

17th Symposium

Study of the Earth Deep Interior – SEDI 2022

Zurich, Switzerland

Meeting Booklet

July 11-15th, 2022

July 7, 2022

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Foreword

Welcome in Zurich for the 17th Symposium on Study of the Earth's Deep Interior!

Since 1988, SEDI symposia have been an important international gathering of scientists from all disciplines to meet and debate on various aspects of the Earth and planets deep interiors, including their physics, chemistry, dynamics, and evolution. This year's meeting takes place at the Department of Earth Sciences of ETH Zurich (Switzerland). The symposium is organized following eight half-day sessions, each session focusing on various aspects of the composition, structure and dynamics of planetary deep interiors. Sessions start with three invited talks: one keynote talk aiming at giving an overview of a field of research; and two research talks focusing on most recent progress on specific topics. All other contributions are posters, in which participants describe their latest research. This year, posters are also available online to encourage and facilitate discussions between scientists from all disciplines at any time of the meeting. Each session ends with a general discussion led by two chair persons. These discussions are a good opportunity to address recent advances in different fields, and hopefully to sow seeds for future research.

Icebreaker is on Monday evening at C-floor of ETH Earth Sciences building. Wednesday afternoon is time for a short rest and excursions. Excursions include a tour to the old town, a visit of the Lindt & Sprüngli chocolate museum, and a boat tour on the lake of Zurich. The conference dinner is on Wednesday night at ETH Faculty club, whose terrace provides a great view on the old town. As usual, these social events are additional opportunities for wide-ranging and informal discussions.

This year, teams from the Institute of Geophysics of ETH Zurich and from the Institute of Earth Sciences of Academia Sinica in Taiwan are in charge of the local organization and of the scientific program. Other people and organizations have actively contributed to this conference, and we would like to take this opportunity to acknowledge them:

- The National Science Foundation (USA) and the Programme National de Planetologie (PNP) of CNRS/INSU (France) for the travel support to PhD students and postdocs.
- The Department of Earth Sciences of ETH Zurich, Abteilung Campus Services of ETH Zurich.
- Academia Sinica and Taiwan Earthquake Center, that both have generously contributed to the meeting organization.

Of course, this conference would not be possible without the contributions of invited speakers and posters' authors. We would like to thank all of them for their time, contributions, and participation to SEDI 2022.

Finally, this year is a bit special, as it is the 1st opportunity for our community to gather on site after the Covid 19 pandemic. We hope that participants will share our pleasure and excitement to be able

to meet again to share findings and ideas.

On behalf of the sponsors and organizers, we welcome you again to this symposium, and we wish you an enjoyable and stimulating meeting.

Jérôme Noir and Frédéric Deschamps
On behalf of the Local and Scientific Organizing Committee

Acknowledgements

SEDI Local Organizing Committee

Jérôme Noir (ERDW-ETHZ)
Frédéric Deschamps (IES, Academia Sinica)
Ban-Yuan Kuo (IES)
Benjamin Chao (IES)
Eh Tan (IES)
Wen-Pin Hsieh (IES)
Karin Emmenegger (ETHZ)
Samantha Hsieh (IES)
Shu Chen Huang (TEC)

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Takashi Nakagawa (Hong-Kong University)
Paul Tackley (ETH Zurich)
Christine Thomas (University of Muenster)
Shijie Zhong (University of Colorado)

The meeting is locally organized by members of The Institute of Geophysics of ETH Zurich, The Institute of Earth Sciences (IES) of Academia Sinica, and all the ETHZ services, with the help and support of the following institutions:

- Department of Earth Sciences, ETH Zurich (ERDW-ETHZ)
- Academia Sinica
- SEDI
- IUGG
- Taiwan Earthquake Research Center (TEC)
- US NSF
- CNRS/INSU
- SNSF

Practical Information

Coffee Breaks

Coffee, tea and refreshments will be served during each poster session.

Help Desk

The help desk is open from 8:30 am to 6:00 pm on Monday, Tuesday and Thursday, and from 8:30 am to 1:00 pm on Wednesday and Friday.

Location and Hours

The meeting takes place in Earth Sciences Building at ETH Zurich, Sonneggstrasse 5, 8092, Zurich. The auditorium is C-60 on the C-floor, follow the signs. Sessions start at 9:00 am, speakers should arrive in advance.

Ice Breaker, Lunch and Dinner

Ice breaker will be held at C-floor on Monday night. Lunches will be on C-floor on Monday, at the ETH Mensa on Tuesday, Thursday and take away on Wednesday and Friday. The conference dinner will take place on Wednesday night 6:00 pm to 11:00 pm at the faculty club of ETH in the main building (HG). Please keep your badges during all social events.

Oral Session

Please upload your presentation to the laptop on the stand before the appropriate session. PDF format is highly recommended.

Poster Session

Posters are to be displayed in NO-C floor (next to the Conference room). Posters of session 1 to 4 will be displayed on 11 and 12 July, and posters of session 5 to 8 on 13-15 July. We ask the authors to remove their posters before 6 pm on Tuesday (session 1-4), and before 1:30 pm on Friday (session 5-8). All remaining posters will be destroyed.

Tourist Information

The Tourist Office Zurich is open daily from 9:00 am to 6:00 pm.

Study of the Earth's Deep Interior 2022

Meeting Overview

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<tr><td>09:00
|
12:30</td><td>Session 1
Mantle Structure and Composition

Chairs:
Chairs Andy Nowaki
&
Paula Koelemeijer</td><td>Session 3
Core-Mantle Boundary

Chairs:
Stéphane Labrosse
&
Sebastian Rost</td><td>Session 5
Inner Core

Chairs:
Séverine Rosat
&
Sébastien Merkel</td><td>Session 6
Outer Core Dynamics and Modelling

Chairs:
Alexandre Fournier
&
Chris Finlay</td><td>Session 8
Experiments

Chairs:
Maylis Landeau
&
Jérôme Noir</td></tr>
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Farewell</td></tr>
<tr><td>14:15
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17:45</td><td>Session 2
Mantle History and Dynamics

Chairs:
Maxim Ballmer
&
Bernhard Schuberth</td><td>Session 4
Outer Core Observations, Structure, Composition
Chairs:
Cathy Constable
&
Nicolas Gillet</td><td>Session 7
Other Planets: Observations & modelling

Chairs:
Doris Breuer
&
Gaël Choblet</td><td></td></tr>
<tr><td>18:00
|
20:00</td><td>Icebreaker</td><td>SEDI Business Meeting</td><td>18:00-23:00
Conference Dinner</td><td></td><td></td></tr>
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Meeting Agenda

Time	Title	Speaker
July 11 Monday		
08:00 - 08:45	Check in	
08:45 - 09:00	Opening	
Session 1 - Mantle Structure and Composition *Chairs: Chairs Andy Nowaki & Paula Koelemeijer*		
09:00 - 09:50	Keynote Presentation Role of water in deep mantle dynamics	Eiji Ohtani
09:50 - 10:15	Research Talk 1 Locating the iron spin transition in the lower mantle with global adjoint tomography	Laura Cobden (Zatman lecture)
10:15 - 10:40	Research Talk 2 Thermochemical heterogeneities in the mantle transition zone linked to ponding plumes and stagnant slabs	Lauren Waszek
10:40 - 11:40	Poster Viewing and Coffee Break	
11:40 - 12:30	General Discussion	
12:30 - 14:15	Lunch	
Session 2 - Mantle History and Dynamics *Chairs: Maxim Ballmer & Bernhard Schuberth*		
14:15 - 15:05	Keynote Presentation Mantle Circulation Constrained	Huw Davies
15:05 - 15:30	Research Talk 1 Beyond 1D magma ocean models	Charles-Edouard Boukaré
15:30 - 15:55	Research Talk 2 Earth's mantle and lithosphere evolution seen through plumes	Maëlis Arnould
15:55 - 16:55	Poster Viewing and Refreshments	
16:55 - 17:45	General Discussion	
18:00 - 20:00	Icebreaker	
July 12 Tuesday		
Session 3 - Core-Mantle Boundary *Chairs: Stéphane Labrosse & Sebastian Rost*		
09:00 - 09:50	Keynote Presentation Core-mantle chemical interactions from ab initio calculations	Taku Tsuchiya
09:50 - 10:15	Research Talk 1 Lowermost-mantle density and CMB topography from recent normal-mode measurements	Rûna van Tent

Time	Title	Speaker
10:15 - 10:40	Research Talk 2 Geodynamic, geodetic, and seismic constraints favour deflated and dense-cored LLVPs	Frederick Richards
10:40 - 11:40	Poster Viewing and Coffee Break	
11:40 - 12:30	General Discussion	
12:30 - 14:15	Lunch	
Session 4 - Outer Core Observations, Structure, Composition *Chairs: Cathy Constable & Nicolas Gillet*		
14:15 - 15:05	Keynote Presentation Layering around the core-mantle boundary	Sanne Cottaar
15:05 - 15:30	Research Talk 1 Measuring the electrical resistivity of liquid iron at the pressures of planetary cores	Kenji Ohta
15:30 - 15:55	Research Talk 2 Global geomagnetic field on multi-millennial scales	Sanja Panovska
15:55 - 16:55	Poster Viewing and Refreshments	
16:55 - 17:45	General Discussion	
18:00 - 20:00	SEDI Business Meeting	
July 13 Wednesday		
Session 5 - Inner Core *Chairs: Séverine Rosat & Sébastien Merkel*		
09:00 - 09:50	Keynote Presentation The Earth's inner core: a review and way forward	Hrvoje Tkalčić
09:50 - 10:15	Research Talk 1 Melting curve of iron determined in a resistance-heated diamond-anvil cell: implications for the Earth and planetary core	Ryosuke Sinmyo
10:15 - 10:40	Research Talk 2 The dynamic history of the inner core constrained by seismic anisotropy	Daniel Frost
10:40 - 11:40	Poster Viewing and Coffee Break	
11:40 - 12:30	General Discussion	
12:30 –	Excursion	
18:00 - 23:00	Conference Dinner	

Time	Title	Speaker
July 14 Thursday		
Session 6 - Outer Core Dynamics and Modelling *Chairs: Alexandre Fournier & Chris Finlay*		
09:00 - 09:50	Keynote Presentation Rotating convection and the many scales of core dynamics	Michael Calkins
09:50 - 10:15	Research Talk 1 Ohmic dissipation in the Earth's outer core resulting from the free inner core nutation	Yufeng Lin
10:15 - 10:40	Research Talk 2 Influence of libration on a stable layer : an application to Mercury	Ankit Barik
10:40 - 11:40	Poster Viewing and Coffee Break	
11:40 - 12:30	General Discussion	
12:30 - 14:15	Lunch	
Session 7 - Other Planets: Observations & modelling *Chairs: Doris Breuer & Gaël Choblet*		
14:15 - 15:05	Keynote Presentation Seismology on Mars	Amir Khan
15:05 - 15:30	Research Talk 1 Probing icy satellites through their rotation	Anthony Trinh
15:30 - 15:55	Research Talk 2 Thermal convection in icy moons' oceans: the influence of inhomogeneous tidal heating	Daphné Lemasquerier
15:55 - 16:55	Poster Viewing and Refreshments	
16:55 - 17:45	General Discussion	
July 15 Friday		
Session 8 - Experiments *Chairs: Maylis Landeau & Jérôme Noir*		
09:00 - 09:50	Keynote Presentation What do lab experiments tell us about planetary dynamos?	Henri-Claude Nataf
09:50 - 10:15	Research Talk 1 The origins of Si, O, and C in planetary cores	Rebecca Fischer
10:15 - 10:40	Research Talk 2 Experiments on core formation	Victor Lherm
10:40 - 11:10	Special Talk The three meter liquid sodium experiment with a rough inner sphere	Dan Lathrop
11:10 - 12:10	Poster Viewing and Coffee Break	
12:10 - 13:00	General Discussion	
13:00	Farewell	

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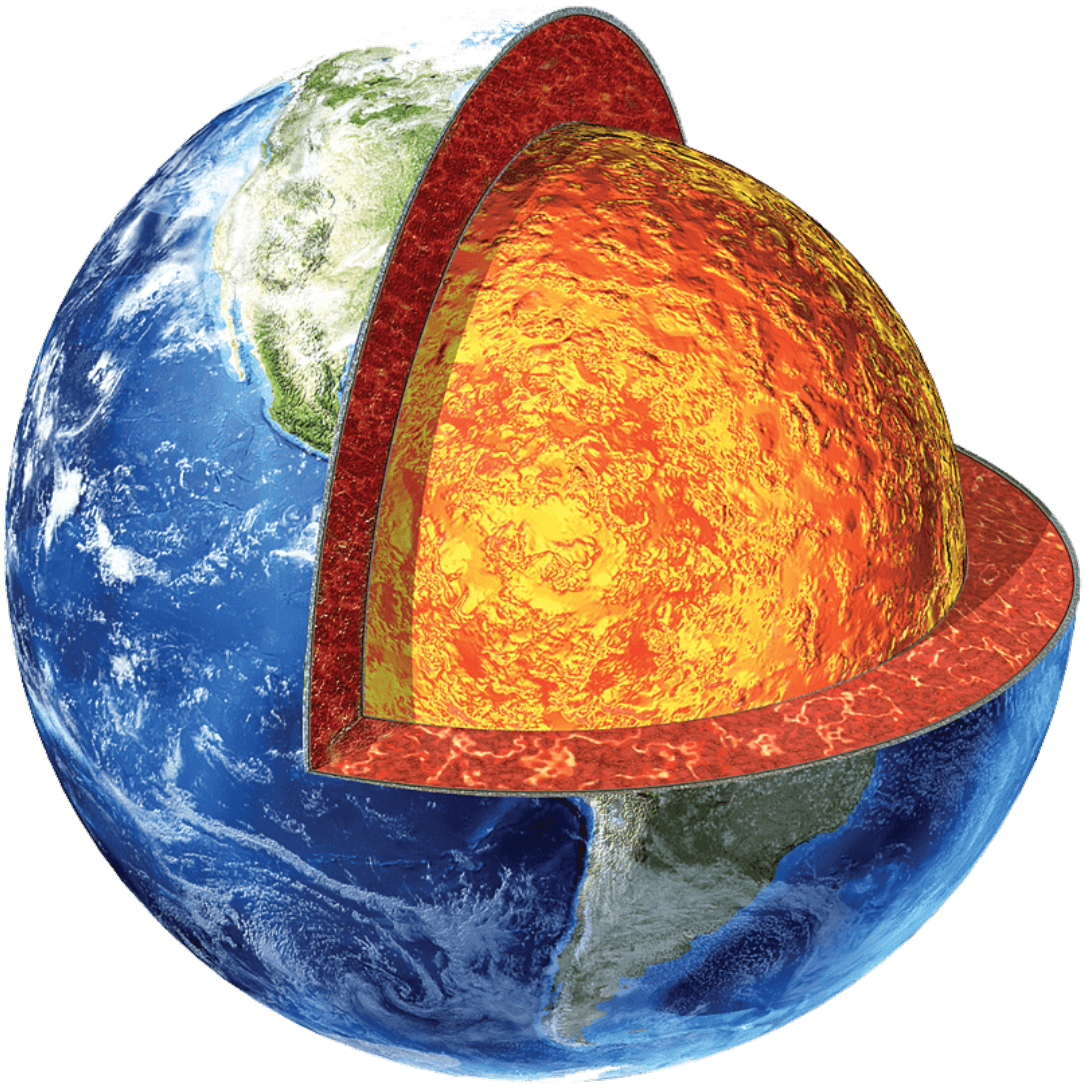
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Oral Presentation Abstracts



Role of water in deep mantle dynamics

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Abstract

Water is an important component which characterizes the water planet Earth. Water budget and in- gassing/degassing ratio between earth's surface and interior has been debated. The recent estimations of the influx of ocean water are equal to or greater than the outgassing flux, resulting in constant or secular reductions of the ocean mass (e.g., [1]).

Water is stored in both hydrous minerals and nominally anhydrous minerals (NAM). We have investigated the water partitioning between nominally anhydrous minerals (NAMs) and high-pressure hydrous phases under the water under-saturated conditions. Our experiments on water partitioning between olivine and hydrous phase A, wasleyite and hydrous phase A, ringwoodite and superhydrous phase B, and bridgmanite and phase D/phase δ revealed that water is strongly partitioned to hydrous phases resulting in formation of nearly dry NAMs such as olivine (<1 ppm), wadsleyite (<300ppm), ringwoodite (~5 ppm), and bridgmanite (<1ppm) coexisting with hydrous phases [2, 3].

Large slab deformation [4] and deep seismicity [5, 6] have been accounted for by rheology of dry olivine and its phase transformation kinetics. Our results solve a paradox of the existence of dry phase transitions which trigger the deep earthquakes [5] and large slab deformation [4] and wet slabs which transport water into the deep mantle. Our results also revealed that the dry MAMs exist at the top of the wet lower mantle coexisting with high pressure hydrous phases. Our results also support an idea that deep earthquakes at the depths exceeding 660 km may be caused by dehydration of superhydrous phase B or phase D which is stable at the top of the lower mantle [7]. The dry nature of bridgmanite coexisting with hydrous phases suggests that the major water carriers in the lower mantle are high pressure hydrous phases. Bridgmanite cannot be a water reservoir at least in the upper part of the lower mantle and can show dry rheology even in the wet lower mantle.

References: [1] van Keken, et al. *J. Geophys. Res.* 116(B1): B01401, (2011), [2] Ishii, T. and Ohtani, E. (2021) https://doi.org/10.1038/s41561-021-00756-7, [3] Ishii, T., Ohtani, E., Shatskiy, A. et al., Earth and Planetary Science Letters 583, 117441 (2022), [4] Mohiuddin, A. et al., Nature Geosci. **13**, 170–174 (2020). [5], Green II, H.W. & Houston, H. Annu. Rev. Earth Planet. Sci. **23**, 169–213 (1995), [6] Kirby, S.H. et al., Rev. Geophys. **34**, 261–306 (1996), [7] Zahradnik, J. et al., Sci. Rep., **7**, 1-11 (2017).

