Fine structure of boundaries of the Earth’s core

Sidao Ni*1, Baolong Zhang[1], Yulong Su[2], Wenbo Wu[3], Yulin Chen†1, Zhichao Shen[3], Wenzhong Wang[2], Daoyuan Sun[2], Zhongqing Wu[2], Mingming Li[4], Heping Sun[1], Mingqiang Hou[1], Xiaoming Cui[1]

1.State Key Laboratory of Geodesy and Earth’s Dynamics, Innovation Academy for Precision Measurement Science and Technology, Chinese Academy of Sciences, Wuhan, Hubei, China.

2.School of Earth and Space Sciences, University of Science and Technology of China, Hefei, Anhui, China.

3.Department of Geology and Geophysics, Woods Hole Oceanographic Institution, Woods Hole, MA, USA.

4.School of Earth and Space Exploration, Arizona State University, Tempe, AZ, USA.

Abstract

The fine-scale seismic features near the boundaries of the Earth's core provide critical insights into the thermal state, chemical compositions, and dynamic evolutions of the Earth's deep interior. We propose two methods to resolve the ultra-low velocity zones (ULVZs) above the core-mantle boundary (CMB) and the structures near the inner core boundary (ICB).

Previous studies have shown that ULVZs are mostly associated with large low-velocity provinces (LLVPs) or hot spots, caused by partial melt or compositionally distinct materials. To enhance the sampling of the lowermost mantle, we collected a global dataset of SKKKP and its B-caustic diffractions. Through systematic analyses, we identified ULVZs not only around two LLVPs but also in previously under-explored high-velocity D″ regions, including Central America, Alaska, Greenland, and West Asia. Our findings suggest that some ultra-low velocity zones might originate from former subducted slabs caused by chemical differences of slab materials and temperature perturbations at the core-mantle boundary.

Additionally, utilizing pre-critical PKiKP waveforms, we constrained the fine structure at the ICB. Our modeling suggests a sharp ICB beneath Mongolia and most of Northeast Asia, but a locally laminated ICB structure beneath Central Asia, Siberia, and part of Northeast Asia. The complex ICB structure might be explained by either the existence of a kilometer-scale thickness of mushy zone, or the localized coexistence of bcc and hcp iron phase at the ICB. We infer that there may be considerable lateral variations in the dendrites growing process at ICB, probably due to the complicated thermochemical and geodynamical interaction between the outer and inner core.

Keywords: Core-Mantle Boundary, Inner Core Boundary, Ultra-low Velocity Zone

*Corresponding author: sdni@whigg.ac.cn

†Speaker

Evolution of the inner core boundary: nucleation and growth of the inner core

Alfred J Wilson[1*], Christopher J Davies[1], Arwen Deuss[2], Andrew M Walker[3], Dario Alfè[4,5,6] and Monica Pozzo[4,5]

[1]University of Leeds, School of Earth and Environment, Leeds, UK
[2]Utrecht University, Department of Earth Sciences, Utrecht, Netherlands
[3]University of Oxford, Department of Earth Sciences, Oxford, UK
[4]University College London, Department of Earth Sciences, London, UK
[5]University College London, London Centre for Nanotechnology, Thomas Young Centre, London, UK
[6]Universita` di Napoli “Federico II”m Dipartimento di Fisica “Ettore Pancini”, Napoli, Italy

[*]a.j.wilson1@leeds.ac.uk

Abstract

Combining mineral physics and nucleation theory with seismological and palaeomagnetic data on the Earth’s solid inner core presents a paradox. Supercooling is necessary for inner core nucleation, as with any freezing process, but theory mandates that the liquid core must have been supercooled several hundred degrees below its melting temperature for the inner core to spontaneous freeze. Geophysical observations of inner core size on the other hand limit this supercooling to be far smaller. We explore prior assessments of inner core nucleation using a new thermal history model which requires the liquid core be supercooled prior to nucleation, a feature missing from all previous models. Our model shows that only ~80 K of supercooling is permissible to satisfy geophysical constraints from seismology, but this implies that the inner core underwent rapid freezing in the immediate past. Modest supercooling of the liquid core (less than 40 K) is able to satisfy both seismological and paleomagnetic constraints, including a consistently strong dipole moment over the past 300 Myrs of the palaeomagnetic record. With moderate supercooling prior to inner core nucleation, much of the inferred heterogeneity of the inner core can be explained, although many of the deformation mechanisms proposed to generate inner core structure are either modified or nullified.

