the mantle, the possible presence of native iron in the mantle, possible seismic signatures of the high-spin to low-spin transition, and seismic reflections from the bridgmanite to post-perovskite transition in peridotitic and basaltic lithologies.

HeFESTo is publicly available at github.com/stixrude/HeFESToRepository.

Towards using array seismology as a tool to detect whole mantle plumes

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The existence and nature of mantle plumes is still ambiguous as their expected structure may leave a small imprint on the seismic wavefield. Motivated by this, we investigate the capabilities of array methods in detecting the extent of a mantle plume as well as the influence of the mantle plume structure and composition. First, synthetic mantle plumes are generated through mantle convection models and transformed into seismic velocity fields using mineralogical data. The propagation of the seismic wavefield is modelled through global, spectral element-based, forward waveform simulations. Here, we locally refine the computational grid around the mantle plume to allow for high frequency solutions and obtain synthetic seismographs from rectangular, closely-spaced arrays around the mantle plume and the source location. For each array, the incoming seismic phases are studied through the arriving energy content for varying slowness and backazimuth (slowness-backazimuth analysis). Here, we present the findings for both purely thermal and thermo-chemical mantle plumes for seismic wavefields with periods down to two seconds.

Comparing lowermost mantle seismic structure of global tomography models updated with a forward, iterative travel time mapping scheme

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Global, whole mantle tomography models are important tools for constraining the Earth's dynamics, composition, and evolution. Nearly fifty years of progress have led to increasingly sophisticated models, which have, in turn, revealed an increasingly detailed portrait of the physical nature of the deep mantle. In particular, Large Low Velocity Provinces (LLVPs), which are apparent in virtually all S- and P-wave models, have been imaged with increasingly sharp lateral boundaries. However, despite this agreement on long-wavelength features, models differ at smaller scales (<1000 km), possibly due to variability in input datasets and modeling approaches. Furthermore, the damping inherent in tomography reduces heterogeneity amplitudes, resulting in underestimation of travel time perturbations compared to observations. In an effort to recover amplitude back into tomographically derived global, whole mantle models, we have developed, tested, and validated a forward modeling workflow that maps travel time anomalies back into model structure. As a forward modeling application, SITRUS (Seismic Iterative TomogRaphy Update Scheme) was developed with highly flexible user-definable input parameters, including model space parameterization, residual datasets, crustal and ellipticity corrections, dynamic smoothing options, and weights for azimuthal coverage, spatial raypath distribution, and path length. This flexibility allows the user to update different models using the same set of input parameters, which in turn allows for the direct comparison between solution models. Our previous work focused on validating the SITRUS workflow with synthetic experiments and testing the effects of the various input parameters on several different tomography models using a single large dataset of travel time residuals from a set of diverse seismic phases. Synthetic test results have shown that SITRUS successfully recovers anomaly amplitudes and patterns for various starting models. Further tests with observed travel time residuals and published models have further shown that SITRUS is able to add amplitudes back into models while preserving the fundamental structure of the original model. Here, we define a set of reference input parameters based on these previous tests and apply them to several published models. We show results for the lowermost mantle for models updated with their own datasets, as well as combinations of datasets and subsets. Preliminary results show higher amplitude solution models and convergence between models updated with the same input data. We particularly focus on the effects of data coverage, including both total coverage and azimuthal sampling, on the degree of convergence of the solution models.

Towards exact free oscillation spectra through generalised normal mode coupling

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Long period free oscillation spectra provide one of the main constraints on large-scale lateral structures within the Earth's mantle. These observations are particularly noteworthy for their direct sensitivity to density variations, which gives them the potential to resolve long-standing questions relating to the nature of the two Large Low Shear Velocity Provinces. However, due to both computational expediency and incomplete theory, there are inaccuracies within existing codes for forward modelling of free oscillation spectra. Previous studies inferring Earth structure from these observations have included these inaccuracies within the forward modelling, and these inaccuracies lead to questions on the reliability of their inferences.

This poster outlines work on a new open-source code for modelling free oscillation spectra within laterally heterogeneous Earth models. We apply a generalised normal mode coupling method that overcomes various limitations with the traditional mode coupling approach. We account fully for the non-linear dependence of the matrix elements on density and boundary topography, and exactly solve the equations of motion. Computational costs have been minimised by using high-performance libraries, and efficient numerical linear algebra, in addition to parallelisation. Our code is also suitable for calculation of sensitivity kernels using the adjoint method. Benchmarks against current codes as well as performance benchmarks are shown to demonstrate the accuracy and efficiency of our new method.