Keywords: Water partitioning, NAMs, High Pressure Hydrous Phases, Mantle, Dynamics

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Locating the iron spin transition in the lower mantle with global adjoint tomography

Laura Cobden[*†1], Jingyi Zhuang[2], Wenjie Lei[2ǂ,3], Renata Wentzcovitch[2], Jeannot Trampert[1], and Jeroen Tromp[3]

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Abstract

GLAD-M25 (Lei et al., GJI 2020) is one of the first global tomography models derived using adjoint methods which capture the complete physics of seismic wave propagation. The result is a model which constrains bulk and shear wave-speeds consistently and at a considerably higher resolution than earlier models based on classical methods. This makes it amenable to a joint interpretation of bulk and shear wave speeds that in turn allows us to distinguish chemical from thermal variations in the mantle. We study frequency distributions of the wave speeds as a function of depth in the lower mantle between 1000 and 2800 km. We use mineral physics modelling to convert the wave speed distributions into distributions of temperature, bulk composition and mineralogy. We find that at all depths, the wave speed distributions cannot be explained by purely thermal effects. In the mid-mantle, a high-to-low spin transition in ferropericlase is required in order to explain bulk and shear wave speeds simultaneously. In the D" region we observe an enrichment in silica towards the core mantle boundary, as has long been implied by geodynamic models and elemental abundances in chondritic meteorites.

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Thermochemical heterogeneities in the mantle transition zone linked to ponding plumes and stagnant slabs

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Abstract

The physical properties (depth and reflectivity) of the 410 and 660-km discontinuities bounding Earth's mantle transition zone (MTZ) are governed by ambient mantle temperature and composition. The local thermochemistry also controls the stability of mineral assemblages and the buoyancy of transforming material, promoting or impeding thermal and chemical fluxes between upper and lower mantle. Constraints on regional-scale variations in MTZ structure therefore permit identification of areas with stagnant or ponding material, and help locate reservoirs of geochemical heterogeneities, with implications for global circulation patterns and the impact of the MTZ on surface activity.

Here, we integrate measurements of the "410" and "660" with mineral physics modelling to generate new thermal and compositional maps of the MTZ. Global observations are obtained from large seismic SS, PP, and ScSScS precursor datasets, using an adaptive stacking technique to adjust the spatial parameterization and account for inhomogeneous data coverage, noise, and discontinuity topography. We predict the depth and reflectivity of mineralogical phase transitions for a range of upper mantle thermochemical models, comprised of mechanical mixtures of varying proportions of basalt and harzburgite, and realistic potential temperature. We then perform Bayesian inversions of the discontinuity measurements, producing global probabilistic maps of temperature and composition.

The limited visibility of P660P indicates very few regions with potential temperature higher than 1800 K, associated with a dominant garnet transition at the base of the MTZ, and corresponding to efficient upwelling flow. Large regions of moderately elevated temperature (1700-1800 K) beneath the Pacific are bounded by hotspots, suggesting ponding of hot materials beneath the MTZ. We find evidence for basalt-enriched reservoirs surrounding the Pacific Ocean, linked to the tectonic plate subduction history of the last 100 Myr. Subducted oceanic crustal material remains trapped in the MTZ, requiring a mechanism for segregation from the underlying subducted lithosphere in the upper mantle.

Keywords: Seismology, mantle, mantle transition zone, mineral physics, geodynamics

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Mantle Circulation Constrained

J Huw Davies[*†1], James Panton[1], James Wookey[2], Tim Elliott[2], Don Porcelli[3], Andy Nowacki[4], Chris Davies[4], Andrew Biggin[5], Paula Koelemeijer[3], Gareth Roberts[6], Andrew Walker[3], Ana Ferreira[7], Oli Shorttle[8], Bob Myhill[2], and Morten Andersen[1]

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Abstract

We will review mantle circulation models (MCMs) and how they have advanced our understanding of mantle dynamics. MCMs are mantle convection models which apply plate motion history as their upper velocity boundary condition. Detailed plate motion histories now go back > 1 Ga. The present-day structures in these realistic vigour simulations can be directly related to seismic imaging studies. This includes seismic tomography models, observations of seismic anisotropy and waveform studies. A leading-edge development is assimilating the seismic signature into mantle circulation models. We can also consider the impact of the core mantle boundary's heat flux on the geodynamo and its implications for palaeomagnetic observations. At Earth's surface, we can compare model predictions with the spatial distribution of dynamic topography and hot spots, and also with petrologic constraints on the spectrum of mantle thermal and chemical heterogeneity.

A longstanding question in the deep Earth community is the nature of the large low velocity provinces (LLVP), two low seismic velocity anomalies in the deepest mantle, one beneath Africa the other beneath the Pacific. Are these primarily the result of thermal structures, or are they primordial material dating from Earth's formation, or collections of recycled oceanic crust, or a combination.

Further, understanding Earth's long-term geophysical evolution demands that we know the core mantle boundary heat flux through time. Current MCMs can contribute to this question by asking what is the temperature at the core mantle boundary, and how has it evolved? We show that current constraints are frequently insufficient to definitively distinguish models.

Links to geochemistry are also important. For example, the lead pseudo-isochron age, derived from lead isotopes in MORB magmas, is ~ 2 Ga. It is a constraint on mantle dynamics, but currently difficult to apply to MCMs, due to short plate motion histories. This case will illustrate the value of considering mantle convection and the need for external processes, like continent generation and recycling.

These studies will advance further when we consider uncertainties in the models, the observations and in the properties relating them. By lowering these uncertainties, including by further constraining mantle's material properties, we will be better able to constrain mantle circulation.

Keywords: circulation models, mantle flow, seismology, LLVP, lead pseudo-isochron age, CMB temperature

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Beyond 1D magma ocean models

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Abstract

Giant impacts, core segregation and radiogenic decay can significantly melt terrestrial bodies early in the solar system, leading to the formation of magma oceans. The latter set the initial conditions for the long- term evolution of terrestrial planets. However, magma oceans remain poorly understood. Since the first magma ocean models proposed in the late 70s, magma ocean evolution is essentially described using 1D vertical models. This limitation is mostly due to the extreme convective vigor of a fully molten mantle that cannot be captured in direct fluid dynamics simulations. Consequently, most of our understanding of silicate mantle differentiation in magma ocean assume that a magma ocean is 1D.

Here, we go beyond these 1D approaches by using direct multiphase fluid dynamics simulations in 2D Cartesian geometry. Our focus is on the last stages of magma ocean solidification. We model mantle solidification from the point where the averaged mantle crystal fraction is above 50%. Above this threshold, the solid-liquid mixture behaves more like a solid and enters geodynamic regime that are accessible to fluid dynamics simulations. We use the new version of the code presented in Boukaré et al., (2017). The numerical implementation couples two Stokes equations to capture thermo-compositional convection as well as phase separation and phase change. Recent major upgrades we implemented to this numerical approach allow accounting for (i) the strong and sharp viscosity contrast between the liquid and the solid phases, i.e. up to four orders of magnitude, and (ii) silicate chemical differentiation as we allow compositional variation within the solid and liquid phases.

We will discuss two major findings. (1) Contrary to 1D models that show crystals forming at the intersection between liquidus and adiabat in the deep interior, our 2D models reveal that most of the solids form in cold thermal boundary layers, i.e. at the surface of the planet. (2) While 1D models favor a “one-step” crystallization scenario where solids progressively accumulate as layers as crystallization proceeds, our simulations point towards a complex multi-stage solidification processes. Crystals form at the surface and remelt partially as they settle. Several solidification and remelting events occur before the mantle can be considered as solid. This raises fundamental questions regarding the geochemical signatures of magma ocean solidification.

Keywords: Early mantle dynamics, Magma Oceans, Mantle differentiation, Multiphase Convection

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Earth's mantle and lithosphere evolution seen through plumes

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Abstract

Studying mantle plume dynamics provides insightful information on both the structure, composition and dynamics of the deep mantle, and the nature and evolution of Earth's lithosphere. Indeed, it's now admitted that at least some of Earth's mantle plumes originate from the core-mantle boundary; and after crossing the mantle, they erupt at the surface, deforming it dynamically and leaving hotspot tracks that notably serve as an absolute reference frame for plate tectonics.

While the dynamics of individual plumes has been extensively studied, the way they interact with other mantle and lithospheric heterogeneities during plume material's travel towards the surface is still uncertain. During this presentation, I will take you on a journey with mantle plume material from the base of Earth's mantle to Earth's surface, and we will see how, using numerical models of whole-mantle convection with Earth-like plate tectonics, we can study how their dynamics affects and is affected by their interactions with their environment. We will notably see how plumes can interact with the lithosphere to produce new subductions, and how subducting material can deflect and deform plume conduits, leading to new interpretations of some Earth's surface observations.

Keywords: mantle convection, mantle plume, numerical modeling

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Core-mantle chemical interactions from ab initio calculations

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Abstract

Chemical reaction and associated element partitioning between liquid iron and silicate melt are the major processes controlling Earth's chemical evolution. Those could be expected to occur during the core formation, at the boundary between the basal magma ocean and the outer core, and also at the present core-mantle boundary through the partially molten ultra-low velocity zones, and closely related to several important solid Earth problems from the reservoirs of primordial components, the core and mantle chemistries, the volatile circulations, etc. Numerous experimental efforts have been made so far primarily in geochemistry to understand the properties of metal-silicate element reactions under high-pressure and high-temperature. However, considerable inconsistencies are often seen in different experiments likely due to the technical difficulties in precise handlings and analyses of tiny samples. Theoretical assessments are therefore of importance, in particular, the ab initio technique, which can predict energetics of materials highly quantitatively at high P,T, might be a powerful one. Within the theoretical framework, chemical reactions are dealt with based on thermodynamics, namely free energy. Since free energy of liquid states is not easy to calculate, we adopted the thermodynamic integration method founded by statistical mechanics. Our technique developed has been applied to metal-silicate partitioning of heat producing elements, noble gases, other volatiles including water (hydrogen), carbon, and sulfur, and indicators of the core-mantle chemical interactions, and opened a new research direction combining theoretical mineral physics and geochemistry. Using the technique, we can predict siderophility/lithophility of elements (molecules). I would introduce some results in this talk.

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Lowermost-mantle density and CMB topography from recent normal-mode measurements

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Abstract

Constraints on the 3-D density structure of Earth's mantle provide important insights into the nature of seismically observed features, such as the Large Low Shear Velocity Provinces (LLSVPs) in the lower mantle under Africa and the Pacific. The only seismic data directly sensitive to density variations at all depths inside the mantle are long-period normal modes: whole Earth oscillations that are observed after large earthquakes ($M_W \geq 7.5$). However, their sensitivity to density is weak compared to the sensitivity to velocity and previous studies have presented conflicting density models of the lower mantle, showing either entirely light (Koelemeijer et al. 2017) or entirely dense (e.g. Ishii & Tromp 1999, Trampert et al. 2004) LLSVPs with respect to the reference model. Recently, Lau et al. (2017) have used tidal tomography to show that Earth's body tides prefer entirely dense LLSVPs.

A large number of new normal-mode splitting function measurements has become available since the last density models of the entire mantle were published. Here, we present our new models of 3-D mantle velocity, density and discontinuity topography, obtained from the inversion of these recent normal-mode measurements using a Hamiltonian Monte Carlo algorithm, which also provides us with model uncertainties. We find a large high-density region in the bottom-300 km of both LLSVPs, while the remaining LLSVP material has a lower-than-average density. These findings are confirmed by the density model obtained from the direct inversion of normal-mode spectra. We also assess the degree of correlation between density and topography at the core-mantle boundary. Our model's partially dense LLSVPs imply that they are at least partially compositionally distinct, as temperature variations alone cannot decorrelate seismic velocity and density. Using a recently developed neural network, we show that our model's dense LLSVP regions correspond to an increase in SiO_2 concentration and temperature.

Keywords: Mantle density, LLSVPs, normal modes

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Geodynamic, geodetic, and seismic constraints favour deflated and dense-cored LLVPs

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Abstract

The Earth's two *large low-velocity provinces* (LLVPs), influence supercontinent cycles, mantle plume generation, and its geochemical budget. Seismological advances have steadily improved LLVP imaging, but their vertical extent and degree of compositional heterogeneity remain controversial. Here, we investigate these aspects of LLVP structure using a wide range of geophysical observations. The relationship between measured geoid anomalies and long-wavelength dynamic surface topography places an important upper limit on LLVP vertical extent of ~900 km above the core-mantle boundary (CMB). Our mantle flow modelling suggests that anomalously dense material must exist at the base of these structures to simultaneously reproduce geoid, dynamic topography, and CMB ellipticity observations. We demonstrate that models incorporating this dense basal layer are consistent with independent measurements of semi-diurnal Earth tides and Stoneley modes. Our thermodynamic calculations indicate that a ~100 km-thick layer of early-formed, chondrite-enriched basalt is the chemical configuration most compatible with this full range of geodynamic, geodetic and seismological constraints. By reconciling these disparate datasets for the first time, we demonstrate that, although dominantly thermal structures, basal sections of LLVPs likely represent a primitive chemical reservoir that is periodically tapped by upwelling mantle plumes.

Keywords: mantle dynamics, thermochemical convection, normal modes, deep Earth seismology, CMB topography, body tides, geoid, geochemical reservoirs, early Earth geodynamics, LLSVPs

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Layering around the core-mantle boundary

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Abstract

Processes and heterogeneity above and below the core-mantle boundary affect heat flux variations and the mechanical and electromagnetic coupling at this boundary, which in turn influence the convection in the outer core and mantle. I will show novel seismic approaches which can resolve or put bounds on the heterogeneity and layering around the boundary.

At the top of the outer core, the presence of a stable layer, the so-called E′ layer, has been proposed. In *Irving, Cottaar, and Lekic* (*2018)*, we update the outer core reference model by fitting the elastic parameters in an equation-of-state using normal mode eigen frequencies. Our resulting model shows slower velocities and a steeper velocity curve at the top of the outer core compared to PREM. Based on normal modes there is no argument for an anomalous E′ layer on top of this model. However, a purely thermally anomalous E′ layer, which would unlikely be visible to seismologists could still be present.

Stronger lateral heterogeneity is present on the mantle side of the boundary. We zoom in on the Hawaiian ultra-low velocity zone in *Li, Leng, Jenkins, and Cottaar (2022).* In this study we present postcursors of Sdiff at higher frequencies than previously observed. The high frequency postcursor is more strongly delayed compared to the lower frequencies. This observed dispersion gives evidence of strong layering within the ULVZ, with a potential model of a 2-km thick basal layer reduced by 40%.

The layering could mean there is increased iron enrichment towards the core-mantle boundary, which also increases the chance of partial melting towards the core-mantle boundary. In Dannberg, Myhill, Gassmoeller and Cottaar (2021), we find that dynamically some of this partial melt would be expected to accumulate on the core-mantle boundary forming a global layer. Russell, Irving, and Cottaar (in review) synthetically explore the potential presence and seismic visibility of such a layer. We find differential times of PKKPdiff and PKKP is the most sensitive tool. Withing the global scatter of these observations, a melt layer of several kilometers could still be hidden. The presence of a global iron-rich silicate- melt layer would mean increased electromagnetic coupling, and increased geochemical interaction across the boundary.

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Measuring the electrical resistivity of liquid iron at the pressures of planetary cores

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Abstract

The present-day Earth's core consists of iron (Fe) with some impurity elements being separated into the liquid outer and solid inner core. The fluid motions in the outer core generate the geomagnetic field that has been sustained over >3.4 billion years. The electrical and thermal conductivity of liquid Fe is important in understanding the thermal evolution and dynamics of deep Earth. Despite its importance in geoscience, experimental determination of the conduction properties of dense liquid Fe has been hindered by instantaneous deformation and chemical reaction with surroundings.

We examined the electrical resistivity of liquid Fe to 135 GPa and 6680 K via a four-probe method in a diamond-anvil cell combined with two novel techniques: 1) enclosing a molten Fe sample in a single-crystal sapphire capsule, and 2) millisecond time-resolved simultaneous measurements of the electrical resistance, X-ray diffraction, and temperature of instantaneously melted Fe. Our results show the liquid Fe resistivity with minimal temperature dependence and an anomalous resistivity reduction around 50 GPa likely associated with a magnetic transition, which is in accordance with previous *ab initio* calculations. The size of the terrestrial body is found to be a key factor in controlling the conductivity of its core.

Keywords: Electrical resistivity, liquid iron, Earth's outer core, diamond anvil cell

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Global geomagnetic field on multi-millennial scales

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Abstract

Reconstructions of the geomagnetic field on long multi-millennial timescales are important to understand the geodynamo processes in the Earth's core, validate the field behavior observed in numerical simulations, and determine space climate conditions. Paleomagnetic sediment records and lava flow data are used to constrain the field on these timescales. Recent progress on long timescales gives us global insight into the field variations over the past 100 000 years and several geomagnetic excursions, including the Laschamps excursion, the best globally documented event that happened 41 000 years ago. Geomagnetic excursions are the most extreme variations of the geomagnetic field during stable polarities. They are characterized by a dramatic field intensity decline, large directional variations, and complex field morphology that deviates strongly from a dipole-dominated field geometry. Though these long-term global models are limited by the data distribution and uncertainties of the underlying data, they provide a holistic data-based view of the global variations, and by combined study and comparison of all the available reconstructions, robust characteristics of the paleomagnetic field can be inferred. Many properties of the geomagnetic field will be presented: the dipole moment, paleosecular variation, global field morphology at the Earth's surface and the core- mantle boundary, and dipole and non-dipole energy variations. Particular focus will be placed on geomagnetic excursions, similarities and differences of these events, their global or regional appearance, the evolving structure at the core-mantle boundary, and the underlying mechanism. Another important issue that will be addressed is the spatial distribution of field intensity and directions, expressed as virtual geomagnetic poles, and the search for indications of mantle control during excursions.

Keywords: geomagnetic field, paleosecular variation, dipole moment, excursions, sediment records

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The Earth's inner core: a review and way forward

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Abstract

Understanding how Earth's inner core develops and evolves, including fine details of its structure and energy exchange across the boundary with the liquid outer core, helps us constrain its age, relationship with the planetary differentiation, and other significant global events throughout Earth's history, as well as the changing magnetic field. Eighty-six years ago, Lehmann discovered the inner core. Since then, global seismology has come a long way in providing insights into its internal structure and dynamics, including 3D heterogeneity, attenuation, anisotropy, and differential rotation. Relatively recently, we (global seismologists) confirmed that its innermost part contains distinct seismic anisotropy. We have also started probing the inner core with probabilistic tomography, which reveals further complexities. However, progress has been impeded by the lack of uniform geometric coverage of body waves from large earthquakes and the fact that the inner core is buried beneath multiple Earth shells that are still not fully mapped. Furthermore, in view of constituting materials and their properties, it is still uncertain which type of iron crystal is stabilized in the inner core, making seismological and other inferences challenging.