Identification of Rare Multiple Core-Mantle Boundary Reflections PmKP Up To P7KP With Deep Learning

Sheng Dong[123], Yulin Chen[*†1],Baolong Zhang[1], Sidao Ni[1], Xiaofei Chen[3], Yi Wang[1]

1.State Key Laboratory of Geodesy and Earth's Dynamics, Innovation Academy for Precision Measurement Science and Technology, Chinese Academy of Sciences, Wuhan, Hubei, China

2.School of Earth and Space Sciences, University of Science and Technology of China, Hefei, China

3.Department of Earth and Space Science, Southern University of Science and Technology, Shenzhen, China

Abstract

The core-mantle boundary (CMB) marks the most dramatic changes in physical properties within the Earth, and plays a critical role in the understanding of the Earth's dynamics. PmKP waves are seismic phases that reflect (m-1) times under the CMB and are useful for studying the complex CMB structure. We present an automated workflow for detecting PmKP phases using multi-station records from global seismic stations. We employ a novel sampling method to extract PmKP waveforms into a 2-D matrix. Two deep neural networks are then utilized for initial phase detections and subsequent slowness validations. Numerous PmKPab ($3 \leq m \leq 7$) and their CMB diffracted signals were identified for deep earthquakes (magnitude > 6) occurred from 2000 to 2020, including diffracted P7KPab waves with diffraction lengths of nearly 20°. Our approach significantly improves the efficiency of PmKP phase identification and holds the capability to detect other weak core phases, such as PKiKP.

Keywords: PmKP Waves, Core-Mantle Boundary, Deep Learning

*Corresponding author: chenyulin@whigg.ac.cn

†Speaker

Title: Resolving Sparsely Constrained Properties of the Deep Earth

Authors: Adrian Mag, Paula Koelemeijer, Christophe Zaroli

The study of Earth's deep interior using geophysical data typically requires solving an inverse problem. The quality of the solution to these problems depends on several factors: data quality, data quantity, and modeling approximations. In seismology, this usually leads to an ill-posed inverse problem with many solutions. Classical inversion methods remove this non-uniqueness by regularizations and model discretization. These assumptions place strong constraints on the resulting model and without a good physical basis they lead to systematically inaccurate models.

Deterministic linear inference methods, such as the Backus Gilbert SOLA (BG SOLA) method, can bypass the non-uniqueness issue by constraining properties of the unknown model, rather than the model itself. Assuming a linear relationship between data and model parameters, this approach can retrieve continuous model parameters with only mild regularizations. The only prior information needed is a norm bound on the model space, which is less stringent than that needed for classic regularized inversions. This reduces the risk of introducing subjective information into the inference problem.

In this contribution, we will introduce the theoretical aspects of the SOLA method with deterministic linear inferences (SOLA-DLI) in a general setting. An advantage of the SOLA-DLI method is that it provides useful uncertainty quantification as well as information about the resolution of the desired property. It can also be used when the data depend on multiple model parameters at the same time. These advantages will be showcased in a simple application of the theory on constraining Earth's 1D structure in synthetic experiments. Specifically, we demonstrate how SOLA-DLI can be used to constrain properties other than local averages (e.g. gradients) and how trade-offs between physical parameters can be quantified. These results indicate that the method may be particularly useful when aiming to constrain core-mantle boundary topography, which strongly trade-offs with lower mantle structure. Finally, we also indicate how SOLA-DLI can be utilised to obtain discretised models, comparing the solution to that obtained using regularized inversion methods.