Mantle discontinuities and reflectors beneath Arctic ocean and Aleutian-Alaska subduction zone: evidence for MORB crust in lower mantle

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We investigate the properties of mantle discontinuities beneath the Arctic ocean and the Aleutian-Alaska subduction zone with underside reflections of PP and SS waves. The depth distributions of the 410-km and 520-km discontinuities suggest a relatively normal mantle transition zone beneath the Arctic ocean and a cold mantle transition zone with the subducted Pacific plate beneath Aleutian-Alaska subduction. The depth of the 660 km discontinuity shows normal behavior beneath the Arctic Ocean. However, the detection of deep reflectors with opposite polarities in depth range of 720~770 km beneath the eastern Aleutians introduces additional complexity for explaining the slab morphology. We test several plausible compositions using mineralogical modeling along a subduction geotherm. The deep reflectors are interpreted as mid-ocean ridge basalt (MORB) crust associated with the Pacific slab that may deform or buckle at the bottom of the mantle transition zone beneath the eastern Aleutians. Meanwhile, an uplifted 660-km discontinuity observed in the adjacent Alaska region suggests a different subduction depth, where the slab may penetrate the 410-km discontinuity but does not reach the 660-km discontinuity, consistent with previous regional studies. Our observations thus depict a complex slab geometry along the Aleutian-Alaska trench, that is, the slab may reach the top of the lower mantle beneath eastern Aleutian but remains at the base of the transition zone underneath central Alaska.

Crystallographic preferred orientation of MgO inferred from high-temperature, high-pressure, and large-strain deformation experiments using rDAC

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The crystallographic preferred orientation (CPO) of lower mantle minerals is key to understand the structure and dynamics of the lower mantle. The seismic observation in the lower mantle has been found the localized seismic anisotropy, however the cause of its formation is not well understood. For instance, the candidates of S-wave anisotropy ($V_{SH}>V_{SV}$) around Large low-shear-velocity province (LLSVP) are CPO induced by deformation of the lower mantle minerals such as post-perovskite, ferropericlase, and bridgmanite, but it’s still controversial. One of the reasons why this discussion remains unresolved is that there are technical difficulties in conducting quantitative deformation experiments under lower mantle conditions. In this study, we performed large strain deformation experiments on periclase (MgO) using the recently developed rotational diamond anvil cell (rDAC) and discuss the crystallographic preferred orientation and slip system that develop in the lower mantle.

Torsional deformation experiments on periclase were conducted using rDAC at BL47XU, SPring-8 (Pressure: atmospheric pressure–80 GPa, Temperature: 300–973 K, Strain: 61–293 %, Strain rate: 10^{-5}–10^{-4} /s). The sample was put into the tungsten gasket and pressurized by rDAC, and heated by the near-infrared focused heating system (halogen lamps and reflectors) under vacuum conditions. Debye-Scherrer rings (Debye rings) were obtained by in-situ XRD measurements during the deformation experiments. The differential stress and development of CPO on periclase were determined from the obtained Debye rings.

Our experimental results indicated that the dominant slip plane changed from {1 1 0} to {1 0 0} under high-pressure and high-temperature conditions. This trend of change of the dominant slip plane is consistent with those reported from previous studies of the first-principles calculation (Amodeo et al., 2012) and compression experiments using the traditional DAC (Immoor et al., 2018), however, the temperature and pressure conditions of its transition was clearly lower than that of previous studies. The difference between our results and those of previous experimental studies might be caused by differences in the magnitude of strain. The slip system transitions inferred from our results suggest that the {1 0 0} is a dominant slip plane throughout the lower mantle. The CPO of the periclase developed in our deformation experiments could reproduce the S-wave anisotropy observed around the LLSVP in the lowermost mantle.