In seeking the ways forward, we started experimenting with earthquake coda correlation. This contributed to the rise of a new paradigm – the coda-correlation wavefield – a type of seismological data based on waveform similarity. The new data probes the Earth with periods ranging between 20 and 50 s, thus representing a new class of studies that falls between body-wave and normal-mode methods. The first application proved the inner core's solidity by unambiguously detecting shear waves. As I hope to demonstrate in this lecture, further advances in this field may hold the keys to refined measurements of all inner core properties, informing dynamical models and strengthening mineral physics interpretations of the inner core's anisotropic structure and viscosity.

Keywords: the inner core, structure, anisotropy, the correlation wavefield

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Melting curve of iron determined in a resistance-heated diamond-anvil cell: implications for the Earth and planetary core

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Abstract

The Earth's core is composed mainly of iron. Since the liquid core coexists with solid at the inner core boundary (ICB), the melting point of iron at 330 GPa offers a key constraint on core temperatures. However, previous results using a laser-heated diamond-anvil cell (DAC) have been largely inconsistent with each other, likely because of an intrinsic large temperature gradient and its temporal fluctuation. Here we employed an internal-resistance-heated DAC and determined the melting temperature of pure iron up to 290 GPa, for the first time above 200 GPa by static compression experiments. A small extrapolation of the present experimental results yields a melting point of 5500 ± 220 K at the ICB, higher than 4850 ± 200 K reported by previous laser-heated DAC by Boehler (1993) but is lower than 6230 ± 500 K by Anzellini et al. (2013). Accounting for the melting temperature depression due to core- alloying elements, the upper bounds for the temperature at the ICB and the core–mantle boundary (CMB) are estimated to be 5120 ± 390 K and 3760 ± 290 K, respectively. Such low present-day CMB temperature suggests that the lowermost mantle has avoided global melting, at least since early Proterozoic Eon. The obtained melting temperature of iron may also help to understand the possibility of the magnetic field in the exoplanet.

Keywords: core; iron; melting; high pressure; inner core boundary; core-mantle boundary

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The dynamic history of the inner core constrained by seismic anisotropy

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Abstract

Progressive crystallisation of Earth's inner core drives convection in the outer core and magnetic field generation. Determining the rate and pattern of inner core growth is thus crucial to understanding the evolution of the geodynamo. The growth history of the inner core is likely recorded in the distribution and strength of its seismic anisotropy, the directional dependence of seismic velocity, which may arise from deformation texturing constrained by conditions at the inner-core solid-fluid boundary.

I will present an analysis of seismic body waves which sample the inner core (called PKP) showing that the strength of seismic anisotropy increases with depth within the inner core, and that the strongest anisotropy is offset from Earth's rotation axis into the western hemisphere. Then, using geodynamic growth models and mineral physics calculations, we simulate the development of inner core anisotropy in a self-consistent manner. We model a range of differential inner core growth rates between the equator and the pole, and a range of asymmetrical growth rates. We test several phases of iron and several iron alloys. From this we find that an inner core composed of hexagonally close-packed iron-nickel alloy, deformed by a combination of preferential equatorial growth and slow translation, can match the seismic observations without requiring hemispheres with sharp boundaries. Our model of inner core growth history is compatible with external constraints from outer core dynamics, and supports arguments for a relatively young inner core (~0.5–1.5 Ga) and a viscosity >10^{18} Pa-s.

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Rotating convection and the many scales of core dynamics

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Abstract

The geomagnetic field is generated by buoyancy-driven turbulence within the outer core. This turbulence is characterized by a broad range of length scales that are thought to be strongly constrained by the Coriolis force. In this talk I will discuss how theory and simulations have informed us about the dynamics of these different length scales. Results from both spherical and simplified planar geometries will be presented. In particular, I will contrast what we know about rotating convective turbulence with non-rotating turbulence, and discuss some of the challenges that result from these differences.

Keywords: Geodynamo, core dynamics

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Ohmic dissipation in the Earth's outer core resulting from the free inner core nutation

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Abstract

The diurnal tidal forces can excite a normal mode of the Earth's core, the free inner core nutation (FICN), which is characterized by a tilt of the rotation axis of the inner core with respect to the rotation axis of the outer core. The differential rotation between the inner core and the outer core induces fluid motions in the outer core and gives rise to Ohmic dissipation in the presence of the Earth's internal magnetic field. Nutation measurements can reflect such dissipation if it is sufficiently strong and thus can provide insights into the properties and dynamics of the Earth's core. In this study we perform a set of numerical calculations of the linear perturbations in the outer core induced by the FICN at very low Ekman numbers (as small as 1e−11). Our numerical results show that the back-reaction of the magnetic field notably alters the structure and length scale of the perturbations induced by the FICN, and thus influences the Ohmic dissipation resulting from the perturbations. When the Ekman number is sufficiently small, Ohmic dissipation tends to be insensitive to the fluid viscosity and to the magnetic diffusivity, which allows us to estimate the Ohmic dissipation associated with the FICN without relying on an extrapolation. In contrast to the results of Buffett (2010, Nature), the estimated Ohmic dissipation based on our numerical calculations is too weak to account for the observed damping of the FICN mode. This also implies that nutation measurements cannot provide effective constraints on the strength of the magnetic field inside the Earth's outer core.

Keywords: Ohmic dissipation, nutation, magnetic field

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Influence of libration on a stable layer: an application to Mercury

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Abstract

Ten years ago, MESSENGER observations enabled us to infer Mercury's magnetic field morphology (Anderson et al., 2012). The field was inferred to be almost completely axisymmetric. Recent reanalyses of the data, by Wardinski et al., 2021 and Plattner et al., 2021 identified weak non-axisymmetric components of the field, most notably in the spherical harmonic order 2 (m=2) components. The aim of this study is to determine whether the longitudinal libration of Mercury can give rise to flows in its core that can explain this non-axisymmetry. We model Mercury's core as a librating ellipsoid with a stably stratified layer at the top. We use the open-source eigenvalue code Kore to study the linearized problem and benchmark the method against the open-source MHD simulation code MagIC. Thereafter we study the fully non-linear problem with MagIC simulations.

Keywords: mechanical forcing; libration; dynamo; planetary interiors; Mercury

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Seismology on Mars

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Abstract

With the successful landing of InSight (Interior Exploration using Seismic Investigations, Geodesy and Heat Transport) and deployment of SEIS (Seismic Experiment for Interior Structure) on the surface of Mars, followed by detection of marsquakes and acquisition of high-quality seismic data since early 2019, Mars represents the second exterrestrial body for which we have seismic data, affording us a unique opportunity to peer inside the planet. A primary goal of the InSight mission is to image the planet's interior structure – the Rosetta stone for deciphering planetary composition, origin, and evolution – from observations of seismic events. To date (Sol 1235), more than 1300 distinct seismic events have been identified by the Mars Quake Service, of which a smaller subset has been employed to infer the structure of the crust, mantle, and core. In this talk, I will present an overview of what we have learned from ~3.5 years of seismic monitoring with InSight about Martian seismicity and Mars's interior structure and composition, and what this implies for its origin and evolution.

Keywords: Mars, InSight, Seismology, Interior Structure, Composition, Core formation

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Probing icy satellites through their rotation

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Abstract

Over the 35 years of SEDI's history, icy satellites have become a major focus of planetary science. Today, many of them are suspected, and some even ascertained, to be ocean worlds, with prospects of exciting developments in our quest for extraterrestrial forms of life.

Such an endeavour relies on a diversity of spacecraft measurements, and, in this talk, I will be discussing how observations of the rotation of icy satellites can probe their interior structure and provide constraints on their ice/water layer independently from gravity and topography measurements, emphasising the insights gained from the Cassini-Huygens mission and expected from future missions.

The rotation of icy satellites can display variations, in both spin rate and spin axis orientation, over a range of timescales, as a result of gravitational torques exerted by the planet they orbit. I will summarise recent advances in theoretical modelling inspired from the literature on Earth's rotation, and explain how a thorough understanding of the intimate connection between rotational and tidal processes can help reconstruct the long-term thermal-orbital evolution of ocean worlds.

Keywords: icy satellites, ocean worlds, rotation, tides, thermal-orbital evolution

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Thermal convection in icy moons' oceans: the influence of inhomogeneous tidal heating

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Abstract

Several icy moons of Jupiter and Saturn, including Europa and Enceladus, host liquid water oceans buried beneath their icy crusts. Geological features of the ice crusts as well as large-scale variations of the ice thickness are often attributed to endogenic processes within the ice. But the dynamics of the ice itself is intricately coupled to the convective ocean located below, through heat and material exchanges. Here, we study the circulation and associated heat fluxes in icy satellites oceans by performing large-scale, 3D direct numerical simulations of turbulent rotating thermal convection using the code MagIC [1]. Such simulations suggest that the heat flux from the convective ocean may be smaller (higher) at the poles than at the equator in Europa's (Enceladus') case [e.g., 2]. However, these results rely on simulations imposing homogeneous thermal boundary conditions at the top and bottom of the ocean. Because of tidal dissipation, the mantle heat flux is contrarily expected to be strongly inhomogeneous, e.g., significantly greater at the poles than at the equator [3]. How such heterogeneous forcing impacts the convection and associated heat fluxes in the ocean remains poorly constrained, and it is also unknown whether thermal anomalies can persist in the ocean and be transposed up to the ice-ocean boundary, or if they are smeared out by the vigorous convection altogether. To this aim, we performed simulations in convective regimes relevant to icy moons' oceans, from weakly to strongly rotationally constrained convection. In each regime, we quantify how thermal anomalies from the ocean floor persist up to the ice-ocean boundary. Preliminary results indicate that convection is inefficient in erasing the latitudinal thermal anomalies. In Europa's regime, this means that even if the equatorial upwelling persists, the ocean switches to a polar cooling configuration, akin to that predicted for Enceladus. Bottom longitudinal anomalies are also persistent through the ocean, and lead to the development of a mean baroclinic circulation, which becomes less prominent as the flow becomes more rotationally constrained.

Keywords: Europa, Enceladus, Subsurface oceans, Rotating thermal convection, Tidal heating

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What do lab experiments tell us about planetary dynamos?

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Abstract

In his 2021 review on the turbulent dynamo, Steve Tobias writes: *"For the construction of models of planetary magnetic fields, the conceptual difficulty lies not in the solution of the induction equation at high Rm, but rather that of the momentum equation in the rapidly rotating limit in the presence of a magnetic field"*. This is where lab experiments can largely contribute.

As numerical simulations are now reaching the relevant hierarchy of dynamic temporal scales, I will introduce a Standard Model of the present-day geodynamo suggested by both observations and numerical simulations, with the following characteristics: mostly QG velocity field, rather weak zonal winds, powered by thermo-compositional convection, predominantly axial dipolar field at the CMB, with large magnetic over kinetic energy ratio, presence of magneto-Coriolis waves, etc. I will then show how lab experiments confirm and illustrate some of these properties, while opening the way for possible complexities.

I will then present experimental work exploring various extensions or deviations from this schematic view: presence of a stable layer, rugous boundaries, heterogeneous heat flux, precession, tides, etc.

The impact of lab experiments largely depends upon the quality, diversity and quantity of data they provide. The development and use of performant techniques is thus essential. I will illustrate recent achievements, leaving to an accompanying poster a more complete survey of measurement techniques used in MHD experiments.

My presentation will end with suggestions for doable lab experiments that could help answer some hot questions on planetary dynamos.

Keywords: MHD; dynamo; turbulence; lab experiments; geophysical fluid dynamics

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The origins of Si, O, and C in planetary cores

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Abstract

Most planetary cores, including the Earth's, contain some "light elements" that are less dense than Fe–Ni. But the identities, abundances, and origins of these light elements have long remained a mystery. Here we present a series of experiments on the metal– silicate partitioning behaviors of Si, O, and C, to inform their behaviors during planetary core formation. We used laser-heated diamond anvil cells to recreate the pressures and temperatures of core formation, allowing the elements to partition between metal and silicate, then recovered the experiments and analyzed them chemically using a FIB, TEM, EPMA, and nanoSIMS. Putting the data into a multistage model of core formation for the Earth, we predict that the Earth's core contains 7.8 wt% Si, 1.2 wt% O, and 0.09–0.20 wt% C, though this still account for 78–89% of the planet's total carbon budget.

Keywords: core, partitioning, light elements, silicon, oxygen, carbon

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Experiments on core formation

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Abstract

During the formation of the solar system, terrestrial planets formed by the successive accretion of increasingly massive bodies. These planets simultaneously differentiate into a metal core surrounded by a silicate mantle. The metal core of the impactors is in thermodynamic disequilibrium with the silicates of the growing planet, which produces metal-silicate mass and heat transfers, and leads to a chemical and thermal partitioning between the mantle and the core. Partitioning is constrained by geochemical data, which also provide information on the chronology of accretion and on the thermodynamic conditions of the differentiation. The interpretation of geochemical data, together with the thermal, chemical and magnetic evolution of the planets, and the resulting geodynamical consequences, depend crucially on the degree of metal-silicate equilibration. In this talk, I will deal with heat and mass transfers in magma oceans in order to better constrain the equilibration efficiency. The first part focuses on the influence of planetary impacts on metal- silicate equilibration. Analogue laboratory experiments are used to study the evolution of the crater size, the mixing produced during the impact and the cratering velocity field. The second part focuses on metal-silicate equilibration during the post-impact stage, *i.e.* during the migration of the metal phase in the magma ocean as a turbulent thermal. Experiments are used to determine the role of the metal phase stretching on the equilibration dynamics.

Keywords: planetary differentiation, magma ocean, metal-silicate equilibration, analogue experiments

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The three meter liquid sodium experiment with a rough inner sphere

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Abstract

The spherical Couette geometry is useful for trying to understand planetary fluid flows. Rotation, shear, zonal flows, turbulence, and the associated angular momentum fluxes are all naturally represented. In addition, by using a conducting fluid one can study the some of the conditions of planetary cores and magnetic field /fluid interactions. Using a series of experiments, of increasing size and increasing power input (now a three-meter diameter system), we have examined liquid sodium spherical Couette flows to better understand planetary cores. We have uncovered precessional flows, inertial waves, turbulent bi-stability, many turbulent states, magnetic field gain by the Omega effect, and most recently magnetic field gain in the axial dipole, all while being sub-dynamo. In addition, we have explored how machine-learning tools can be used to do short-term prediction of the time evolution of our laboratory magnetic fields variation. Our current experimental goal has increased the helicity in the system by putting baffles on the inner sphere as motivated by Finke and Tilgner's 2012 computational dynamo studies. We are now progressing from the previous amplified magnetic fields toward possible dynamo states. We will present initial results on this modified experimental set up that exhibits enhanced magnetic activity. Analysis and experiments on these states are ongoing.

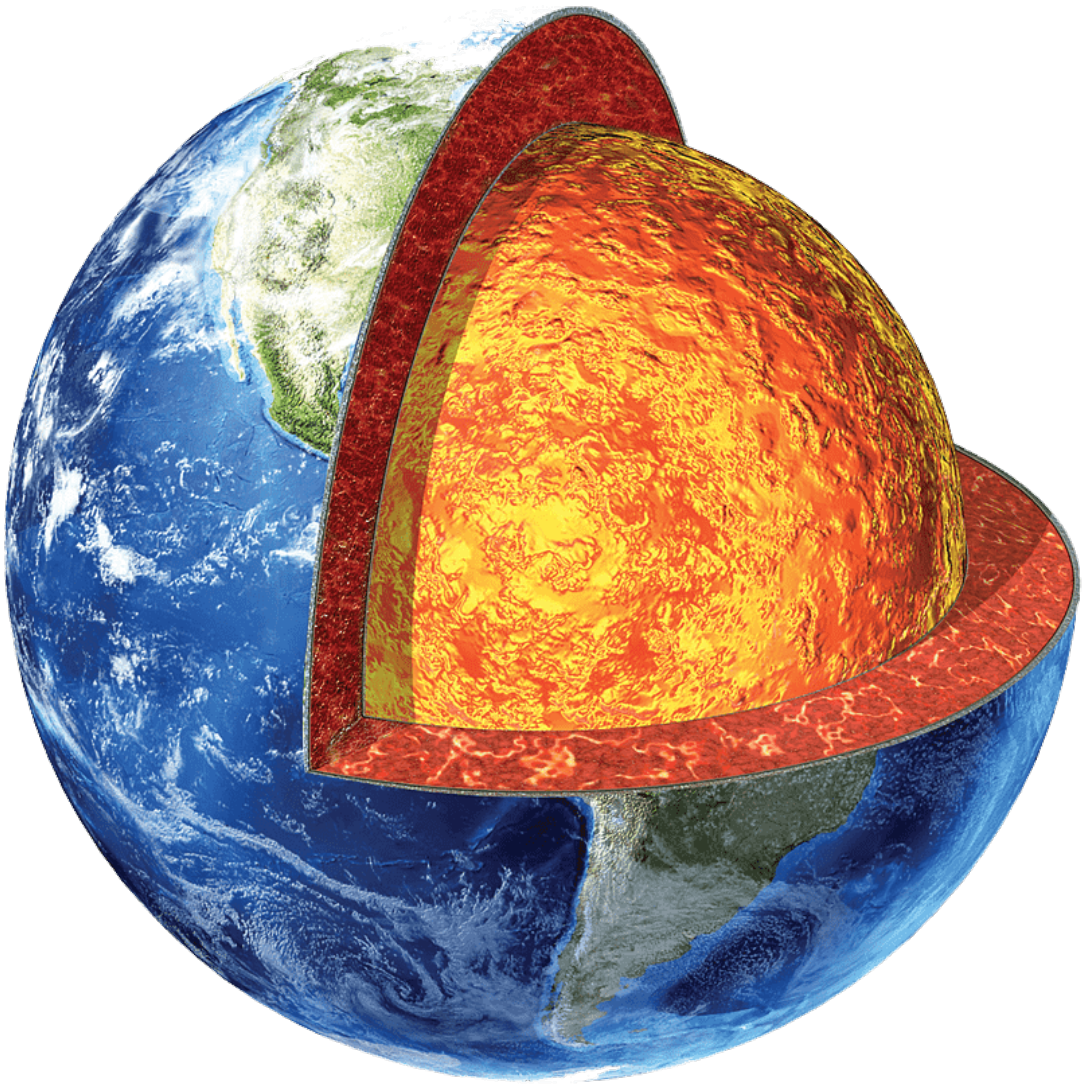
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Poster Abstracts



Imaging the meso-scale structure of the upper mantle beneath the southern and central Atlantic ocean

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Abstract

Although seismic tomography has provided important constraints on the long- wavelength structure of the mantle and its planform of convection, much is yet not well understood about the dynamic interaction of tectonic plates and deep mantle circulation at intermediate wavelengths (i.e., below plate-scale). In particular, a better understanding of the seismic structure of the oceanic upper mantle could potentially help unraveling the relationships between different scales of mantle convection, hotspot volcanism, and surface observables (e.g., MORB geochemistry, gravity gradients and bathymetry). We here present a new tomographic model of the shear- wave velocity and radial anisotropy structure beneath the central and southern Atlantic ocean constructed from the inversion of surface and body waves waveforms down to 30s period. Preliminary results confirm the existence of quasi-periodically distributed low-velocity regions in the upper mantle (200–350 km depth) organized in horizontally elongated bands some of which are parallel to the direction of absolute plate motion, as previously found in a lower resolution global tomographic models SEMum2 (French et al., 2013) and SEMUCB_WM1 (French and Romanowicz, 2014). Many of these elongated structures overlie vertically elongated plumelike conduits that appear to be rooted in the lower mantle, located, when projected vertically to the surface, in the vicinity of major hotspots. However, there is no direct vertical correspondence between the imaged plumelike conduits and hotspots locations suggesting a complex interaction between the upwelling flow and the lithosphere/asthenosphere system. We discuss possible relations of this structure with trace element chemistry of the corresponding hotspots.