A non-equilibrium slurry model of the F-layer above the inner core boundary

Andrew M. Walker, Chris J. Davies, Alfred J. Wilson, Michael I. Bergman
University of Oxford; University of Leeds; Bard College at Simon's Rock

Email: andrew.walker@earth.ox.ac.uk

The region just above the inner core boundary has unexpectedly low P-wave velocity. This challenges our understanding of core evolution because light elements excluded from the inner core as it grows would be expected to result in an increase in the P-wave velocity of the deepest outer core. A longstanding suggestion is to imagine a slurry zone at the base of the outer core where a low volume fraction of solid iron particles coexists with the liquid iron alloy so that the inner core grows as the solid particles fall out of the liquid. Similar slurry layers have been proposed to exist in the cores of other planetary bodies including Ganymede, Mercury and Mars. However, models of all these layers usually assume thermodynamic equilibrium such that the volume fraction of solid and the liquid composition are set directly by the temperature. A corollary of this approach is that the physical size and falling time of the iron particles cannot be known without making additional assumptions.

We outline the key results obtained from a model of a slurry layer based of the important processes experienced by a single iron particle as it falls and grows. These processes are driven by a thermodynamic model but do not assume thermodynamic equilibrium. Processes such as kinetically hindered growth, diffusion of light elements through a boundary layer created by the falling particle, and an energy barrier to nucleation all act to allow deviation from thermodynamic equilibrium while a balance between buoyancy and drag as the particle falls sets the timescale over which equilibrium can be approached. For typical parameters, particles grow to become a few cm across and fall through the 200 km thick F-layer in 10 to 100 days. This single particle models can be used to build a simple description of the whole F-layer where particles are permitted to nucleate throughout the layer before falling onto the inner core. Key results then include the solid production rate in the layer, the size distribution of the falling particles, and rate at which the inner core grows by sedimentation. The growing particles release latent heat and light elements which we assume escape from the layer to power the geodynamo in the overlying convecting outer core. A small number of key parameters control these model predictions, and we find a window in parameter space that is consistent with the gross properties of the F-layer. Within this family of models, lower rates of nucleation must trade-off for higher particle growth rates. Furthermore, as the material properties change to decrease nucleation or growth rates the departure from equilibrium and thus cooling below the liquidus increases to compensate.

Inferring the relationship between core-mantle heat flux and seismic tomography from mantle convection simulations

Choblet, G.,[a] Deschamps, F.,[b] Amit, H.,[a] Lasbleis, M.,[a]

[a] Nantes Université, Univ Angers, Le Mans Université, CNRS, Laboratoire de Planétologie et Géosciences, LPG UMR 6112, 44000 Nantes, France.
[b] Institute of Earth Sciences, Academia Sinica, 128 Academia Road, Section 2, Nangang, Taipei 11529, Taiwan.

The heat flux pattern at Earth's core-mantle boundary (CMB) imposes a heterogeneous boundary condition on core dynamics that may profoundly affect the geodynamo. Owing to the expected temperature dependence of seismic velocities, this pattern is classically approximated as proportional to the lowermost layer of seismic tomography models for the global mantle. Two biases however undermine such a simple linear relationship: 1) other contributions than thermal (compositional and mineralogical) influence seismic velocities and 2) the radial average is inherent to tomographic models whereas the local thermal state at the CMB is relevant for the heat flux. We analyze here simulations of thermochemical mantle convection where, owing to their spatial characteristics, specific mantle components are readily identified: hot thermochemical piles (TCPs), "normal" mantle (NM) and, when post-peroskite (pPv) is included, a cold region where this phase is present. Synthetic seismic velocities (i.e. from the mantle simulations) are then computed based on thermal, compositional and mineralogical sensitivities. A formalism to infer the CMB heat flux from these seismic shear velocity anomalies is derived. In this formalism, within each mantle population (i.e. TCPs, NM or pPv) the CMB heat flux vs. seismic anomalies follows a unique fitting function. The transition from one mantle population to another is marked by a jump in the seismic anomaly, i.e. a range of seismic anomalies in between two mantle populations corresponds to a similar CMB heat flux. Applying our formalism to the seismic anomalies from the mantle convection simulations provides far superior fits than the commonly used linear fits. The results highlight reduced negative heat flux anomalies beneath large low shear velocity provinces (LLSVPs), while positive heat flux anomalies are enhanced, both with respect to the classical linear interpretation.