Lowermost mantle vs. top of the outer core: a tale of seismological stories

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Both the seismic structures in the Earth's lowermost mantle and top of the outer core are important for our understanding of deep Earth's dynamics, albeit in very different aspects. Seismologically, the seismic structure in the lowermost mantle could significantly influence the inference of the seismic structure in the outer core, which has been inadequately taken into account in previous studies. Here we jointly study the seismic structures in the lowermost mantle and outermost core based on waveform modeling of a unique untapped SKS and ScS dataset near bifurcation distances, collected from global seismic arrays for earthquakes occurring from 2000 to 2020. Using the SKS-ScS array dataset minimizes the effects of many uncertainties associated with earthquake source parameters and seismic heterogeneities in the shallow mantle, and affords an opportunity to study and assess the seismic structures in the both regions of the lowermost mantle and outermost core. We show that the seismic observations cannot be explained by the current outer core models and would require unreasonable large lateral variations of more than 3.1% in the outermost core, suggesting a PREM-like seismic velocity structure and a lack of strong thermochemical anomalies in the topmost ~200 km of the outer core. In contrast, the inferred D" models based on a PREM-like outer core exhibit large-scale seismic anomalies that are consistent with the tomographic models and small-scale anomalies that are confirmed by further analysis of the seismic array data. We will discuss further the implications of the identified small-scale seismic anomalies and sharp velocity variations in the lowermost mantle beneath the south coast of Alaska, northwestern Atlantic and the middle of Central America.

Testing the consistency of D" reflected waves beneath Siberia for different crossing paths

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In recent geomagnetic field models , patches of intense magnetic flux can be identified. The north magnetic field is characterized by two such flux lobes, one underneath Canada and one underneath Siberia, known as High Latitude Flux Lobes (HLFL). A third HLFL is postulated underneath the Norther Atlantic but has not been observed. Studies show that the lower mantle influences the magnetic field through the control of the geodynamo . The aim of this study is to investigate how the underlying lower mantle structure and mineralogy may influence these regions of high magnetic signature.

Using array methods, we search for D" reflected PdP and SdS waves which arrive as precursors to the core-reflected PcP and ScS waves and that sample the lowermost mantle beneath Siberia with a number of intersecting paths. Especially the new Alaskan station (TA) deployment allows for a better number of crossing paths that are needed to establish whether anisotropy is present. Vespagram and slowness-backazimuth analysis are carried out to detect the presence of lower mantle reflectors at the top of the D" and establish the wave's travel direction (in plane versus out-of-plane). A comparison with synthetic seismograms establishes whether the observations can be explained by a previously suggested 300km thick D" layer. We present a number of observations in this region and a wider coverage than previously possible by showing the results for PdP and SdS waves, their travel time and polarity measurements for different crossing paths and focus on the consistency of the observations.

MMTZ - A New Mid-Mantle Transition Zone

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Abstract

The location and source of the Earth's interior heterogeneities remains an important area of research. Despite our advances in understanding structural changes in the Earth, there is still controversy over the cause and location of viscosity jumps in the mantle. In this work, we use K-Means clustering (a form of cluster analysis in machine learning) to generate heterogeneity percentage profiles for different tomographic models. Key cluster percentage shifts, which are observed at approximately 400 km, 650 km, 1050 km, 1500 km, and 2700 km, suggest global mantle discontinuities at corresponding depths. A mid-mantle transition zone (MMTZ) bounded between the 1050km and 1500 km discontinuities is detected for the first time. Potential viscosity changes associated with this mid-mantle transition zone are tested using geoid anomalies.

Keywords: mid-mantle transition zone, machine learning, viscosity, discontinuities

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ABSTRACT

Title: Receiver function imaging of the 660 discontinuities beneath Yellowstone: New constraints on the origin of thermal upwelling

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Description: The debate surrounding the origin of the Yellowstone super-volcano has persisted for decades. Additional evidence is required to reach a common understanding of whether the intra-plate volcanic activities stem from lower-mantle upwelling or are caused by lithosphere extension and slab subduction within the upper mantle. This study examines the mantle-transition-zone structures beneath the Yellowstone region by a combination of P and SKS receiver functions collected across the Western United States. Individual migration of both types of receiver functions using common-conversion-point stacking reveals reasonably consistent outcomes of transition-zone topography, including an uplifted 660 discontinuity near Yellowstone. We observed systematic amplitude reductions of the 660 in SKS receiver functions in the southeastern Yellowstone caldera. Two-dimensional forward wavefield modeling of conversion amplitudes confirms the presence of a low-velocity structure in the lower mantle. Assuming a simple geometry, a grid search over the size and magnitude of velocity reduction determines the optimal Vs perturbation of ~-2%. The estimated low-velocity structure, which spans approximately 500 km in width, rises from the southwest to the northeast and reaches the base of the mantle transition zones. Despite the poorly constrained geometry beyond 2000 km, our integrated analysis of the converted waves offers compelling evidence for the existence, geometry, and possible origin of a deep source of thermal upwelling underneath the Yellowstone caldera.