Keywords: Full-waveform inversion, oceanic mantle, deep mantle circulation, hotspot volcanism.

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Caribbean plate tilted and actively dragged eastwards by low-viscosity asthenospheric flow

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Abstract

The importance of a low-viscosity asthenosphere underlying mobile plates has been highlighted since the earliest days of the plate tectonics revolution. However, absolute asthenospheric viscosities are still poorly constrained, with estimates spanning up to 3 orders of magnitude. Here we follow a new approach using analytic solutions for Poiseuille-Couette channel flow to compute asthenospheric viscosities under the Caribbean. We estimate Caribbean dynamic topography and the associated pressure gradient, which, combined with flow velocities estimated from geologic markers and tomographic structure, yield our best-estimate asthenospheric viscosity of $(3.0 \pm 1.5)*10^{18}$ Pa s. This value is consistent with independent estimates for non-cratonic and oceanic regions, and challenges the hypothesis that higher-viscosity asthenosphere inferred from postglacial rebound is globally-representative. The active flow driven by Galapagos plume overpressure shown here contradicts the traditional view that the asthenosphere is only a passive lubricating layer for Earth's tectonic plates.

Keywords: mantle rheology, residual topography, dynamic topography, slab window

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Seismic evidence for partial melt below tectonic plates

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Abstract

The seismic low velocity zone (LVZ) of the upper mantle is generally associated with a low-viscosity asthenosphere that plays a key role for the dynamics of plate tectonics. However, its origin remains enigmatic, some authors attributing the reduction in seismic velocity to a small amount of partial melt, and others invoking solid-state mechanisms near the solidus, or the effect of volatile contents. Observations of shear attenuation provide additional constraints to unravel the origin of the LVZ. Here, we report the discovery of partial melt within the LVZ from the simultaneous interpretation of global 3D shear attenuation and velocity models. We observe that partial melting down to 150-200 km depth beneath mid-ocean ridges, major hotspots and back-arc regions feeds the asthenosphere. A small part of this melt (<0.30%) remains trapped within the oceanic LVZ. The amount of melt is related to plate velocities and increases significantly between 3 and 5 cm.yr−1, similarly to previous observations of mantle crystal alignement underneath tectonic plates. Our observations suggest that by reducing viscosity, melt facilitates plate motion and large-scale crystal alignment in the asthenopshere. Melt is absent under most of the continents.

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Mantle Phase Changes Detected from Stochastic Tomography

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Abstract

Stochastic tomography, made possible by dense deployments of seismic sensors, is used to identify previously undetected and poorly detected changes in the composition and mineral structure of Earth's mantle. This technique inverts the spatial coherence of amplitudes and travel times of body waves to determine the depth and lateral dependence of the spatial spectrum of seismic velocity. The inverted spectrum is interpreted using predictions from the thermodynamic stability of different compositions and mineral phases as a function of temperature and pressure, in which the metamorphic temperature derivative of seismic velocities can be used as a proxy for the effects of heterogeneity induced in a region undergoing a phase change. Peaks in the metamorphic derivative of seismic velocity are found to closely match those found from applying stochastic tomography to elements of Earthscope and FLEX arrays. The interpretation of this heterogeneity spectrum will enable new constraints to be found on the history of tectonic plate subduction beneath North America and the compositional component of crustal and tectonic plate fragments that have been cycled through Earth's mantle.

Keywords: Mantle phase changes, mantle heterogeneity, mantle composition

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Seismic full-waveform inversion of the crust-mantle structure beneath China and adjacent regions

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Abstract

We present the first-generation full-waveform tomographic model (SinoScope 1.0) for the crust-mantle structure beneath China and adjacent regions. The three-component seismograms from 410 earthquakes recorded at 2,427 stations are employed in iterative gradient-based inversions for three successively broadened period bands of 70 - 120 s, 50 - 120 s, and 30 - 120s. Synthetic seismograms were computed using GPU-accelerated spectral-element simulations of seismic wave propagation in 3-D anelastic models, and Fréchet derivatives were calculated based on an adjoint-state method facilitated by a checkpointing algorithm. The inversion involved 352 iterations, which required 18,600 wavefield simulations. SinoScope 1.0 is described in terms of isotropic P-wave (Vp), horizontally and vertically polarized S-wave velocities (Vsh and Vsv), and mass density (ρ), which are independently constrained with the same data set coupled with an L-BFGS quasi-Newton optimization scheme. It systematically reduced differences between observed and synthetic full-length seismograms. We performed a detailed resolution analysis by repairing input random parametric perturbations, indicating that resolution lengths can approach the half propagated wavelength within the well-covered areas. SinoScope 1.0 reveals strong lateral heterogeneities in the lithosphere, and features correlate well with geological observations, such as sedimentary basins, Holocene volcanoes, Tibetan Plateau, Philippine Sea Plate, and various tectonic units. The asthenosphere lies below the lithosphere beneath East and Southeast Asia, bounded by subduction trenches and cratonic blocks. Furthermore, we observe an enhanced image of well-known slabs along strongly curved subduction zones, which does not exist in the initial model.

Keywords: Computational seismology, Seismic tomography, Lithosphere, Mantle, Asia

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Adjoint modeling of load-tide sensitivity

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Abstract

The deformation of the solid Earth in response to ocean tidal loading (OTL) is sensitive to the material properties of Earth's interior across a broad range of spatial and temporal scales and provides complimentary constraints to seismology on the interior structure particularly at low frequencies (~10^{-5} Hz). Previous research (e.g. Ito & Simons, 2011, Martens et al., 2016) has shown that the tidal surface displacements may be sensitive to elastic properties of the interior to the same extent as to the mass distribution in the lithosphere and the mantle, which is of interest to all fields of geophysics and especially geodynamics.

We present a numerical approach to simulate the elastic and gravitational responses of the solid Earth that relies on the spectral-element method. Modeling the governing equations in a 3-D Earth using a coupled system of the elastostatic and Poisson's equations enables us to include effects like topography and lateral variations in Earth structure. The adjoint method is a powerful technique to simultaneously compute sensitivity with respect to all material parameters, e.g., density and elastic moduli, by solving an auxiliary linear system. We introduce a recipe for computing adjoint-based sensitivities of the complex-valued amplitude of surface displacement by two simulations for the real and imaginary part of the surface load. Those two simulations are independent under assumption of negligible attenuation. We show numerical 3D examples of Earth's OTL response.

Keywords: ocean tide loading, Earth structure, elastostatic problem

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Spatial Distribution of Upper Mantle Heterogeneity Beneath Africa

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Abstract

Previous studies of the East African upper mantle have invoked one or more mantle upwellings of varying thermochemical nature to underly the distribution of surface magmatism. For example, Boyce and Cottaar (2021) suggest that a hot, chemically distinct upwelling beneath the southern East African Rift (EAR) is sourced from the African Large Low Velocity Province (LLVP), while magmatism in Ethiopia may lie above an additional purely thermal upwelling. Constraints on chemical heterogeneities in the upper mantle may be derived from studying the seismically observable impedance contrasts that they produce. Away from subduction zones, two causal mechanisms are possible to explain the intermittently observed X-discontinuity (X) at 230-350km depth: the coesite-stishovite phase transition and/or carbonate silicate melting, both of which require a local enrichment of basalt. Because mantle plumes have been suggested to recycle basalt from the lowermost mantle, characterising the X across East Africa has the potential to discern between various models of mantle upwellings in this region.

Traditional approaches used to map the spatial distribution of RFs like common conversion- point (CCP) stacking ignore the slowness information crucial for discriminating converted upper mantle phases from surface bouncing multiples. By manually assessing depth and slowness stacks for overlapping bins of 1° radius, a normalised vote mapping approach of RF stacks is undertaken to robustly assess the spatial distribution of converted upper mantle phases. We capitalise on the new TRAILS dataset from the Turkana depression (Bastow, 2019; Ebinger, 2018) and an adjacent network in neighbouring Uganda (Nyblade, 2017), to supplement our existing RF database and characterise the X across an active continental rift setting in unprecedented detail. The X is mapped beneath Africa revealing patches of heterogeneity proximal to mantle upwellings in Afar, Canaries, Cape Verde, East Africa, Hoggar, and Réunion with further observations beneath Cameroon, Madagascar, and Morocco. There is a lack of an X beneath the whole of southern Africa, and strikingly, the magmatic western rift branch of the southern East African Rift.

Keywords: X-discontinuity, Chemical Heterogeneity, Upper Mantle, Africa

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Geodynamic predictions of seismic structure and discontinuity topography of the mantle transition zone

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Abstract

The mantle transition zone (TZ) is expected to strongly influence convective flow as it hosts a complex set of mineral phase transitions and an increase in viscosity. Still, neither its seismic structure nor dynamic effects have conclusively been constrained. Topographic variations of seismic discontinuities at 410 and 660 km depth ('410' and '660') are seismically visible and can potentially provide insight on temperature and phase composition. Besides the classically invoked phase changes in olivine, the 660 may be impacted by the transition of garnet at higher temperatures. However, the volume of material affected by this garnet transition and its dynamic implications have not yet been quantified. Here, we present hypothetical realizations of TZ seismic structure and major discontinuities for a range of different mineralogies, inclu- ding simple as well as more complex earth-like models such as pyrolite or mechanical mix- tures (MM). Synthetic TZ structure is computed based on the temperature field of a 3-D mantle circulation model using elastic parameters from thermodynamic mineralogical models. Statistical analysis reveals standard deviations of topography of ~6 and ~4 km for 410 and 660, respectively, for earth-like mineralogies. In a pyrolitic mantle, slabs and plumes are both found to depress the 660, by on average 14 and 6 km, respectively, reflecting effects of garnet. For MM, the 660 is found at similar depths for plumes and ambient mantle, as garnet is less abundant. Garnet only occurs where excess temperatures exceed 150 to 300 K, resulting in ~3 % garnet at the 660 in pyrolite and ~1 % in MM. For plausible geotherms, this amount could vary between ~1 and ~39 % in pyrolite, while remaining largely unaffected in MM.

Keywords: Mantle transition zone, Phase transitions, Seismic structure, Mantle convection

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Roles of partial hydration of mantle transition zone and wadsleyite–olivine phase transition in wet plume development: Origin of Quaternary intraplate volcanoes in Korea

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Abstract

The Quaternary intraplate volcanoes in Korea have a sparser distribution (~330-563 km) than that of Japanese arc volcanoes (~80 km), geochemistry indicating mixing of components from the stagnant slab and mantle transition zone, and a longer elapsed time (~10-20 Myr) of the Quaternary eruption after the stagnation of the Pacific Plate. Although volcanism can be explained by wet plumes originating from the hydrous layer of the stagnant slab, previous numerical studies could not consistently explain the spatiotemporal and geochemical observations because of the neglected partial hydration of the mantle transition zone and wadsleyite–olivine phase transition at a 410 km depth, both of which affect the viscosity and buoyancy structures. Thus, we constructed a series of two-dimensional numerical models by considering the partial hydration of the mantle transition zone and phase transition at a depth of 410 km. The results showed that the wet plumes are retarded at 410 km depth by the phase transition and merge into batches forming hybrid plumes in the asthenosphere, explaining the mixing of components from the hydrous slab and mantle transition zone, evidenced by the geochemical observations. The spacing (~485 km) and elapsed time (~24 Myr) of the hybrid plumes beneath the lithosphere are consistent with the spatiotemporal observations. Furthermore, the degree of mixing of the components from the hydrous slab and mantle transition zone found in the hybrid plumes explains the spatial distribution of water in the mantle transition zone beneath Korea.

Keywords: Intraplate Volcanism, Water, Wet Plume, Mantle Transition Zone, Phase Transition, Numerical Modeling

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Integrating Thermochemical Modelling and Seismic Observations of Earth's Upper and Mid-Mantle Discontinuities using ScS Reverberation Data

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Abstract

Seismic tomography models show that both down-going slabs and upwelling plumes are deflected and become stagnant in the mantle transition zone (MTZ) and mid-mantle (800-1300 km depth). While the geodynamic effects of the major MTZ discontinuities at 410 and 660-km depth are relatively well-understood, the cause of deflections in the mid-mantle remains debated. The relationship between the thermochemistry in the MTZ and mid-mantle reflectors remains elusive. Here we extend previous efforts to map reflectors observed at these depths [Waszek et al., 2018]

In this study, we introduce a new large global dataset of ScS reverberations, compiled with an automatic waveform identification code which uses Convolutional Neural Networks [Garcia et al., 2021]. We build new topography maps for the MTZ and mid-mantle discontinuities using an "Adaptive Stacking" technique based on Voronoi tessellation, which automatically adjusts its parameterisation to account for topography of the discontinuities, noise, and data coverage.

We then integrate our seismic observations in the context of mineral physics predictions for various thermochemical models, inverting for a realistic range of potential temperatures and basalt-harzburgite mixtures. The new geometries supplement our existing maps of the MTZ and mid-mantle, to improve resolution in regions with previously poor data coverage. Our results offer new insight into the relationship between the MTZ discontinuities and mid-mantle reflectors, informing regarding compositional layering beneath the MTZ and the regionally diverse styles of mantle mixing.

Keywords: Mid-mantle, MTZ, Discontinuities, Adaptive Stacking, Convolutional Neural Networks

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Seismic anisotropy due to textures above and below the 410 km discontinuity

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Abstract

We investigate the effect of various geodynamic contexts on the reflection coefficients of P and S waves underside reflections off the 410 km discontinuity, to detect seismic anisotropy at this boundary layer due to textures above and below the 410 discontinuity. We calculate the reflection coefficient for P and SH underside reflections using velocity perturbations resulting from aligned minerals above and below the 410 km discontinuity for different deformation scenarios. Our preliminary results indicate some differences in amplitude and polarity patterns of reflection coefficients of different deformation geometries in the case of an anisotropic olivine layer above an anisotropic wadsleyite layer, compared to the case of anisotropic olivine above an isotropic wadsleyite layer. The amplitudes of P and SH waves are influenced by the effect of angle of incidence and polarity reversal of the P wave is observed for some deformation styles. Furthermore, water content of wadsleyite plays an important role in creating the polarity reversal of the waves compared to the case of dry wadsleyite.

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Mantle Transition Zone Structure from PP and SS Precursors

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Abstract

The mantle transition zone (MTZ) is characterized by seismic discontinuities at global average depths of 410 km, 520 km, and 660 km (the `410', `520', and `660', respectively) that are associated with mineral phase transformations. Mapping the depth, amplitude, and sharpness of the discontinuities allows for insights into the thermochemical makeup of the MTZ which is of importance for improving our understanding of mantle dynamics. In this study, we have assembled a global waveform data set of PP and SS precursors, i.e., P- and S-waves reflected from the underside of the 410, 520, and 660, respectively, and jointly invert it with Rayleigh wave phase velocity measurements for upper mantle and MTZ structure. To model waveforms as accurately as possible, we account for effects arising from data processing, shallow structure, incoherent stacking, attenuation, and source effects, among others. We perform two independent inversions based on a "traditional" seismic and a mineral physics-informed thermodynamic parametrization. Our inversion results indicate lateral variations in temperature and composition that are also reflected in seismic velocity and discontinuity structure. The thermal structure of the mantle underneath continents and subduction zones found to be colder relative to oceans and hotspots, with similar trends in MTZ thickness. Subduction zones appear to be enriched in basalt, which explains complex mid-MTZ discontinuity structure associated with these regions. Overall, a mechanical mixture model of the mantle appears more likely than an equilibrium assemblage across ~2/3 or the globe. Finally, a comparison of the seismic and thermodynamic inversions indicates that complexities beyond an adiabatic and isochemical mantle are required by the data.

Keywords: Transition Zone, Mantle discontinuities, Surface waves, Body waves, Waveform inversion

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Search for Regional Seismic Discontinuities in the Earth's Upper Mantle using SS- and PP- precursors

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Abstract

Several mineralogic and petrologic mechanisms have been proposed to explain the seismic observations of regional-scale discontinuities in the upper mantle. The distribution of the 300-km "X" discontinuity is relatively poorly resolved globally, likely due to its small impedance contrast. Features observed near this depth are usually local, detected beneath subduction zones, and linked to a coesite-stishovite transition in an eclogite assemblage. Imaging the X-discontinuity may provide insights into the thermal and chemical heterogeneities associated with basaltic fraction and identify locations of subducted oceanic crust remnants or delaminated crustal roots.

Another discontinuity, at 520-km depth, is detected more frequently and sometimes observed to be split into two signals. Its existence is predicted by the wadsleyite to ringwoodite mineral phase transition. However, parameters such as temperature or compositional heterogeneity, which contribute to its presence or absence, depth variation, strength, and/or splitting, are not fully understood, necessitating further investigations.

Here, we use two large global datasets of SS and PP precursors to obtain new maps of these discontinuities. Our observations indicate regionally weak yet clear signals at both depths linked to variations in basalt fraction and potential temperature. We perform mineral physics modelling to investigate the characteristic temperature and composition associated with the signatures of these signals. These preliminary results provide insight into our understanding of the chemical segregation and plume stagnation in the upper mantle.