Title: Identification of Rare Multiple Core-Mantle Boundary Reflections PmKP up to P7KP with Deep Learning

Authors(s): Yulin Chen, Sheng Dong, Baolong Zhang, Sidao Ni, Xiaofei Chen, Yi Wang

Affiliation(s): State Key Laboratory of Geodesy and Earth’s Dynamics, Innovation Academy for Precision Measurement Science and Technology, Chinese Academy of Sciences, Wuhan, Hubei, China

The core-mantle boundary (CMB) marks the most dramatic changes in physical properties within the Earth, and plays a critical role in the understanding of the Earth’s dynamics. PmKP waves are seismic phases that reflect (m-1) times under the CMB and are useful for studying the complex CMB structure. We present an automated workflow for detecting PmKP phases using multi-station records from global seismic stations. We employ a novel sampling method to extract PmKP waveforms into a 2-D matrix. Two deep neural networks are then utilized for initial phase detections and subsequent slowness validations. Numerous PmKPab ($3 \leqslant m \leqslant 7$) and their CMB diffracted signals were identified for deep earthquakes (magnitude > 6) occurred from 2000 to 2020, including diffracted P7KPab waves with diffraction lengths of nearly 20°. Our approach significantly improves the efficiency of PmKP phase identification and holds the capability to detect other weak core phases, such as PKiKP.

Seismic Evidence for Ancient Intraoceanic Subduction Beneath the Nazca Plate

Jingchuan Wang*†1, Vedran Lekić[1], Nicholas Schmerr[1], Jeffrey Gu[2], Yi Guo[2], and Rongzhi Lin[2,3]

[1]Department of Geology, University of Maryland, College Park, MD, USA
[2]Department of Physics, University of Alberta, Edmonton, AB, Canada
[3]School of Mathematics and Center of Geophysics, Harbin Institute of Technology, Harbin, China

Abstract

The morphology of the Large Low Shear Velocity Provinces (LLSVPs) has been a subject of debate for decades. Large-scale features of the Pacific LLSVP, as revealed by cluster analysis of global tomographic models, suggest three distinct portions. Notably, the East Pacific Anomaly and the Superswell Anomaly are characterized by a ~20 deg wide gap. However, the cause of the structural gap remains unclear, and there has been no direct evidence for a subduction episode beneath the region. In this study, we take advantage of an up-to-date SS precursor data set that samples the Nazca Plate and investigate the high-resolution seismic structure at mantle transition zone (MTZ) depths. We find that much of the southern East Pacific Rise is underlain by a thin MTZ due to the depressed 410 by up to 15 km, which suggests along-ridge temperature variations extending into the MTZ. East of the East Pacific Rise, the MTZ is characterized by anomalous thickening and fast seismic velocities from seismic tomography, consistent with the presence of cold subducted slab material intersecting the MTZ. Furthermore, recent global tomographic models reveal a slab-like structure throughout the MTZ and lower mantle, which is also evidenced by tomographic vote maps, albeit with less visibility. The observations reconcile with Mesozoic intraoceanic subduction beneath the present-day Nazca Plate, which is predicted by an earlier plate reconstruction model of proto-Pacific Ocean. The subduction initiated ~250 Myr ago and ceased before 120 Myr ago. The implications of this discovery are that the shape of the eastern portion of the Pacific LLSVP was separated by downwelling associated with this ancient subducted slab. Our discovery provides a new perspective on linking deep Earth structures with surface subduction.

Substantial global radial variations of basalt content near the 660-km discontinuity

Shangqin Hao[1], S. Shawn Wei[2], Peter M. Shearer[1]

[1]Institute of Geophysics and Planetary Physics, Scripps Institution of Oceanography, University of California, San Diego, La Jolla, CA, USA
[2]Department of Earth and Environmental Sciences, Michigan State University, East Lansing, MI, USA