Travel time catalog and mantle tomography for global P- and S-wave arrivals based on deep learning

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Mantle velocity structure is an essential constraint to geodynamic models and planet formation theories. Previous studies have suggested the importance of using multiple velocities to distinguish changes in composition from temperature variation. However, making full use of the large volume of data from globally deployed seismic stations still requires a scalable analysis rather than correlating with synthetic waveforms. In this study, we implemented deep learning on phase picking for P and S onset arrivals and acquired a global travel time catalog for intermediate to large earthquakes to the latest.

We modified the machine learning approach from Mousavi et al. (2020) and trained a phase-picking model for teleseismic P and S arrivals with the dataset labeled by Houser et al. (2008). We apply the trained model to a dataset containing all available long-period (sampling at 1 Hz) data on IRIS-DMC for earthquakes cataloged in GCMT from 1976 to mid-2023 (~60,000 events) to obtain a travel time catalog for worldwide seismic stations.

To test the effectiveness of our travel time picks for global seismology, we conducted a tomographic inversion using the LSQR method to obtain a preliminary three-dimensional P and S velocity model. The new model generally agrees with previous studies on velocity structure, suggesting our measurements are consistent with hand-picked data, and future work using statistical inversion will improve the model's resolution and allow better interpretation of the data.

Some issues on the rheological properties of the lower mantle

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The lower mantle occupies a large fraction of the mantle (~72%) and therefore convection in the lower mantle has an important control over the thermal and chemical evolution of the whole Earth. However, experimental studies on the rheological properties of minerals (and rocks) under the lower mantle conditions are challenging, and consequently a few major controversies exist on the lower mantle rheology. They include the mechanisms of plastic deformation, the relative strength of two major phases (Fp (ferropericlase) and Bm (bridgmanite)), the depth variation of viscosity, and the evolution of rheological behavior of a two-phase mixture at finite strain. We use an inter-disciplinary approach where materials science of deformation (both experimental and theoretical) and geophysical observations (distribution of seismic anisotropy, depth variation of viscosity) are integrated. Particularly important geophysical observations are (i) the lower mantle is mostly seismologically isotropic although a substantial fraction of the D” layer is anisotropic and (ii) viscosity increases only modestly with depth in the lower mantle.

The main conclusions are:

1. Deformation occurs mostly by diffusion creep but also by power-law dislocation creep in high stress regions (but not by pure climb creep or asthermal creep).
2. Ferropericlase (Fp) is substantially weaker than bridgmanite (Bm) in the lower mantle.
3. When a mixture of Fp (~20%) and Bm (~70%) deforms by diffusion creep, strength contrast is enhanced with finite strain (caused by the increase in stress concentration at grain-boundaries) leading to substantial strain-weakening particularly for simple shear deformation.

The conclusion (1) is largely based on materials science considerations based on experimental data on a large number of materials and the theoretical models of plastic deformation (for a review see Frost-Ashby (1982)) as well as on the distribution of seismic anisotropy (pure climb creep nor athermal creep predicts no anisotropy in all lower mantle).

The conclusion (2) is based on the available experimental data on deformation (e.g., Girard et al., 2016, Tsujino et al. (2016, 2022)) as well as experimental data on diffusion (Yamazaki et al. 2001, van Orman et al., 2003) and theoretical studies on diffusion (Karato, 1981; Ita and Cohen, 1997; Ammann et al. 2010; Cordier et al., 2023). However, there are large uncertainties in this conclusion because of the uncertainties associated with the extrapolation of laboratory data to geological strain-rate and because of the large uncertainties in diffusion coefficients in the lower mantle minerals including the role of impurities (extrinsic versus intrinsic diffusion) as well as the pressure dependence of diffusion.

Finally (3), we use the self-consistent model in modeling the deformation of a Fp and Bm mixture, but this method has a limitation in evaluating strain-weakening behavior.

Some implications for the preservation of geochemical reservoirs will be discussed including the contrasting behavior between the upper and the lower mantle.

The sensitivity of lowermost mantle anisotropy to past mantle convection

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Seismic anisotropy in the lowermost part of the Earth's mantle—called D″—is widely thought to be caused by the flow-induced alignment of crystals, for example post-perovskite (ppv). Therefore, it is possible that observation and modelling of this anisotropy could allow us to infer the present-day flow field of the mantle in D″, and thereby better constrain mantle flow as a whole. However, texture and anisotropy may also reflect a longer-term history of mantle convection. If this is preserved in crystal alignment in D″, then this is both a complicating factor and a potential source of extra information about how flow has developed over recent geological history. However, as yet there are few constraints on just how far back in time the mantle may preserve flow patterns via anisotropy, and we do not have evidence either way that the mantle has a 'memory' of mantle flow in the anisotropy recorded in D″.