Keywords: upper mantle discontinuities; numerical modelling; SS-precursors; PP-precursors.

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Investigating Short-Scale 660 km Discontinuity Topography Using Scattered P'P' Precursors

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Abstract

Topography along the 660 km seismic discontinuity, the boundary between the upper and lower mantle at the base of the mantle transition zone, has been shown to vary across a range of length scales. Some common phases used for these studies include teleseismic phases PP, SS, P'P', and their associated precursors P660P, S660S, and P'660P': underside reflections off the 660 km discontinuity. It has been shown that amplified out-of-plane P'660P' scattered waves can be detected on large, dense arrays and can be used to identify small-scale 660 boundary topography (Wu et al. 2019). These scattered P'660P' waves are sensitive to small-scale (~10km) anomalies along the 660 discontinuity and have previously been used to assess regional 660 boundary topography. Here we collect more observations of out-of-plane P'660P' to expand on these observations.

We gathered data from a selection of dense, high-quality arrays and produced linear stacks of smoothed envelope seismograms filtered between 1.5 Hz-2.5 Hz and 3 Hz-4 Hz to amplify scattered P'660P' arrivals. Our preliminary results focus on the Alice Springs (AS) array in Australia, for which we carried out beamforming and slowness analyses. This uncovered a set of highly consistent P'660P' observations from a group of nine events beneath the Vanuatu Islands, generated by scattering from an area south of Iceland. We validated these observations through comparison to the P'P' surface-scattered arrivals and to source radiation patterns. We are still uncovering the implications of this for local 660 discontinuity structure.

Keywords: 660 km boundary, discontinuity topography, P'P' precursors.

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Segregated melts near the 660-km seismic discontinuity beneath mantle upwelling in the central Pacific

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Abstract

Traditionally, P-to-S receiver function (RF) is constructed by deconvolving the vertical-component seismograms from the horizontal-component seismograms to retrieve small converted arrivals scaterred from the velocity boundary beneath seismic stations (e.g., P-to-S converted phase from the 660 seismic continuity, or P660s), predominantly at the continents. On the other hand, stacking long-period waveform data against PP and SS waves has led to observations of PP and SS precursors from the 410 and the 660 seismic discontiuties, which helps sample and elucidate their reflectivity particularly beneath the oceans.

Following the merit of global long-period waveform stacking, we compute RFs in the L-Q-T coordinate system. Specifically, we highlight novel observations of seismic converted phases P660sP and PS660P, which are converted from the 660 seismic discontinuity as the postcursors of surface reflected PP waves. While the amplitude ratio A_{660}/A_{PP} is expected to decrease with distance in isotropic media, the amplitude versus offset (AVO) displays a clear trend where the amplitude ratio increases with distance.

We consider a radially anisotropic (or vertical transversely isotropic, VTI) layer either below or above the 660-km discontinuity. In each scenario, we estimate the contrast in shear velocity and density (Δv_s, $\Delta\rho$) across the discontinuity, the strength of radial anisotropy in P- and S-waves (r_p, r_s), and the new fifth parameter η_x through a Markov Chain Monte Carlo method. We will discuss the optimal anisotropic parameters and how such an anisotropy layer may represent segregation of ultra-deep melts under strong shear deformation induced by mantle upwellings.

Keywords: the 660, seismic anisotropy, aligned melt layering.

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Slab graveyards versus mantle plumes: clues from the mantle transition zone beneath the Carpathian region imaged with ambient noise

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Abstract

The mantle transition zone acts as a geo-thermometer. Its thickness variations can be related to temperature or fluid-content perturbations often associated with mantle plumes or subducting slabs. These processes may change the depth or sharpness of the 410 km and 660 km discontinuities, consequently modifying the travel times and pulse shapes of the body waves sampling them. The Carpathian region is an excellent natural laboratory to study the impact of slabs and possible mantle plumes on transition zone topography. A high seismic velocity slab graveyard accumulated from the subduction of several NeoTethys oceanic branches is thought to exist beneath the region. The last remaining slab connected to it is the Vrancea slab, a large high-velocity sinking lithospheric body thought to be the end-product of a ~10 million year slab roll-back that swept across the present-day Pannonian and Transylvanian Basins. Using ambient seismic noise recorded at broadband seismic stations in Romania, empirical Green's functions were estimated between pairs of seismic stations and Pv410P and Pv660P reflections were identified. To better extract these faint body waves that reflect off transition zone discontinuities, inter-station Green's functions were binned in 1o grid cells, they were corrected for normal move-out, trimmed after the surface wave arrivals, normalised, and phase-weight stacked. Forward modelling of travel-time anomalies with respect to a modified version of ak135 that includes the local crustal structure show marked changes in the 410 km and 660 km discontinuity depths across the Carpathians. We discuss the implications of the transition zone thickness variations in the context of relic slab subduction and possible signatures of mantle plumes often invoked to explain Neogene volcanism and dynamic topography in the intra-carpathian basins.

This work is carried out within the EENSANE (Eastern European Seismic Ambient Noise) Project.

Keywords: Mantle Transition Zone, Ambient Noise, Vrancea slab, Volcanism

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Correlating seismic discontinuity observations with tectonic regimes using SS precursor data

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Abstract

Seismic discontinuities, characterized by jumps in density and seismic velocity, are closely linked to mineralogical properties and processes within the mantle. Thus, accurately mapping the discontinuities and their spatial variations in sharpness, depth, and topography is key to understanding the thermal and chemical properties of the Earth's mantle as well as its dynamic behaviour. This study aims to correlate seismic discontinuity anomalies to diff t tectonic regimes by combining seismic SS precursor data, geochemistry, and geological interpretations. Potential temperatures and compositions relating to the observed anomalies will be evaluated via thermodynamic modelling.

We have obtained a global data set consisting of ~25.000 SS traces that have been automatically picked and aligned on the SS phase peak. Several types of fi and corner frequencies were carefully tested to finally obtain a configuration that allows us to not only observe the transition zone discontinuities but also the discontinuities in the more shallow and deeper parts of the mantle. Traces are stacked, for diff t tectonic regimes and regions of interest, to suppress noise and enhance precursor visibility. Resulting stacks will then be compared to synthetic SS seismograms created for a range of mineralogical models to assess the influence of temperature and composition on the discontinuity anomalies and its potential correlation to different tectonic regions.

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In search of Earth's electromagnetic response at periods extending to the Schwabe solar cycle

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Abstract

The study of sub-decadal to centennial secular variations in the geomagnetic field has been greatly boosted by ready availability of magnetic data from geomagnetic observatories and low earth orbiting satellites. Both have been exploited for time varying geomagnetic field models and geomagnetic induction studies. At periods between 100 days and 11 years the separation of internal and external field contribution remains challenging and may provoke the need for *a priori* assumptions about each signal. We adopt a simple approach to extracting the external P_1^0 variations and their inductive response from 117 years of hourly mean geomagnetic data from 192 widely distributed observatories drawn from a recent compilation distributed by the British Geological Survey. Observatories were selected to be within 65° of the geomagnetic equator and data gaps of up to 48 hours were repaired using linear interpolation. Baseline corrections were estimated using the International Geomagnetic Reference Field (IGRF), and the time varying IGRF was then removed from the data, which were finally rotated into geomagnetic coordinates year by year to allow for migration of the geomagnetic poles. Data were processed year by year starting in 1905 by fitting hourly estimates of the internal and external coefficients of a P_1^0 field to the set of observatories that had no missing data for that year (a number that varies between 3 and 93), using one month overlaps between years to remove the small bias from year to year fits. Observatory years with excessive misfit were iteratively removed from the processing.

Multi-taper spectral analysis was used to estimate the power spectra and transfer functions between the two time series. A clear peak at the 11-year solar cycle appears in the external field spectrum, with a smaller but discernible peak at the first harmonic of 5.5 years, with associated peaks in the coherency spectrum. The transfer function at 11 years period suggests a larger internal to external field ratio and higher phase shift than estimated by Harwood and Malin (1977).

Keywords: Geomagnetic spectrum, solar cycle, geomagnetic response function, mantle conductivity

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A new seismic phase to detect mid-mantle heterogeneities

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Abstract

Teleseismic PP waves and their precursors have been routinely used to study the upper mantle discontinuities as well as lower mantle scatterers. In most studies, the slowness of precursor is close to that of PP. Here, we present observations of a new PP precursor with the epicenter distance larger than 80º, called PdpP phase ("d" indicate the depth of heterogeneity), which represents the P wave "top" reflected by the heterogeneity and a following second reflection under surface. The PdpP arrives 20-50s before PP but with a slowness between PP and Pdiff, which is not present for reference Earth models. We collect the vertical-component records of China National Seismic Network of large earthquakes (Mw>5.8), that occurred between 2010 and 2020 within the epicentral distance range from 80° to 130°, and identify PdpP from earthquakes that occurred in the Tonga-Fiji region. We find that the PdpP phases are often observed in two forms: (I) a wave train with increasing slowness; (II) a single arrival with unique slowness. The 2D waveform modeling results suggest that the two types of PdpP signals can be simultaneously generated by a series of mid-lower mantle scatterers with scales larger than 20 km. Furthermore, by calculating joint likelihood, we locate the scatterers within the depth range of 800~1300 km, which may be related to the Pacific slab subducting along the Tonga-Kermadec trench.

Keywords: New seismic phase, PP precursor, PdpP phase, mid-lower mantle, scatterers

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Imaging Europe's Deep Mantle Plumes from Array Observations of Diffracted and Multipathed SKS waves

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Abstract

Mantle plumes are an integral part of the Earth's dynamic system because of their role in transporting heat and material from depth, intraplate volcanism, and their relationship with lower mantle structure such as the large low-velocity provinces (LLVPs) and ultra-low velocity zones (ULVZs). It has been challenging to image mantle plumes in the lower mantle due to wavefield effects such as wavefront healing and inherent resolution limitations of seismic tomography. Array seismology methodologies measuring the horizontal slowness vector (backazimuth and horizontal slowness) have been shown in synthetic studies to be able to image mantle plumes by measuring the deflections of waves at their boundaries and a phenomenon known as multipathing. Multipathing occurs when a wavefield is incident on a strong lateral velocity gradient, usually at the boundaries of mantle heterogeneity, and results in multiple arrivals with different slowness vectors. Array measurements can quantify theeffect on the wavefield of lateral velocity gradients at the boundaries of the plumes, and may give information about the thermal and chemical gradients present. In this work, we use array methods to image deeply rooted plumes by measuring the deflection of SKS waves at the plumes' boundaries. We focus our analysis on the European mantle due to the hypothesised presence of deeply rooted plumes and the high density of seismic stations. We make approximately 4500 observations over three frequency bands (0.10 - 0.20, 0.15 - 0.30, 0.20 - 0.40 Hz) quantifying the deflection at the boundaries of mantle plumes on the wavefield and identify multipathing. By comparing to simple forward modelling, we find evidence for deeply rooted slow structures which then extend over 1000 km above the core-mantle boundary (CMB) and cause multipathing in up to 60% of the waves sampling them. In addition to this, we observe evidence for a fast anomaly extending up to approximately 600 km above the CMB. Our interpretation is we have located the deep roots of the Eifel and Etna plumes and possibly the Perm anomaly also. The multipathing observations suggest the transition from mantle to heterogeneity occurs over a length of at most 500 km, suggesting the scale lengths of convection in the mantle must be like this, and therefore should be replicated in geodynamic simulation. These observations show that full horizontal slowness vector measurements are vital when studying mantle dynamics and we hope these measurements could be included in tomographic inversions to further constrain the Earth's structure and dynamics.

Keywords: Mantle plumes, Array Seismology, LLVPs, mantle dynamics

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On the hunt for seismic anisotropy in the lower-mantle from the crystallographic preferred orientation of bridgmanite aggregates induced by large-scale flow

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Abstract

Intrinsic seismic anisotropy provides valuable information to constrain mantle flow and deformation. They result from the crystallographic preferred orientation (CPO) of mantle minerals as they get progressively sheared over time. Although intrinsic anisotropy in the upper- mantle is well-established, and that there is a growing consensus about the origins of anisotropy in the lowermost mantle, the existence and nature of anisotropy across the lower-mantle (660 – 2000 km) is still highly debated. Here, we display the ubiquity of intrinsic anisotropy of a lower-mantle composed of deformed bridgmanite aggregates. We base our calculations on several mantle flow patterns mimicking a large-scale unimbricated convection. Using the most recent experimental deformation data of bridgmanite, we then model its texture evolution using a viscoplastic self-consistent (VPSC) approach. The resulting textures (and single-crystal elastic constants) are then used to build several local elastic tensors that would map into our lower- mantle model (i.e., an anisotropic medium). Finally, to see how our anisotropic medium fairs with tomographic observations, we implement a non-periodic homogenization algorithm to produce an effective anisotropic medium as seen by long-period seismic waves. The effective medium may be interpreted as the best image one could possibly obtain from the inversion of long-period seismic data assuming perfect data coverage. Since the effective medium is a smooth representation of our anisotropic medium, we anticipate that the wavelength of the seismic wavefield considered directly impacts the amplitude of anisotropy.

Keywords: Lower mantle, seismic anisotropy, crystallographic preferred orientation

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Gravitational Inversion for LLSVP Density and Core-Mantle Boundary Topography

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Abstract

The two Large Lower Shear Velocity Provinces (LLSVP) in the Earth's lower mantle are structural features well observed by seismic tomography, but their physical properties remain elusive. Recent studies using geodynamics, geoid, and seismological constraints suggest a dense-core LLSVP. In this study, we study the mass distribution at lower mantle from a geodetic point of view. We use the gravitational multipole, $q22$ of degree 2 and order 2 of the interior type that largely constitutes the LLSVP, determined by relating the 5.9-year oscillation in length of day (LOD) variations with the gravitational coupling between mantle and inner core (Shih and Chao, 2021). Layered model is built to simplify the problem, whereupon the isostasy is introduced to further constrain the relation between lower-mantle mass anomaly and the CMB topography. Our preliminary test shows that further consideration of dynamic departure from static isostasy can lead to a more realistic model. This finding implies the importance of dynamic effects of the mantle convection on the CMB topography.

Keywords: LLSVP; Core-mantle boundary; gravitation; Inversion

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Differential attenuation in teleseismic shear-waves: a probe for lower mantle partial melt

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Abstract

Melting is an important process within the mantle, exerting control over the composition and dynamic processes throughout the mantle. Upper mantle melt weakens the lithosphere, facilitating rifting (Buck, 2004, Kendall et al., 2005) and other surface expressions of tectonic processes. Observed low seismic velocity zones in the mantle transition zone are interpreted in terms of melt (e.g., Schmant et al., 2014, Liu et al., 2016a) although these features can also be interpreted as temperature anomalies or as artefacts of seismic anisotropy (Bezada et al., 2016). The presence of melt in the mantle transition zone can be interpreted as a proxy for increased volatile content, which acts as a catalyst for melting and results in intraplate volcanism (e.g., Yang and Faccenda, 2020). Melt is also hypothesized to by present in the lowermost mantle, often localized within ultra-low velocity zones (ULVZs, e.g., Liu et al., 2016b, Li et al., 2022) and perhaps represent remnant fragments of a basal magma ocean (Labrosse et al., 2007). However, the presence and extent of melt in the lowermost mantle is unknown. Observations of seismic anisotropy in the lowermost mantle can be plausibly explained by the shape- preferred orientation of melt inclusions, but it is challenging to differentiate between these models and the lattice-preferred orientation of bridgmanite, post-perovskite or ferropericlase. Preserving discrete melt pockets at the base of a mantle that do not coalesce into a global layer is geodynamically challenging (Dannberg et al., 2021) and unambiguous observations of melt would grant insights into the temperature and composition of the lowermost mantle. Measurements of differential shear-wave attenuation offer an alternate approach to seismically detect the presence of melt at a range of length scales throughout the mantle. Here we present a technique for measuring differential attenuation (Δt^*) by matching the instantaneous frequencies of the fast and slow shear-waves using an adaptation of the method of Mathenay and Nowack (1995). We demonstrate the effect that Δt^* can have on standard techniques for measuring shear-wave splitting, such as eigenvalue minimization (Silver and Chan, 1991). Using synthetic data and SKS measurements from the Yellowknife array, Canada and Afar, Ethiopia we illustrate how instantaneous frequency can be used to jointly measure Δt^* and shear-wave splitting. Through forward modelling of Δt^*, using both crack scattering (Hudson, 1982) and squirt flow (Chapman, 2003) models, we demonstrate the power of differential attenuation to constrain the extent of melt in different regions of the mantle.

Keywords: Seismic Attenuation, Mantle Composition, Shear-wave splitting

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On the stress dependence of the elastic tensor

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Abstract

The dependence of the elastic tensor on the equilibrium stress is investigated theoretically. Using ideas from finite elasticity, it is first shown that both the equilibrium stress and elastic tensor are given uniquely in terms of the equilibrium deformation gradient relative to a fixed choice of reference body. Inversion of the relation between the deformation gradient and stress might, therefore, be expected to lead neatly to the desired expression for the elastic tensor. However, solution of this inverse problem shows that the deformation gradient can only be recovered from the stress up to a choice of rotation matrix. Hence it is not possible in general to express the elastic tensor as a unique function of the equilibrium stress. By considering material symmetries, though, it is shown that the degree of non-uniqueness can sometimes be reduced, and in some cases even removed entirely. These results are illustrated through a range numerical calculations, and we also obtain linearized relations applicable to small perturbations in equilibrium stress. Finally, we make a comparison with previous studies before considering implications for geophysical forward- and inverse-modelling.

Keywords: Elasticity and anelasticity; Seismic anisotropy; Theoretical seismology.