Basalt and harzburgite, generated at mid-ocean ridges, are introduced into the mantle through subduction as a mechanical mixture, contributing to both lateral and radial compositional heterogeneity. The possible accumulation of basalt in the mantle transition zone has been examined, but details of the mantle composition below the 660-km discontinuity (hereafter 660) remain poorly constrained. In this study, we utilize the subtle waveform details of *S660S*, the underside shear-wave reflection off the 660, to interpret the seismic velocity and compositional structure near, and particularly below, the 660. We identify a significant difference in *S660S* waveform shape for bouncepoints near subducting slabs compared to other regions. Our results reveal globally enriched basalt (approximately 36%) at the 660, in agreement with recent seismological observations. However, the basalt fraction decreases to less than 10% at 800-km depth, forming a harzburgite-enriched reservoir that agrees with geodynamic models. The decrease in basalt fraction also results in a steep seismic velocity gradient just below the 660, consistent with 1D global reference models. The striking chemical radial variations near the 660 challenge the applicability of homogeneous radial compositional models in the mantle, such as the pyrolite model, and may exert a significant effect on mantle convection at the boundary between the upper and lower mantle.

Geodynamic Subduction Models Illuminate Seismotectonic Stress Indicators

Craig R. Bina[1] and Hana Čížková[2]

[1]Dept. of Earth and Planetary Sciences, Northwestern University, Evanston, Illinois, U.S.A.

[2]Dept. of Geophysics, Faculty of Mathematics and Physics, Charles University, Prague, Czech Republic

Ambient stress fields associated with subduction processes are revealed by seismotectonic stress indicators such as earthquake focal mechanisms. Insight into the origins of these stress fields can be gained through analysis of simplified geodynamic models representing major components of relevant regional subduction regimes. Here we illustrate how such geodynamical modeling can illuminate some of the driving factors behind seismic stress indicators in several regions.

Down-dip extension in the subducting Sunda plate reflects incipient arc-continent collision between the Palawan continental fragment and the Philippine Mobile Belt, accompanied by increases in slab dip and tensional plunge, with increasing approach to collisional locking, from north to south along the southern Manila Trench to Mindoro Island. This extension may be enhanced by interaction of the slab tip with the thermally uplifted olivine → wadsleyite phase transformation (Bina et al., 2020).

Deep seismicity in the subducting Nazca plate, including large 2015 events beneath the Peru-Brazil border, indicates down-dip compression in a steeply dipping region near 600 km depth, in agreement with geodynamical modeling of Nazca subduction and slab stagnation (Zahradník et al., 2017).

Geodynamical modeling of the subducting Pacific plate beneath the Japan Sea and eastern China suggests that down-dip compressional stresses arising from buoyant and viscous forces are augmented by slab bending and unbending stresses, so that down-dip compressional seismicity may trace the upper and lower surfaces of the slab in the respective bending and unbending regions (Čížková et al., 2020).

Deep seismicity beneath Tonga shows a down-dip compressional stress regime undergoing a transition to vertical extension below ~680 km depth. This could arise from juxtaposition of positive petrological buoyancy just above the thermally depressed ringwoodite → bridgmanite + ferropericlase transition with negative thermal buoyancy just below this phase boundary. However, geodynamic models suggest that these stresses may be significantly overprinted by slab bending stresses, so that the observed stress transition may also be related to tightening of a fold during slab stagnation (Pokorný et al., 2023).

Bina, C. R., H. Čížková, and P.-F. Chen, Evolution of subduction dip angles and seismic stress patterns during arc-continent collision: Modeling Mindoro Island, *Earth and Planetary Science Letters*, **533**, 116054, doi:10.1016/j.epsl.2019.116054, 2020.

Čížková, H., J. Zahradník, J. Liu, and C. R. Bina, Geodynamic subduction models constrained by deep earthquakes beneath the Japan Sea and eastern China, *Scientific Reports*, **10**, 5440, doi:10.1038/s41598-020-62238-x, 2020.

Pokorný, J., H. Čížková, C. R. Bina, and A. van den Berg, 2D stress rotation in the Tonga subduction region, *Earth and Planetary Science Letters*, **621**, 118379, doi:10.1016/j.epsl.2023.118379, 2023.

Zahradník, J., H. Čížková, C. R. Bina, E. Sokos, J. Janský, H. Tavera, and J. Carvalho, A recent deep earthquake doublet in light of long-term evolution of Nazca subduction, *Scientific Reports*, **7**, 45153, doi:10.1038/srep45153, 2017.