In this work, we test the hypothesis that lowermost mantle anisotropy only records the present-day flow by using an Earth-like simulation of mantle circulation, where the past 500 Myr of plate motion history are incorporated into a 22 km-resolution mantle dynamical model. We trace particles back through time from the present day and record the velocity gradients experienced along the calculated path lines. These are then used to drive a viscoplastic self-consistent (VPSC) model of texture development in a pure-ppv aggregate of 500 crystals. This yields a fully elastically anisotropic model of D″. We can then compare this to a companion model where texture is developed by only using the present-day velocity gradients, which represents the texture inferred by assuming a present-day instantaneous flow field.

We find, on the scales to which global radial seismic tomography is sensitive, the steady-state approximation holds well, and the majority of D″ appears the same in both dynamic and steady-state texture models, recording a difference of less than 2% in radial anisotropy parameters almost everywhere. There are some areas (1000s km across) where parameters differ by more than 10%; these are mainly near upwellings and are caused by the migration of flow features over the last ~100 Myr. Considering general anisotropy, local observations of anisotropy such as shear-wave splitting would therefore also record mainly the present-day flow field; however there are many more areas of the model where the elasticity is very different when assuming a steady-state flow field and considering the fully-dynamic case. We find here that the mantle's memory may be around 80–100 Myr. In summary, whole-mantle observations are likely primarily sensitive to the most recent mantle flow only, while regional observations may hold information on past mantle flow. As such, we advise caution when interpreting such data in terms of flow.

Seismic constraints on mantle oxidation

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The Earth's atmosphere and crust are highly oxidized (sharing electrons), while the core is highly reduced (storing electrons), such that the planet operates much like a battery. Thus, the deep mantle is conduit through which electrons must flow in order to power planetary chemistry. The planet's capacity to store and release electrons is a driving force for the chemical reactions that promote the ability for life to develop and sustain itself. Given this large redox gradient between the surface and core, it is not clear how this is accommodated by the mantle rock which lies between. While the early atmosphere present during the first emergence of life depends on the redox state during magma ocean crystallization, there are few rocks from this time period at the surface. Here we seek to compare observations of the seismic properties in the deep mantle to examine the current and ancient mantle oxidation.

Seismic wave properties vary with changes in composition, temperature, and mineral crystal structure. Seismic tomography 3D mapping of fast and slow wave speeds provides a window into Earth's deep time chemical evolution. In addition, reflections of body waves a few hundred kilometers above the core-mantle boundary indicate regions where the temperature and composition conditions are favorable for the post-perovskite transition. In the lower mantle, iron in (Mg,Fe)O ferropericlase exists in the Fe2+ state while iron in (Mg,Fe)SiO3 bridgmanite and post-perovskite phase exists as Fe2+ or Fe3+. The relative amount of Fe3+ over the total iron indicates the oxidation of the mineral assemblage. Using P- and S-wave travel time curves from a new modern arrival time catalog combined with the depth of reflectors from the post-perovskite transition, we aim to determine if the observations are more compatible with predictions for a more oxidized or reduced lower mantle.

Towards a global map of ultra-low velocity zones using S diffracted waves

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Ultra-low Velocity Zones (ULVZs) are regions of greatly reduced wavespeed that lie on the core-mantle boundary, with lateral and vertical length scales of 100s of km and 10s of km respectively. As well as being linked to the two Large Low Shear Velocity Provinces (LLSVPs), they may also play a role in whole mantle dynamics, potentially as passive tracers or more actively feeding into or anchoring plume hotspots.

While ULVZs have been found near and far from hotspots, the largest ULVZs appear to be found near the hotspots with the highest buoyancy flux. Their actual nature in terms of composition and origin also remains uncertain. Knowledge of both the global locations of ULVZs and locations where they conclusively do not exist would allow for their relationship with LLSVPs and hotspots, and related origin scenarios, to be probed further.