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A neural network tool to constrain mantle thermal and chemical properties from seismic observables

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Abstract

Three-dimensional variations of wave speeds and density have shown the presence of seismically distinct structures in the Earth's mantle. To determine the thermochemical properties and dynamic relevance of these structures, it is crucial to understand the relationship between seismic properties and temperature/composition. However, multiple thermochemical parameters influence seismic wave speeds simultaneously. A given wave speed pair (compressional and shear) and density can be generated by many possible combinations of thermochemical parameters, which makes the inversion of wave speeds and density for thermochemical parameters a non-unique problem. In this study we use a neural network based approach to implicitly learn the non-linear mapping between temperature and bulk composition (expressed in terms of six end-member oxides: SiO2, MgO, Al2O3, FeO, Na2O, CaO) and seismic wave speeds and density at temperature and pressure conditions of the lower mantle. Wave speeds are calculated for 750,000 thermochemical models whose temperature and composition are selected at random from pre-defined ranges using thermodynamic modelling. We train neural networks with wave speeds plus or minus density as the input, and temperature and bulk composition as target outputs. The network then approximates probability density function for each output, which allows us to interpret seismic observables in terms of physical parameters, crucially, with uncertainties. When working with wave speeds (Vp and Vs) only, we found correlation between pairs of parameters such as temperature - FeO, SiO2 - MgO, SiO2 - Na2O, and SiO2 - Al2O3. By including density along with wave speeds, we found linear trade-off between temperature - CaO, temperature - SiO2, temperature - MgO, FeO - MgO, FeO - SiO2, FeO - Al2O3, FeO - Na2O, FeO - CaO, and CaO - MgO. Along with wave speeds and density, a fourth observable, such as attenuation, which is sensitive to temperature, may help to break down the linear trade-off of temperature with CaO, MgO and SiO2. The main advantage of including density with wave speeds is that it helps to better constrain the temperature and the most abundant and dynamically relevant compositional end-members, namely, the SiO2, MgO and FeO. Combining density with wave speeds breaks the correlation between temperature and FeO and the trade-off between MgO and SiO2 is much less, although some correlations (between pairs: SiO2 - Na2O, SiO2 - Al2O3) remain. In general, excluding MORB, most rocks only have a small fraction of (CaO,) Na2O and Al2O3, therefore, most of the apparent trade-offs will disappear when considering more average mantle compositional ranges.

We have developed a tool which efficiently captures the mapping between seismic wave speeds (/density) and thermochemical properties, with the capacity to represent both the inherent trade-offs between parameters as well as data uncertainties. These trade-offs and uncertainties are represented by the posterior probability density function provided by the neural network. We have demonstrated the concept for seismic wave speeds and density, but the same tool can also be adapted for other parameters such as attenuation or properties of seismic discontinuities. This tool is available for the wider community and is intended to facilitate interpretations of seismic structures inside the Earth, or in general, any planetary bodies.

Keywords: neural networks, probability density, lower mantle, bulk composition, temperature, wave speeds, density

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3D seismic wavefield simulations for tomographic filtering of mantle circulation models

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Abstract

For quantitative comparisons of tomographic and mantle circulation models (MCMs), the latter need to be "tomographically filtered". This means that the geodynamically predicted mantle structures have to be modified to account for the spatially variable resolving power of tomographic images. Two currently available methods are: 1) classic filtering with the resolution operator and 2) the "Generalized Inverse Projection" (GIP). Given an accurate prediction of synthetic seismic data, only the GIP approach allows for a fully consistent link between the different types of models. In addition to accounting for limited resolution, the GIP method includes the possibility to analyze uncertainties through error propagation.

Here, we investigate the effects of the two filtering approaches in a fully synthetic framework. For the first time in a global MCM, we simulate 3D-wavefields and seismograms for an entire tomographic earthquake catalog with over 4,200 events using SPECFEM3D_GLOBE. The generalized inverse operator of Zaroli (2016) is then applied to synthetic S-wave traveltime residuals measured by cross-correlation of the seismograms. Additionally, we predict the corresponding data with ray theory and paraxial finite-frequency kernels. We compare the predicted data sets and differently filtered models. By taking the GIP-filtered model that is based on the 3D-wavefield simulations as a reference, we can quantify the impact of reparametrization in classic filtering versus the lack of exact wave physics when using less accurate methods for traveltime predictions in the GIP filtering. Additionally, all filtered models can be compared to the underlying original structure of the MCM.

Keywords: Seismic tomography, Mantle convection, Computational Seismology

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Constraints on global mantle structure using Backus-Gilbert tomography applied to normal mode data

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Abstract

Seismic tomography is a powerful tool to study the deep Earth. When interpreted together with geodynamics and mineral physics, seismic structures can provide valuable information about the structure, dynamics and evolution of the mantle.

Commonly, tomography studies exploit inversion methods that require *ad hoc* regularisation constraints to remove the non-uniqueness of the model solution, potentially leading the model amplitudes to be biased and thus to physical misinterpretations. Moreover, the computation of uncertainties of global problems can be computationally expensive.

We aim to build tomography models of the mantle with associated uncertainties and unbiased amplitudes using the SOLA method (Zaroli, 2016), which is based on a Backus-Gilbert approach. SOLA explicitly constrains the amplitudes to be unbiased and inherently computes the model uncertainty and resolution. We apply the SOLA method to observations of normal modes – i.e. the Earth's free oscillations – which provide us with insights on the long wavelength structure of the mantle. Normal mode data provide global coverage and they are sensitive to multiple parameters, including both Vs and Vp anisotropy as well as density.

Here, we report on our progress towards a new 3-D mantle model based on the inversion of normal mode splitting functions. We discuss initial results from synthetic tests and isotropic inversions for mantle structure in terms of model estimates, uncertainties and resolution.

Keywords: Seismic Tomography; Backus-Gilbert; Normal Modes; Mantle Structure

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Global 3D models of mantle attenuation using two methods of normal mode inversion

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Abstract

Seismic tomographic mantle models of wave velocities have a limited ability to distinguish between a thermal or compositional origin for 3D structure variations. Comparing 3D velocity variations to 3D variations in seismic attenuation (loss of energy due to conversion into heat) can help us to make that distinction, contributing to understanding mantle convection evolution and the origin of lower mantle Large Low Shear-wave Velocity Provinces (LLSVPs). If the LLSVPs have a thermal origin, it will point to them being short-lived, whereas a compositional origin may point to them being long-lived stable features, anchoring convection into its degree-2 configuration. Efforts in imaging 3D attenuation have mainly focused on the upper mantle, using surface waves and body waves. Here, we present two global 3D attenuation mantle models using whole Earth oscillations, or normal modes, allowing us to include focusing and scattering without the need for approximations, by jointly modelling the elastic and anelastic 3D structure. We compare two methods of normal mode inversion: i) the one-step direct spectrum inversion, and ii) the more commonly used two-step splitting function inversion. We expect that the method of inverting normal mode spectra will be very important for 3D attenuation models, as normal mode sensitivity to this parameter is low.

Both inversion methods show very similar elastic and anelastic structure, although slightly shifted in the anelastic models, which gives confidence in our global attenuation models. We generally find high attenuation in the low velocity spreading ridges, suggesting the upper mantle is dominated by a thermal origin and agreeing with previous studies. In the lower mantle, we find low attenuation in the center of the slow LLSVPs and the highest attenuation in the fast 'slab graveyard' surrounding the LLSVPs. Comparing these observations with a laboratory-based viscoelastic model indicates that high attenuation in the slab regions can be explained by a small grain size in combination with cold temperatures, while low attenuation in LLSVPs can be explained by a large grain size combined with high temperatures.

Keywords: Attenuation – Tomography – Normal modes – LLSVPs – Mantle convection – Grain size

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Uncorrelated velocity variations in the lowermost mantle: Towards a new perspective

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Abstract

Seismic tomography has been utilized to access the composition and structure of the Earth's deep interior and provides important constraints and implications for geodynamics. Previous studies associate large low shear velocity provinces (LLSVPs) with hot superplumes that facilitate whole-mantle convection and potential reservoirs of primordial materials. Such structure can explain the isotopic differences in volcanic rock samples and reconcile seismic observation. However, it remains unclear to what extent the slow-velocity anomalies may account for chemically distinct materials because of the uncertainty in tomography models due to the resolving power and the lack of interpretive tools.

Su et al. (submitted) found that uncorrelated variations in shear and compressional wave velocity cannot be explained as artifacts of relative resolution of the models. Thus, "cross-filtered" results of the two tomographic models are useful to distinguish the contribution of non-thermal heterogeneity and map large uncorrelated moduli provinces (LUMPs). This study investigates the possible nature of such non- thermal piles by comparing distributions of LUMPs in the filtered results of geodynamic models from Deschamps and Li (2019) with that in the cross-filtered observation. The results suggest that purely thermal convection is incapable of generating LUMPs of comparable sizes, especially the positive LUMPs beneath the Pacific and Africa in the observation, no matter whether post-perovskite components are included in the D'' layer. In contrast, models with primordial materials enriched in bridgmanite and iron can partly recover the observation, and the participation of post-perovskite increases the area of positive LUMPs. We infer that the reservoir of primordial materials is stable against entrainment and possibly responsible for the thermo-chemical heterogeneity suggested by uncorrelated velocity variations.

Keywords: Composition and structure of the mantle; Seismic tomography; Inversion theory; D'' layer

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Double-diffusive layering during the evolution of planetary mantles

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Abstract

Ever since it has been realized that planetary mantle material behaves as a viscous fluid, the style of the flow has been debated. A big question is whether the mantle is, or at least was, stratified to some degree, as this largely determines the evolution of the entire planet (core, magnetic field, surface behaviour, atmosphere). Especially for the Earth a layered structure has been favored on the basis of seismological, mineralogical and geochemical observations. Various factors are known to allow stratification, e.g. phase transitions or intrinsic density jumps. However, most of these processes require a predefined internal boundary.

We will present numerical experiments on double-diffusive convection in a fluid akin to mantle material and demonstrate the influence of an initial compositional gradient with regard to the thermal and chemical evolution of a planet. We will show that in a wide parameter range (Ra, B, $\Delta\eta$T) distinct layers are formed self-organized from a continuously stratified state by dynamical fractionation. Considering this as a plausible model for planetary mantle evolution it provides a dynamical explanation for the existence of distinct chemical reservoirs within their history and for the Earth a primordial source for the LLSVPs.

Keywords: "Mantle Evolution, Double-diffusive Convection, Layer Formation"

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Silicate dynamo in a basal magma ocean

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Abstract

The Earth's magnetic field is currently powered by convective motions in the outer core. These motions arise from the concomitant action of both thermal and compositional convection, the latter being a consequence of the release of light elements as the inner core crystallizes. As shown by paleomagnetic data, this geodynamo has been sustained for at least 3.45 Ga. However, the inner core crystallized no more than ~ 1 Ga, which means that the early Earth dynamo was not powered by the release of light elements and latent heat at the inner core boundary. With a potentially high thermal conductivity of the outer core, an alternative mechanism could be required to sustain a geodynamo prior to the inner core nucleation. The recorded paleomagnetic field could have been produced by a silicate dynamo in a long-lived basal magma ocean (BMO), which might be possible if the electrical conductivity of the silicates is large enough. These silicate dynamos have been investigated using energy and entropy budget as well as scaling laws developed in the context of the outer core. In this study, we are investigating the properties of a possible silicate dynamo in a thin BMO using numerical simulations with the code Rayleigh. We focus in particular on the influence of the BMO aspect ratio and its influence on the magnetic field geometry. We are also investigating the possible influence of the underlying core on the dynamo produced in the BMO. Finally, we will generalize the results to super-Earth exoplanets in which magma oceans are expected to be a common feature due to their extreme conditions of pressure and temperature.

Keywords: geodynamo, early Earth, basal magma ocean, MHD simulations

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Can a basal magma ocean produce a large-scale planetary magnetic field?

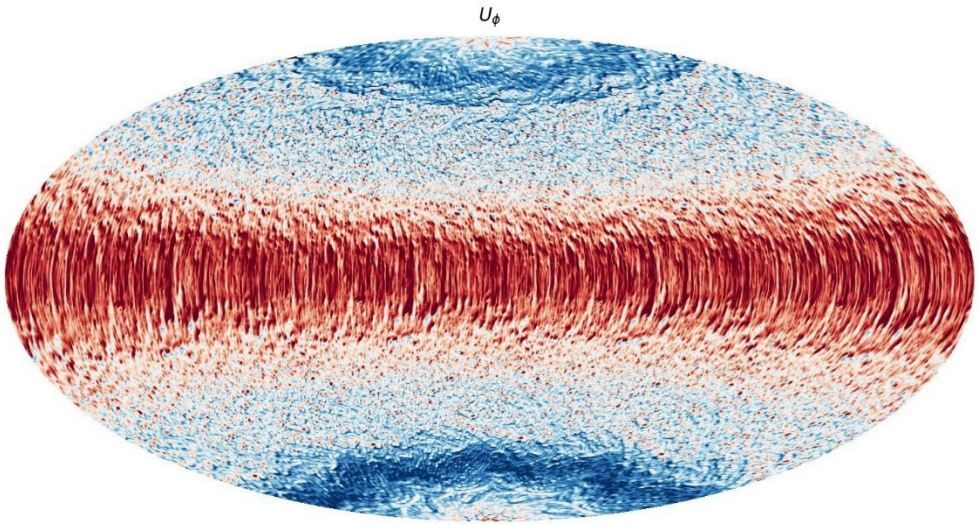
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Abstract

It has been suggested that vigorous convection in a magma ocean at the base of the mantle could produce a magnetic field (Stixrude+ 2020). The argument relies solely on energetic considerations, and, for the Earth, the magnetic Reynolds number (Rm) remains too small to hope for a dynamo (Landeau+ 2022). Nevertheless, we solve the equations of the convective dynamo problem in a thin shell (ri/ro=0.9, where ri and ro are the inner and outer radius respectively), using the xshells code on GPUs.

In our preliminary runs, we find that the magnetic field is small scale, unless strong zonal flows are allowed by stress-free boundary conditions. In any case, large Rm (a few thousands) are needed to obtain a dynamo. This supports the idea that a basal magma ocean in the early Earth could not produce a dynamo, but this remains a possible mechanism for other planets.



Stixrude+ 2020: https://doi.org/10.1038/s41467-020-14773-4

Landeau+ 2022: https://doi.org/10.1038/s43017-022-00264-1

Keywords: Dynamo, Magma Ocean, Early Earth, Planetary magnetism, Convection, Turbulence

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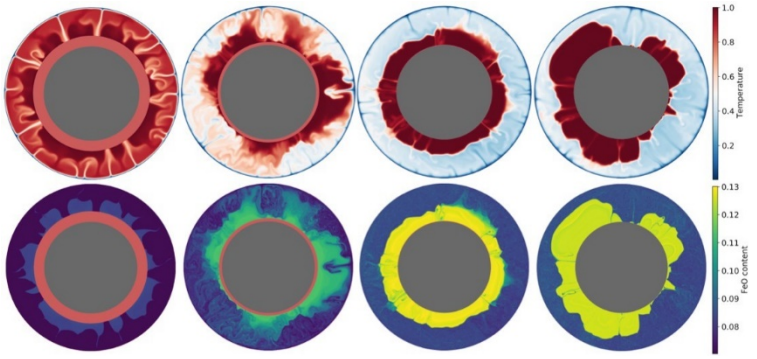
Mantle evolution with a long lasting basal magma ocean

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Abstract

The current seismological structure of the lowermost mantle, with very small scale ultra-low-velocity zones (ULVZ) and large low velocity provinces (LLVP) have been proposed to result from the long term evolution of the Earth with a basal magma ocean (BMO) [1]. The basal magma ocean influences convection in the overlying solid mantle in several ways. Firstly, the possibility of melting and freezing implies a phase change boundary condition that allows for direct mass transfer with very strong implications for convection compared to the standard non-penetrative condition: a reduced critical Rayleigh number, larger scale flow, dominance of down-welling currents and enhanced heat transfer [2, 3]. Secondly, fractional crystallization at the boundary leads to a solid that is depleted in FeO compared to the liquid it originates from. Conservation of species leads to a gradual enrichment of the magma in FeO, which acts as an anti-freeze agent, and makes the solid gradually richer in FeO and therefore denser with time. The anti-freeze effect could allow for the persistence of liquid to the present day, explaining ULVZs, while the density effect on the solid could explain the formation of LLVPs. Testing this scenario requires a model that includes several ingredients: a mantle convection code, StagYY [4, 5], able to treat variations of composition and of physical properties (notably viscosity) and the phase change boundary condition [3], a model for the thermal and compositional evolution of the core and the BMO, and a treatment of the moving boundary problem associated to the net freezing of the mantle. In this presentation, we show results from such a model and discuss the regime change for mantle convection associated to the crystallization of the BMO and stabilization of the compositionally distinct reservoirs in the deep mantle (see figure).



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Keywords: Mantle convection, basal magma ocean, thermal evolution, chemical evolution.

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On the effects of planetary rotation on the dynamics of a terrestrial magma ocean

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Abstract

About 4.5 billion years ago, an impact of a mars-sized body caused a deep magma ocean of global extent on Earth. An important but mostly neglected process in studies on such magma oceans is the effect of planetary rotation. Early Earth rotated much faster than today, with a minimum period of 2-5 hours. Owing to the small viscosity of the vigorously convecting melt, planetary rotation may have far-reaching consequences for magma ocean solidification and Earth's early differentiation. It may not only be of key importance for the chemical structure and the development of chemical heterogeneities, but it may also set the stage for the initiation of plate tectonics. In addition to that, impacts of differentiated projectiles into the magma ocean are thought to deliver additional metal to Earth during a stage called late accretion. To understand to what extent the present-day geochemical signature of the Earth's mantle reflects the processes of core formation and late accretion, it is important to comprehend how the metal delivered by impacts is dispersed and settles within a terrestrial magma ocean.

Therefore, by means of numerical experiments in a rotating spherical shell, we demonstrate the crucial effect of planetary rotation on two processes occurring in a magma ocean, namely on the dynamics of silicate crystals during an early stage of magma ocean solidification and on the settling of impact-delivered metal within a magma ocean. Planetary rotation may provide a possible mechanism for the generation of chemical heterogeneities and isotopic anomalies within Earth's mantle, and for heterogeneous metal-silicate equilibration, potentially shaping the geochemical signatures being observed today.

Keywords: magma ocean, differentiation, metal-silicate equilibration, rotating convection, metal settling history, impact

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Reactive Crystallization of the Basal Magma Ocean: Consequences for present-day mantle structure

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Abstract

Terrestrial planets evolve through multiple magma-ocean stages during accretion and differentiation. Magma oceans become progressively enriched upon fractional crystallization (FC), which should be dominant at least in the upper mantle. The resulting upwards enrichment of the cumulate package drives gravitational overturn(s), and ultimately stabilizes a FeO- and SiO_2-enriched basal magma ocean (BMO). Alternatively, a pyrolitic BMO may be formed due to a liquid-solid density crossover at high pressures. In any case, a slowly cooling BMO is expected to freeze by FC. However, we find that the consequences of FC of the BMO are inconsistent with geophysical constraints: the first FC cumulates (mostly $MgSiO_3$) are entrained by mantle convection, but final FeO-enriched cumulates stabilize a layer at the base of the mantle with extreme density anomalies that is several 10s of km thick. Such a layer should be extremely long-lived (*Ismail+, this meeting*), but not detected by seismic imaging.