Previous studies have made a global compilation based on studies using heterogeneous data types (Yu & Garnero, 2018) or algorithmically modeled anomalous SPdKS waveforms (Thorne et al., 2021) to maximise coverage. Postcursors to the diffracted shear wave, Sdiff, has previously been used to locate and model 3D ULVZ properties. The long diffracted portion on the CMB for this phase makes it well suited to studying large areas of the core-mantle boundary, although the postcursors are refracted out of plane, which needs accounting for to locate a ULVZ. This poster will showcase work towards making a global map of ULVZs using a large handpicked Sdiff postcursor dataset, which will in the future be used to statistically test the aforementioned spatial relationships with LLSVPs and hotspots.

Probing Deep Mantle Density Variations Using Full-Spectrum Tomography

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Abstract

Long-period free oscillations, triggered by large earthquakes, have provided valuable insights into the elastic properties and the density profile of the Earth's interior structure. Initially used to constrain the radial structure of the Earth, their spectra have progressively been applied to study lateral variations in the mantle. The lowest frequency modes, in particular, exhibit increased sensitivity to long-wavelength density anomalies in the deep mantle, and characterizing this property of Earth’s heterogeneity remains a key goal in geodynamics. A feature of significant interest in the lower mantle is the buoyancy of the Large Low-Velocity Provinces (LLVPs), which have important implications for our understanding of mantle convection and the overall thermochemical evolution of the Earth. Current debates center on the degree to which LLSVPs are dominated by chemical heterogeneity (and therefore negatively buoyant) or thermal heterogeneity (and therefore positively buoyant). This ambiguity in the nature of LLVPs underscores the need for more precise modeling techniques and comprehensive data analysis.

Traditional methods for modeling seismic normal modes involve forward and inverse modeling approximations, resulting in significant uncertainties in the resulting tomography models. In this work, we demonstrate how our framework overcomes these limitations by employing a more comprehensive forward theory and an efficient inverse problem formulation using the adjoint method. Specifically, we focus on preliminary results produced from the first “full spectrum” tomographic analysis of directly inverted global seismic spectra. This new methodological development allows us to investigate deep mantle density variations with greater accuracy, which is crucial for advancing current debates on the thermochemical nature of the deep mantle. Our approach provides a more detailed understanding of deep mantle structures, thereby refining our knowledge of Earth's interior and its dynamic processes.

Depth-dependent anisotropy in the lower mantle reveals anisotropic discontinuity at 1000 km

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There is growing evidence, both from a modelling perspective and seismic observations, that seismic anisotropy in the lower mantle is localized around penetrating slabs where large straining is anticipated. It is believed that the high stresses experienced near the slab activate dislocation creep mechanisms that drive the crystallographic preferred orientation (CPO) of bridgmanite aggregates. Still, deformation mechanisms in bridgmanite remain enigmatic. In recent years, deformation experiments in bridgmanite subjected to mantle temperatures and pressures suggest that its microstructures evolve with pressure, providing another perspective on the debated structure and deformation in the lower mantle. Using this information, we develop a numerical technique that calculates pressure-dependent large-scale seismic anisotropy in a pyrolitic mantle with variable velocity gradients. As a first test, we use the method to predict seismic anisotropy by calculating anisotropic reflection coefficients of underside reflections off a depth corresponding to 50 GPa where pressure-induced slip transitions in bridgmanite are expected. For this, we consider two simple deformation styles: (1) uni-axial compression, akin to vertically penetrating slabs, and (2) simple shear associated with corner-type flows. Finally, we demonstrate a multiscale approach that calculates large-scale seismic anisotropy from a fully time-dependent thermo-chemical model of free subduction. The result is a long-wavelength equivalent radial anisotropy maps that are actually comparable to a seismic tomography model. Finite strain analysis helps determine the relevant distribution of anisotropy. We demonstrate how such approaches can create discontinuities in anisotropy at ~1000 km that is potentially detectable by underside reflection of precursory waves. We provide insights as to how it relates to the heterogeneous distribution of the 1000-km discontinuity.

Towards constraining global-scale lowermost-mantle anisotropy using normal modes

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The relation between seismic anisotropy and flow-induced deformation in the mantle has the potential to constrain large-scale patterns of mantle dynamics. Global-scale, 3-D mantle models of radial anisotropy have mostly been inferred from shear-wave splitting and surface-wave phase velocities, and agreement between models in the lowermost mantle is poor. Global-scale mantle models of azimuthal anisotropy are limited to the upper mantle and the transition zone. Here we assess the ability of a different type of seismic data, normal modes, to constrain global-scale radial and azimuthal anisotropy, focusing on the lowermost mantle. Normal modes are whole Earth oscillations that are induced by large earthquakes and have sensitivity to large-scale elastic structure throughout the entire Earth. Normal-mode splitting functions have previously been used to infer azimuthal anisotropy in the upper mantle and the transition zone, but the large number of model parameters for a fully anisotropic medium limits their resolvability. We perform a principal component analysis on the sensitivity kernels of the normal-mode dataset, allowing us to determine which elastic parameters will account for most of the data variations. We find that the principal component analysis successfully reduces the number of model parameters and that there is significant sensitivity to radial and azimuthal anisotropy throughout the entire mantle, allowing for a future inversion of normal-mode splitting functions for global-scale mantle anisotropy.