Using a thermodynamic model (*Boukaré+, JGR* 2015), we here investigate the chemical consequences of an alternative scenario: reactive crystallization (RC) of the BMO. As long as the BMO-mantle boundary remains exposed due to the efficient entrainment of newly-formed cumulates, the BMO reacts with mantle pyrolite due to chemical disequilibrium. We find that the final RC cumulate sequence consists of two discrete layers: the first is Mg-rich bridgmanite (~$MgSiO_3$); the second is a moderately FeO-enriched pyrolite. In a second scenario for RC of the BMO, the BMO reacts with (partially) molten subducted Hadean/Archean crust instead of with solid-state pyrolite. This scenario is attractive, because large volumes of crust may be readily delivered to the lowermost mantle, and will produce dense magmas there, which sink into the BMO to promote efficient reaction. We find that the cumulate sequence for this scenario also consists of two discrete layers, and that the first layer is also dominated by $MgSiO_3$. The second layer (which may evolve into thermochemical piles), however, is bridgmanitic instead of pyrolitic, and enhanced in Fe_2O_3 and Al_2O_3 (i.e., with high oxygen fugacity). Such thermochemical-pile compositions are in very good agreement with the geophysical signatures of the large low-velocity provinces (*Vilella+, EPSL* 2021). For combined BMO cooling and reaction with mantle pyrolite/basalt, we can moreover predict the BMO temperature and composition, at which it stops evolving further due to a balance of chemical fluxes. This composition may correspond to that of seismically-detected ultra-low velocity zones.

Our results imply that large rocky planets such as Earth, Venus or even Super-Earths may host only a rather short-lived BMO due to efficient RC (instead of inefficient FC due to slow cooling). In turn, small stagnant-lid planets with limited crustal recycling, such as e.g. Mars, may host longer-lived BMOs (*Samuel+, JGR-planets* 2021). These predictions have important implications for the long-term thermal/chemical evolution of terrestrial planets.

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The influence of rheological and fluid dynamical parameters on the stability of thermochemical piles at the CMB

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Abstract

Seismic tomography studies suggest the presence of two large low shear velocity provinces (LLSVPs) below Africa and the Pacific. They are generally assumed to have been at or near their current positions for at least the last 200 Ma. Since lower seismic velocities correlate with a higher temperature, and therefore lower density and viscosity, an additional compositional difference between the LLSVPs and the surrounding mantle material might be necessary to explain why they have not become entrained in the mantle during this large timespan.

We use a 2D numerical model of thermochemical convection with temperature-, pressure-, stress- and composition-dependent viscosity in a rectangular box to simulate the Earth's mantle. We observe the formation of piles at the core-mantle boundary (CMB), which could represent LLSVPs or small-scale ultra-low velocity zones (ULVZs). We investigated these piles' longevity and their lateral movement. We find that variations in fluid dynamical (Lewis number, Rayleigh number and buoyancy ratio) as well as rheological (composition and pressure dependence of the viscosity) parameters influence the behavior of the piles and their longevity.

A stronger pressure dependence of the viscosity generally increases both the time required for piles to form and the time it takes for them to become fully entrained in the surrounding mantle through convection. Furthermore, an increase in the pressure dependence of the viscosity decreases the piles' lateral movement, thus increasing their spatial stability. A higher composition dependence of the viscosity, higher Lewis number, lower Rayleigh number or higher buoyancy ratio also increases the piles' longevity, but without increasing their spatial stability as well.

Keywords: LLSVP, thermochemical convection, numerical modelling

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LLSVPs of primordial origin: Influence on the evolution of plate tectonics

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Abstract

Early periods of Earth's history are of great interest for the evolution of plate tectonics. For instance, neither the formation of lithospheric plates nor the nature of Archean plate tectonics is well known. As a remnant of the magma ocean period, a compositionally dense layer at the core-mantle boundary is assumed to interact with the convective flow of the Earth's mantle forming todays LLSVPs. Since plate motions are strongly coupled to the convection of mantle material, stabilizing effects of compositionally dense material have a profound impact on mantle convection and plate tectonics and will be of major importance for its evolution.

To investigate the influence of dense LLSVP-like structures, we employ thermochemical mantle convection models with self-consistent plate generation. We perform an extensive parameter study to analyze the influence of different parameters, e.g., the Lewis number (i.e., the diffusivity of the dense basal layer) or the density contrast between dense and ambient mantle material.

Generally we observe an evolutionary path from a stagnant lid, via episodic surface mobilizations to a permanently mobile state with continuous plate-like surface motion. Yet, this evolution, particularly the episodic stage, is considerably altered by the presence of dense basal material. An increase of the density contrast leads to a longer episodic stage and thus to a delayed mobile state. Similarly, a thicker layer or a larger Lewis number (i.e., lower chemical diffusivity) also lead to a longer evolution. An infinite Lewis number (i.e., zero chemical diffusion), however, causes a substantially different behavior, combined with a large density contrast it results in a much shorter evolution which directly turns to a permanently mobile state after the initial stagnant lid phase.

Keywords: plate tectonics, delayed evolution, LLSVPs, compositionally dense layer, Lewis number

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Influence of heterogeneous thermal conductivity on the long-term evolution of the lower mantle thermochemical structure: implications for primordial reservoirs

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Abstract

The long-term evolution of the mantle is simulated using 2D spherical annulus geometry to examine the effect of heterogeneous thermal conductivity on the stability of reservoirs of primordial material. In numerical models, mantle conductivity is often emulated using purely depth-dependent profiles (taking on values between 3 and 9 W/m-K. This approach is meant to synthesize the mean conductivities of mantle materials at their respective conditions in-situ. However, because conductivity depends also on temperature and composition, the effects of these dependencies in mantle conductivity is masked. This issue is significant because dynamically evolving temperature and composition introduce lateral variations in conductivity, especially in the deep-mantle. Minimum and maximum variations in conductivity are due to the temperatures of plumes and slabs, respectively, and depth-dependence directly controls the amplitude of the conductivity (and its variations) across the mantle depth. Our simulations allow assessing the consequences of these variations on mantle dynamics, in combination with the reduction of thermochemical pile conductivity with iron composition, which has so far not been well examined. We find that the temperature- and depth- variations combined characterize the mean conductivity ratio from top-to-bottom. For the mean conductivity profile to be comparable to the conductivity often assumed in numerical models, the depth- dependent ratio must be at least 9 times the surface conductivity. When the conductivity profile is underestimated, the imparted thermal buoyancy (from heat-producing element (HPE) enrichment) destabilizes the reservoirs and influences CMB coverage configuration and the onset of entrainment. The compositional correction for conductivity only plays a minor role that behaves similarly to conductivity reduction due to temperature. Nevertheless, this effect may be amplified when depth- dependence is increased. For the cases we examine, when the lowermost mantle's mean conductivity is greater than the surface conductivity, reservoirs can remain stable for periods exceeding the age of the solar system.

Keywords: Thermal conductivity, thermo-chemical piles, thermo-chemical convection

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Seismic anisotropy of the lowermost mantle predicted from Earth-like mantle circulation models

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Abstract

Seismic anisotropy is present ubiquitously in the boundary layers of the Earth's mantle, and provides information about the history of mantle flow. Therefore it has long been a goal to try to interpret anisotropy in terms of flow. We can use forward models of mantle flow and compare their predictions to data to address questions such as whether the mantle contains dense, chemically distinct piles of material which form the Large Low-Velocity Provinces (LLVPS), or whether these are thermal structures. We tackle this problem by creating Earth-like mantle circulation models (MCMs) incorporating plate motion histories from 400 Ma to present, and with Rayleigh numbers of order 10^8. These should therefore contain thermal and chemical structures on the same length scale as the Earth. At each point of interest, we use the recent (~120 Ma to present) flow field to compute the crystallographic texture (lattice-preferred orientation, LPO) of 500 post-perovskite grains and combine them with single-crystal elastic constants to compute the full elastic tensor at all points in the lowermost mantle. A key difference between this and previous work is that the flow field varies through time, and that we trace particles backwards to allow us to evaluate texture at arbitrary positions. We are then able to synthesise seismic observations such as shear-wave splitting, normal mode eigenfrequencies and splitting from each model, and compare to observed data.

We initially investigate the predicted average radial anisotropy structure and compare it to recent 1D models of $\xi = V_{SH}^2/V_{SV}^2$, $\varphi = V_{PV}^2/V_{PH}^2$ and the parameter η. We test three models of post-perovskite deformation via dislocation creep where the most active dislocations are on (100), (010) and (001). We find that for our preferred model of post-perovskite deformation on (001), the pattern of $\xi > 1$ and $\varphi < 1$ holds. In all cases, the strength of the average radial anisotropy parameters ($\log(\xi)$ or $\log(\varphi)$) is similar to one percent, matching previous inferences, even though we do not limit the texturing in our simulations through recrystallisation or similar approaches. However, we also find that the average radial anisotropy parameters predicted by MCMs are not the same as those predicted under the common assumption that flow is horizontal. Instead, the complexity in the flow field is important in determining the texture and hence anisotropy both at any one point in the lowermost mantle, and on a globally averaged scale. This work represents a further step in constraining mantle flow and its recent history from seismic anisotropy in the lowermost mantle.

Keywords: anisotropy; lowermost mantle; post-perovskite; mantle flow

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Microstructures and anisotropy in pyrolite at lower mantle pressures and temperature

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Abstract

The Earth's lower mantle is thought to hold a composition relatively close to that of pyrolite, with approximately 80% of bridgmanite (Mg,Fe)SiO3, 15% of ferropericlase (Mg,Fe)O, and 5% of davemaoite CaSiO3. In this work, we investigate the microstructures induced by phase transformation and deformation in a pyrolitic composition at Earth's lower mantle pressures and temperatures. Lower-mantle pyrolitic composition is formed at pressures between 20 and 30 GPa and temperatures on the order of 1900 K and further compressed up to pressures above 100 GPa at simultaneous temperatures on the order of 2000 K, corresponding to depths of approximately 2500 km in the Earth's mantle.

We rely on a novel technique, multigrain X-ray diffraction in the laser heated diamond anvil cell, which allows tracking hundreds of individual grains simultaneously during processes including phase transformation, pressure increase, and deformation. Our results show that *i)* pyrolite is formed with a non-random transformation texture, due to the compressive stress applied during the diamond anvil cell experiments, *ii)* microstructures further evolve with increasing pressure.

The experimental results are then used to *i)* identify deformation mechanisms in bridgmanite within a pyrolitic composition, *ii)* evaluate the effect of pressure on those mechanisms, and *iii)* evaluate the resulting seismic anisotropy, either from the synthesis of pyrolite at 660 km depth discontinuity conditions or from deformation deeper in the Earth's lower mantle.

Keywords: bridgmanite, pyrolite, deformation, phase transformation, anisotropy, microstructure

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The interplay between recycled and primordial heterogeneities: constraints on Earth mantle dynamics via numerical modeling

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Abstract

The chemistry, origin and geometry of the heterogeneities that populate the lower mantle remain controversial. Geodynamic models predict a range of viable scenarios for mantle convection and heterogeneity preservation. We identify two end-member scenarios: in the “marble cake” model, slabs of subducted Recycled Oceanic Crust (ROC) are deformed but never fully homogenized in the convecting mantle. Conversely, $MgSiO_3$-rich primordial material may resist convective entrainment due to its intrinsic strength, leading to a “plum pudding” mantle. Few past geodynamic studies have explored the influence of subducted ROC properties on mantle dynamics while also including primordial heterogeneity. Moreover, predictions from numerical models must be compared to geophysical observations, but current imaging techniques may be unable to discriminate between these two end- members, due to insufficient resolution in the lower mantle.

We model mantle convection in a 2D spherical-annulus geometry with the finite-volume code StagYY. We investigate the style of heterogeneity preservation as a function of the intrinsic density and the intrinsic viscosity of basalt at lower mantle depths. Furthermore, we use the thermodynamic code Perple_X and the spectral element code AxiSEM to compute, respectively, seismic velocities and synthetic seismograms based on the predictions of our models.

We obtain two mantle-mixing regimes: while low-density basalt leads to a well-mixed, "marble cake"-like mantle, dense basalt aids the preservation of "plum pudding" blobs of primordial material in the mid-mantle. In addition, we select two models that are representative of these end-member regimes: via Perple_X, we map their respective temperature, pressure and compositional fields into thermoelastic properties and build seismic velocity models. Then, via AxiSEM, we compute seismic waves propagation in both the "plum pudding" and "marble cake" mantle. Finally, we carry out a preliminary attempt to discriminate between these two end-members based on their respective synthetic seismograms.

Keywords: mantle convection, numerical modeling, synthetic waveform study

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Metrics and Measures for Comparing Mantle Circulation Models: Drawing Inspiration from Weather Forecasting

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Abstract

A crucial goal in geodynamics is the development of time-dependent Earth models so that poorly known mantle convection parameters can be refined against observables gleaned from the geologic record. To this end one must construct model trajectories to link estimates of the current heterogeneity state to future or past flow structures via forward or inverse mantle convection models. Unfortunately, the current heterogeneity state which is derived from seismic imaging methods is subject to substantial uncertainty due to the finite resolution of seismic tomography. These uncertainties are likely to considerably affect the computed flow trajectory, in what is known as the butterfly effect. Here we study mantle convection models to assess the effects of varying initial conditions on the evolution of mantle flow. We perform twin experiments (Lorenz 1965), that is, we compute convection calculations with identical flow parameters but different initial temperature fields and follow their trajectories.

We also introduce a framework for the comparison of model output with geological observables. To this end, we perform a comparison between the dynamic topography maps of our twin models by applying object-based verifications that identify and match uplift and subsidence objects in the dynamic topography maps for the twin models similar to what a human observer would identify. Borrowing from the wealth of work in meteorology, we calculate SAL scores (Wernli et al 2008) and a Critical Success Index (Schaefer 1990). Finally, for successfully matched objects, a Procrustes shape analyis (Michaes et al 2007) is performed.

Keywords: butterfly effect, twin experiments, dynamic topography

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Deep Mantle Flow Over LLSVPs Reproduces Surface Hotspot Motions

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Abstract

The Large Low Shear Velocity Provinces (LLSVPs) are seismic structures at the base of the Earth's mantle from which deep-source hotspots arise (Morgan & Phipps-Morgan, 2007; Jackson et al, 2018). Over the past 20 years, researchers from the disciplines of seismology, geochemistry, geodesy, and geodynamics have presented evidence suggesting the LLSVPs are compositionally distinct and slightly denser than the surrounding mantle (McNamara and Zhong, 2005; Jackson et al., 2010; Garnero et al., 2016; Lau et al., 2017), but understanding of their origin, structure, and dynamical implications remains quite poor. Here, we seek to constrain the structure and dynamical implications of the LLSVPs by investigating the conditions under which surface hotspot motions can be reproduced by basal flow in the mantle. Previous studies have acknowledged that subducted slabs may push plume sources around in the deep mantle (Olson, 1987), and that the fixity of plume sources may be influenced by the presence of thermochemical piles (Jellinek & Manga, 2002). In this study, we find that the surface hotspot motions are rapidly convergent in the South Pacific (24 mm/year average speed), but relatively stationary in the Indo-Atlantic region (11 mm/year average speed), and investigate for the first time whether the rapid convergence of hotspots in the South Pacific and relative fixity of hotspots in the Indo-Atlantic can be reproduced by deep mantle flow over the LLSVPs.

We compute instantaneous numerical simulations of mantle convection with a buoyancy field scaled from the seismic tomographic model S40RTS, and then scale the convective velocities predicted in the deep mantle to the surface so they may be compared with hotspot motions. First, our results show that if the density field is purely scaled from %dVs (i.e., no special treatment is applied to the LLSVPs), then the predicted flow velocities are broadly consistent with observed hotspot motions in the South Pacific, but overestimate those in the Indo- Atlantic. Next, we treat the LLSVPs as structures that divert ambient mantle flow and analyze the velocity of ambient mantle material along the LLSVP surface. Results show that deep mantle flow is consistent with surface observations of hotspot motions to within +-4 mm/year or 17% error if the African and Pacific LLSVPs are assigned topography uniformly equal to 1500 km and 500 km, respectively, based on results from a recent study (Yuan & Li, 2022). We also find that flow along the surface of the LLSVPs simultaneously reproduces rapid convergent motion in the South Pacific and relative stationarity in the Indo-Atlantic for a broad range of estimates of LLSVP topography from S40RTS which include lateral variations in the estimated LLSVP height. Our results suggest that the LLSVPs may play a significant role in organizing the flow field around them in the deep mantle, and hotspot motions observed at the surface.

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Compressible convection

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Abstract

We have studied compressible convection in a two dimensional numerical model of large aspect ratio and periodic boundary conditions in the horizontal direction. Two different classes of equations of states have been tested. In the first one, we take the extreme limit of an equation of states where entropy depends only on density. This makes density nearly constant in the bulk of the convective region and minimizes non-Oberbeck-Boussinesq effects. The other class is that of Birch-Murnaghan equations of state, which are realistic models for condensed matter, in particular for the Mantle and Core of the Earth. We have specifically studied the profile of dissipation. We found that it is directly related to the fraction of the heat flow carried by the flux of entropy. With both types of equations of state, when the dissipation number is of order one and when the superadiabatic Rayleigh number is large enough, above 10^7 or 10^8, we find that the heat flux is carried mostly by the entropy flux and that consequently the profile of viscous dissipation can be predicted, in terms of the profiles of thermal expansion coefficient, heat capacity and gravity along the adiabat. In terms of flow structure, small scales of convection are dominant.

Keywords: Compressibility, Equation of States, Mantle, Core

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Supercritical Thermal Convection in a Sphere

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Abstract

Thermal convection is an essential mechanism for mantle convection. We present results from direct numerical simulations of highly supercritical thermal convection in non-rotating full sphere and spherical shell geometries at finite Prandtl number and investigate the scaling of heat transfer and global flow properties with the thermal forcing. We report on the effects of boundary conditions and of varying the Prandtl number and the ratio of inner to outer radii in the shell case. The simulations are performed using highly accurate and efficiently parallelised fully spectral methods for solving the relevant equations of motion and of heat transfer.