ULVZs, LLVPs, and attenuation in the lowermost mantle

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The lowermost mantle is one of the most heterogenous and enigmatic regions in Earth. Over recent decades, seismologists have uncovered structures from the large- (large low velocity provinces, LLVPs) to the small-scale (ultra-low velocity zones, ULVZs). Whilst LLVPs are thought to be weakly reduced in S and P velocity, ULVZs on the other hand have been imaged to be up to 50% reduced in S velocity. The origin and longevity of LLVPs and ULVZs is poorly understood. In this study, we present an up-to-date global overview of ULVZs imaged across all studies. Whilst there was initially a correlation proposed between ULVZs and hotspots (Williams et al, 1998), with the detection of more structures in the last three decades using a variety of phases this correlation has been obscured. ULVZs have been detected near hotspots, away from hotspots, within LLVPs, at the edges of LLVPs, in regions with a history of subducted slab material/away from LLVPs. However, those detected using Sdiff postcursors are still only observed within or at the boundaries of LLVPs. We note that this subset of detections is likely partially due to the bias of the source-receiver distribution, but that it more likely indicates that Sdiff is only sensitive to the very largest ULVZs. This correlation supports a geodynamical link between LLVPs and ULVZs, which has been previously suggested (e.g. Li et al, 2017). From these detections, there also remains a strong correlation between ULVZs and hotspots associated with geochemical signatures (Cottaar et al, 2022).

The second part of this study relates to attenuation in the lowermost mantle and, in particular, attenuation within and outside LLVPs. Recent attenuation tomography from normal modes (Talavera-Soza et al, in revision) is in good agreement with attenuation observations from body waves and surface waves in the upper mantle (e.g. Dalton et al, 2008), but diverge in the lowermost mantle. In particular, normal modes observe LLVPs to be weakly attenuating, whilst body waves studies have observed the opposite (e.g. Liu & Grand, 2018). Our aim is to make a new body wave attenuation dataset for the lower mantle to compare with the normal mode attenuation observations. We will benchmark two different methods to measure attenuation for S/ScS data, spectral ratio and the instantaneous frequency matching. Within these methods, we will test the effectiveness of recovering δt* values for the lowermost mantle in the Pacific from synthetics; specifically accounting for the common source mechanisms observed in this region and making corrections for de/focussing caused by elastic structure in this region.

Electromagnetic torque in numerical dynamo simulations

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The core flow at the core mantle boundary (CMB) and its contributions to magnetic induction and the electromagnetic (EM) torque are the main focus of this study. First, the possibility of expressing the EM torque using the core surface velocity field is being investigated. Schwaiger et al. (2024) have found that in the case of a stress-free dynamo with a homogeneous conducting layer on top of the CMB, the major part of the EM torque is solely due to the solid body rotation. It has also become clear that there is little room for the additional torque, the leakage torque, which is created by electrical currents leaking from the core into the mantle. In this framework, observed length-of-day (LOD) changes cannot be explained by the EM torque alone. However, one of their main hypotheses is to ignore the effect of a possibly non-homogeneous conductivity. Therefore we extend their study in order to allow for lateral variations in the conducting layer. Based on this, attempts to invert for a conducting layer which could explain alone the total torque from the simulation (i.e., including the gravitational torque as well as the rather unimportant leakage torque) were unsuccessful. So are tests performed with geodetic measurements and flow models inverted from geomagnetic observations. This leads to the preliminary conclusion that the EM torque cannot act alone to account for the temporal changes in the length of day. Additionally, a new expression of the complete EM torque is considered, allowing it to be calculated by one single and rather simple integral from simulations, rendering the differentiation into poloidal and toroidal components unnecessary. This first study is being completed using a non-slip dynamo created with XSHELLS (Schaeffer et al., 2017) in the absence of gravitational torque but with a conducting layer at the bottom of the mantle, investigating its effects on LOD changes and the reproducibility of the previous study's conclusions.

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The challenges posed by core undertones within solid-Earth geophysics

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Abstract

The vast majority of global tomographic models contain continent-sized regions at the base of the mantle – the 'Large Low Velocity Provinces' (LLVPs) – within which both S- and P-waves travel anomalously slowly. The LLVPs' provenance is not known. Are they simply evidence of upwelling mantle at the base of a thermal convection cell? Or are they a chemically distinct 'slab graveyard'? The answers to these questions are tied intimately to the nature of lower mantle convection.

For a better understanding of LLVPs it is crucial to obtain measurements of their density. But lateral density variations are notoriously hard to invert seismic data for, much more so than seismic wave speeds. This is because we must consider long-period ($\gtrsim$ 10 mins) motions if we are to probe density, while accounting fully for the effects of gravity in forward models. **This poster discusses the forward modelling of such long-period motions, particularly the associated behaviour of the outer core.**

It is first shown why only long-period motions should be expected to carry information on density. The poster focuses on normal modes, body tides and rotational variations.

The current state of the modelling of such motions is then reviewed, with particular reference to the computational technique of normal-mode coupling. It is argued that existing studies of lateral density variations should be interpreted with caution, and that the full effect of lateral density variations on some long-period motions – such as diurnal tides, the Nearly-Diurnal Free Wobble and the Chandler Wobble – might not be modelled adequately at present.

It is then pointed out that the assumption of an inviscid outer-core could pose an **additional** problem in the long-period context. This is due to the existence of long-period 'core undertone modes', motions within the outer-core that are related to both rotation and stratification and that have periods $\gtrsim$ 10 hours (or $\geq$ 12 hours if the core is everywhere neutrally stratified). The main issue with core undertones is that their characteristic lengthscale *decreases* with period in an inviscid Earth model, in stark contrast to the behaviour of a solid body's elastic normal modes. It follows that the long-period motions discussed earlier may excite flows of extremely short wavelength within the outer core. The mathematical difficulties associated with such flows means that they cannot readily be modelled computationally – and since they are expected to couple to the elastic motion within the solid Earth, it follows that simulations of an inviscid Earth-model's long-period motions might not be reliable.

The inviscid assumption is common in solid-Earth geophysics. Moreover it is not problematic at the seismic timescales usually considered because those timescales are far removed from undertone timescales. But the mathematical issues caused by neglecting viscosity could be important when seeking to model tides and rotational motions.

The remainder of the poster gives a more holistic discussion of core undertones, reviewing the associated issues from both theoretical and computational perspectives, discussing the solutions that are employed at present, and speculating on ways forward. Topics covered include:

- the validity of state-of-the-art normal-mode coupling calculations, which routinely ignore core-undertones;
- one- and two-potential formulations for core flows;
- the effect of including a realistic viscosity;
- the effect of including a realistic magnetic field (which might be expected to damp the core motions in a manner somewhat similar to viscosity).

In particular, it is argued that just including a realistic viscosity – which would *in principle* remove all the mathematical difficulties alluded to in the previous paragraph – is probably not practical from a computational standpoint, at least not in the parameter range associated with the Earth.

Mid-mantle imaging through a reverberant transition zone: A CRISP-RF approach

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On a planet that dissipates heat through whole mantle convection, no sharp changes in elastic properties are **expected in the mid-mantle: ~750-1300 km**. Yet, a growing number of seismic studies continue to document evidence of discontinuities across these depths. Compared to the upper mantle, the global prevalence and causal origins of such features remain relatively enigmatic. Here, we investigate mid-mantle layering beneath two large seismic arrays (US and Alaska) using high-resolution Ps-converted waves. The challenge is that top-side reflections **(reverberations) from the mantle transition zone** interfere with and contaminate desired mid-mantle conversions and make their interpretation difficult. In the past, the slowness slant stack (vespagram) approach has been used. We extend the resolution of this stacking scheme using a newly developed sparsity-promoting, non-linear, CRISP-RF technique (***C****lean* ***R****eceiver function* ***I****maging with* ***Sp****arse* ***R****adon* ***F****ilters*). Preliminary results suggest that CRISP-RF can isolate high-frequency (0.5Hz) mid-mantle body wave conversions buried within transition zone reverberations. With our filtered Ps-RFs and machine learning, we will present tighter constraints on mid-mantle layering (depth, sharpness, spatial variation) exploring important implications for its origin.