Keywords: Thermal convec0on, Heat transfer, DNS

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Asthenospheric Flow through the Izanagi-Pacific Slab Window and its influence on Dynamic Topography and Intraplate Volcanism in East Asia

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Abstract

The tectonics of East Asia are notoriously complex. Consisting of an intricate patchwork of microplates and accreted terranes, even the Cenozoic tectonic history of the region remains controversial, and many differing reconstructions have been proposed. While the exact kinematics remain poorly constrained, it is generally accepted that the region has been characterised by a long history of subduction and downwelling. However, numerous geological and geophysical observations, at a first glance, appear to lie in stark contrast to this history. Regions of present-day dynamic uplift inferred from residual topography studies, the observation of seismically slow anomalies in numerous tomographic models, and the widespread occurrence of intraplate volcanism in East Asia since the latest Paleogene are all at odds with the expected cold upper mantle and downwelling flow associated with a history of subduction. Here, we propose a solution to this paradox, in which hot asthenospheric material flows from the Pacific domain into East Asia—passing through the slab window opened by the subduction of the Izanagi-Pacific ridge during the early Cenozoic. To investigate this hypothesis, we compare several independent geological observations to the asthenospheric flow predicted by a suite of recently published 3D global mantle circulation models. We compare observations linked to uplift and erosion to the changes in dynamic topography induced by this influx of hot material. These include the widespread late Eocene–Oligocene sedimentary hiatus in far eastern China and the regional erosion of the South China Block (SCB) since the Miocene inferred from Apatite Fission Track Thermochronology studies. We additionally compare the timing and location of intraplate volcanism with the predicted distribution of hot material through time. We find the westward influx of asthenospheric material to be a robust feature in the models, being predicted under all considered tectonic reconstructions. Nevertheless, the influence of this material is significantly affected by differing implementations of the Philippine Sea Plate (PSP) history, which allows us to distinguish between these reconstructions based on our comparisons with the evidence considered. A larger PSP is found to predict dynamic subsidence in regions where uplift and erosion is present, such as the East China Sea Shelf Basin and the SCB, while also predicting large-scale mantle downwelling in regions where intraplate OIB-type magmatism has been recorded. A smaller PSP and the consequent existence of the hypothesised 'East Asian Sea' slabs instead allows the hot asthenospheric material to predominate over a larger region, providing a better fit to the spatial distribution of regional-scale erosional episodes and OIB-type magmatism.

Keywords: East Asia, Asthenospheric Flow, Dynamic Topography, Intraplate Volcanism, Slab Window, Ridge Subduction, Mantle Circulation Models, Plate Reconstructions

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Asthenospheric flow estimates in the Atlantic realm based on Poiseuille/Couette flow models

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Abstract

Mantle convection has profound effects on the Earth's surface, such as inducing vertical motion, which is commonly termed dynamic topography. Sophisticated mantle convection models have been used to study current and past dynamic topography. But many input parameters, like complex rheologies and thermo---chemical flow properties remain poorly known, requiring ad---hoc model parameterization and long---range extrapolation. This makes it attractive to explore simple analytic models of upper mantle flow. The existence of a weak asthenosphere allows one to explore upper mantle in the context of Poiseuille/Couette flow. The latter provides a geodynamically plausible link between flow properties and dynamic topography. Here we construct simple upper mantle flow models parameterized in terms of sources/sinks (plumes/slab) of Poiseuille/Couette flow. Our approach provides physical insight into the pattern of upper mantle flow, makes it easy to assess uncertainties of key model parameters, such as poorly resolved asthenospheric thickness and viscosity, and can be extended back in time, given first---order estimates of plume and subduction flux deduced from geological records. Importantly, it demands low computational cost relative to a time dependent geodynamic models. We present results for the Atlantic realm, and link our estimates of upper mantle flow history to Base Hiatus Surfaces (BHS). The latter serve as proxy for inferring past dynamic topography variations. We also relate our calculations to seismically inferred anisotropy, as a further proxy for upper mantle flow. Our results indicate that asthenospheric flow pattern can be explained through the concept of source to sink and that this flow type is testable against first---order seismic and geologic observables.

Keywords: Geodynamics, Mantle Convection, Poiseuille/Couette flow

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Tracing active upper mantle flow using continental-scale hiatus surfaces and spreading rates changes in the Atlantic and Indo-Australian Realms since the Upper Jurassic

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Abstract

Mantle convection is an essential driving force of plate tectonics. It affects the horizontal and vertical motion of the Earth's surface. The horizontal motion of the lithosphere is observed in the spreading rates, while its vertical motion leaves an imprint the geological record. In particular, positive surface deflections driven by mantle convection create erosional/non-depositional environments, which induce gaps in the stratigraphic record (i.e., hiatus). Modern digital geological maps allow us to map no-/hiatus surfaces at continental scale systematically and use them as a proxy for mantle flow induced dynamic topography. We compare our continent-scale hiatus mapping to plate motion variations in the Atlantic and Indo-Australian realms from the Upper Jurassic onward. In general, we find the datasets correlate except when plate boundary forces may play a significant role. There is a timescale on the order of a geologic series between the occurrence of continent-scale hiatus and plate motion change. This is consistent with the presence of a weak upper mantle. Also, we find significant differences in the spatial scale of inter-regional hiatus, on the order of 2000-3000 km in diameter, which can be linked by fluid dynamic analysis to active upper mantle flow regions. Our results highlight the importance of geological datasets to further understand geodynamic processes in the deep Earth. Also, they indicate that studies of horizontal and vertical motion of the lithosphere to track past mantle flow would provide powerful constraints for adjoint based geodynamic inverse models of past mantle convection.

Keywords: Dynamic topography, hiatus, oceanic spreading rates, mantle convection

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Self-Consistent Formation of Thermochemical Piles by Core-Mantle Interaction

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Abstract

Seismic anomalies at the core-mantle boundary (CMB), such as the large low shear-wave velocity provinces (LLSVPs), are possibly induced by chemically distinct material. Typically, models of mantle convection made some ad hoc assumptions in order to simulate the dynamics of the CMB. In particular, the volume and density of a compositionally enriched layer were prescribed. Both conditions are critical for the dynamics but hardly constrained. This dense CMB layer is considered to be either a remnant of the magma ocean or formed by segregated slabs or by core-mantle interaction processes. One proposed metal-silicate interaction at the CMB is diffusion-controlled enrichment of molten iron. As such, we employ models where a thermochemical layer at the base of the mantle develops self-consistently by a diffusive chemical influx rather than prescribing the thickness or density of this layer. Our simulations indicate that the chemical diffusion is strongly affected by the convective flow within the mantle. The convection-assisted diffusion yields a large compositional influx mainly in the areas where slabs spread over the bottom boundary and sweep dense material aside to form accumulations below the rising plumes. Like in the cases with a prescribed dense layer this process leads to chemically distinct piles. Here, however, the chemical structures are larger and more persistent due to the constant chemical influx.

Keywords: thermochemical mantle convection, numerical modelling, LLSVPs

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Seismic Visibility of Melt at the Core-Mantle Boundary from PKKP Diffracted Waves

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Abstract

Ultra-low velocity zones (ULVZs) are discrete patches of low seismic velocity immediately atop the core-mantle boundary (CMB). There are many hypothesised origins of ULVZs including that they may be comprised of melt, partial-melt or strongly iron enriched material. Melt in the lower mantle is itself expected to be iron rich and dense and should therefore drain to the CMB under gravity, as has been shown in geodynamic models. Therefore ULVZs that are partially molten should be accompanied by a far more extensive layer of melt that has so far not been observed by seismologists.

Using short period synthetic seismograms we have examined the effect that a one-dimensional thin layer of melt at the CMB would have on seismograms. We find that PKKP diffracted is an extremely sensitive measure of low velocities above the CMB and can, in synthetic waveforms, resolve melt layers that are single kilometres thick, and is a phase that has been previously underused. We have constructed and examined a global dataset of PKKP diffracted observations but find that we cannot exclude nor observe a thin melt layer at the CMB due to scatter in the dataset. Thus, within the bounds of our dataset, a thin melt layer at the CMB remains a possibility and would greatly affect core-mantle interaction.

Keywords: PKKP diffracted; core-mantle boundary; lower mantle melting; seismic visibility

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Detection of Pdiff postcursors in high frequency data for the Hawaii mega-ULVZ

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Abstract

Core-diffracted shear waves (Sdiff) have been used to study the large-scale deep anomalies called Large Low Velocity Provinces (LLVP) and small-scale Ultra Low Velocity Zones (ULVZ) at the base of the mantle. With an estimated radius of 450km, a thickness of 20km, and a 20% shear wave velocity (Vs) reduction, the Hawaii mega-ULVZ is one of the best studied small-scale anomaly in the lower mantle, but there are virtually no observational constraints on its compressional wave velocity (Vp) structure. In this study, we use array seismology stacking methods to study the high frequency wavefield (2~10 seconds of period) recorded in the central USA from an event in Papua New-Guinea in March 2010. We were able to detect a post-cursor to the core-diffracted compressional (Pdiff) wave on multiple sub- arrays and to estimate the P-wave anomaly required in the basal layer of the Hawaii mega- ULVZ to explain the observed delay times. Using a 2D raytracer, we find that for a 450km radius anomaly, a reduction of ~35% in both Vp and Vs is needed to explain the high frequency post-cursors for the core-diffracted P and S waves. As shown by Li, et al. 2022 for Sdiff, we observe a frequency dependence of the delay times for the Sdiff and Pdiff postcursors, with the latter seemingly merging with the main phase when low pass filtered under 8~10 seconds of period. This highlights the sensitivity of the Pdiff phase to the lowermost part of the ULVZ, and could mean that the ULVZ has a layered structure. If this is the case, differences in wavelength and sensitivity kernels for Pdiff and Sdiff could help decipher the internal structure of the Hawaii mega-ULVZ. Moreover, Pdiff could sense a deep melt-rich layer, which Sdiff cannot sense, that could explain the strong anomalies required to explain the delay times.

Keywords: Seismology, Core-Mantle Boundary, Ultra-Low Velocity Zones, Diffracted waves

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A Global Search for ULVZs with Sdiff Postcursors

Carl Martin*†, Felix Davison, and Sanne Cottaar

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Abstract

The search for ULVZs using shear diffracted waves has thus far broadly been a result of several targeted studies (e.g. Hawaii [To et al, 2013; Cottaar and Romanowicz, 2013], Iceland [Yuan and Romanowicz, 2017], Galapagos [Cottaar et al, submitted]). In this study we present the results of a global search for ULVZs using postcursors in S core-diffracting phases, Sdiff, for earthquakes from 1990 to 2021 of magnitude 5.7+ and at all depths.

Shear diffracted phases are sensitive to particularly large and highly reduced ULVZs, often referred to as "mega-ULVZs". We find these are rare across much of the core-mantle boundary. We present a compilation of global raypaths with sensitivity to ULVZs, which elucidates for the first time previously unknown ULVZs; including 3D modelling from one such new ULVZ in the southern Pacific ocean, near the root of the St Helena and Ascension hotspot plumes [Davison et al, in prep], and an example of an earthquake which samples multiple ULVZs.

Keywords: Seismology, ultra-low velocity zone (ULVZ), Sdiff, core-mantle boundary (CMB)

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The sensitivity of the Six-Year length-of-day oscillation to the geoid at the CMB

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Abstract

Large Low-Shear Velocity Provinces (LLSVPs), as revealed by global tomographic models, correspond to two large-scale horizontal slow velocity anomalies in the deep mantle, rooted at the Core Mantle Boundary (CMB), one beneath Africa and the other beneath the Pacific ocean. Their lateral extent is relatively well constrained and consistent across many studies. However, global seismic tomography is not very sensitive to the buoyancy structure in the deep Earth, and it is, to this day, unclear if the LLSVPs are produced by a purely thermal effect, or a compositional effect, both resulting in opposite buoyancy fields. Finding a way to better constrain the buoyancy of the LLSVPs would have major implications on our understanding of global mantle dynamics, thermal evolution of the Earth. Several recent studies have proposed new ideas of LLSVP buoyancy that include these structures representing compositional heterogeneity and thus being negatively buoyant. However, the details of the depth extent of this heterogeneity is an open question.

Here we use improved geodetic constraints on the length of day (LOD) six-year oscillation (SYO) period in order to provide an independent estimate of the LLSVPs buoyancy structure, testing the latest hypotheses of the depth of compositional heterogeneity within the LLSVPs. A possible explanation for the SYO is linked to the perturbation in the gravitational potential due to coupling between the inner core and the lower mantle. In particular, the period of this SYO is directly sensitive to the density of the deep mantle and the topography of the CMB. By computing the predicted period associated with many hypothetical buoyancy fields of the lower mantle, and comparing it with the observed period, we identify the sensitivity of this oscillation period to the perturbation of the buoyancy structure and to the discontinuity topography, and attempt to constrain the range of acceptable models that is able to explain the SYO period, while being consistent with the total moment of inertia of the Earth and its mass. Our tested models are designed to address the questions on the height extent, buoyancy sign, and magnitude of LLSVP, thus helping us identify the potential source of anomalously slow shear wave speed.

Keywords: LLSVP, gravitational potential, deep mantle, length of day oscillation, buoyancy structure.

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Estimating the core-mantle boundary temperature from changes in seismic attenuation and shear-wave velocity

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Abstract

The temperature at the Earth's core-mantle boundary (CMB), T_{CMB}, is a key property for a better understanding of our planet dynamics and evolution, but remains poorly constrained. Because the CMB is a material boundary between silicate rocks and molten iron, T_{CMB} cannot be deduced directly from a single phase diagram. Estimates from mineral physics extrapolate either the solidus of mantle rocks to large pressure, or the ICB temperature to lower pressure, assuming that the outer core is adiabatic. Here, we propose a new approach to the determination of T_{CMB} based on the analysis of observed lateral variations in shear-wave seismic velocity, V_S, and attenuation, measured with the quality factor Q_S, in the lowermost mantle. Shear velocity is sensitive to the presence of post-perovskite (pPv), a high pressure phase of bridgmanite that is stable at lowermost mantle conditions. Because the stability field of pPv strongly depends on temperature, the presence of this phase and its impact on V_S provides a constraint on the horizontally averaged temperature in the lowermost mantle. On another hand, seismic attenuation is a thermally activated process, implying that its amplitude depends on temperature. At a given depth, and using an appropriate modeling of Q_S, its deviation from a global average can then give access to the average temperature at this depth. Our approach is based on the knowledge of several parameters, of which the temperature of the phase transition to pPv, T_{pPv}, appears to be the most sensitive. We then performed a preliminary application using models of V_S and Q_S obtained for beneath the Central America and the Northern Pacific, and found that for T_{pPv} = 3500 K, the CMB temperature should be in the range 3400-3800 K.

Keywords: Core-mantle boundary temperature, Seismic attenuation, shear-wave velocity

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Fractional crystallization of the Basal Magma Ocean: The consequences on present-day mantle structure

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Abstract

Constraining thermal evolution for the deep interior of terrestrial planets is substantial to understanding their evolution as a whole. Thermal evolution is controlled by stages of large- scale melting, or magma oceans -due to the energy released during accretion, differentiation and radioactive decay of heat-producing elements- and crystallization of this melt. Thus, exploring the crystallization sequence of the Basal Magma Ocean (BMO) is vital for understanding the thermal evolution of the planets and their related structures in the lower mantle. Previous work shows that a FeO-enriched molten layer or basal magma ocean (BMO) is stabilized at the core- mantle boundary for a few billion years. The BMO itself is expected to freeze by fractional crystallization (FC) because it cools very slowly, FC always yield a highly iron-enriched BMO and last stage cumulates. Other crystallization mode could be dominated and has not yet been systemically explored.

To explore the fate of the BMO cumulates in the convecting mantle, we explore 2D geodynamic models with a moving-boundary approach. Flow in the mantle is explicitly solved, but the thermal evolution and related crystallization of the BMO are parameterized. The composition of the crystallizing cumulates is self-consistently calculated in the FeO-MgO-SiO2 ternary system according to Boukaré et al. (2015). In some cases, we also consider the effects of Al2O3 on the cumulate density profile. We then investigate the entrainment and mixing of BMO cumulates by solid-state mantle convection over billions of years as a function of BMO initial composition and volume, BMO crystallization timescales, distribution of internal heat sources, and mantle rheological parameters (Ra# and activation energy), . We varied the initial composition of BMO by manipulating the molar fraction of FeO, MgO, and SiO2 -based on published experiments- to model different BMO-compositions: Pyrolitic composition, After 50% crystallization of Pyrolitic composition *Boukaré et al.* (*2015*), After 50% crystallization of Pyrolitic composition *Caracas et al.* (*2019*), and Archean Basalt.

For all our model cases, we find that most of the cumulates (first ~90% by mass) are efficiently entrained and mixed through the mantle. However, the final ~9% of the cumulates are too dense to be entrained (either fully or partially), and rather remain at the base of the mantle as a strongly FeO-enriched solid layer. We highlight that this inevitable outcome of BMO fractional crystallization is inconsistent with the geophysical constraints. Our results suggest that a BMO was either very small initially which is tested in our study and the results are only consistent with the geophysical constraints when BMO volume less than or equal to 100 km, or did not crystallize by FC. An alternative mode of crystallization may be driven by an efficient reaction between a highly-enriched last-stage BMO with the overlying mantle due to chemical disequilibrium.

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Indicators of mantle control from the Matuyama Brunhes geomagnetic reversal?

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Abstract

Global paleomagnetic field models based on spherical harmonic functions offer the possibility to study global properties of the geomagnetic field. They allow to directly compare results from data-based field reconstructions and numerical simulations that consider the underlying physics. A long-standing question in geomagnetism is the potential influence of the mantle, in particular of heat flux heterogeneities, on the geodynamo. Clustering of virtual geomagnetic pole (VGP) paths and the recurrence of intensity minima resembling the present-day South Atlantic Anomaly have been discussed in this context. An influence of imposed mantle heat flow heterogeneities on the distributions of these properties can be clearly seen in long dynamo simulation runs. In a recent study, distributions of VGP paths and field intensity minima from geomagnetic field models spanning up to the past 100 000 years and including three excursions have been investigated. Although the results were less straightforward to interpret than for numerical simulations, and VGP distributions of individual events have been found to be poor statistical samples, the non-uniform distributions of intensity minima might be indicative of mantle control. Here, we extend the analysis to a recently derived global reconstruction of the Matuyama-Brunhes field reversal and the surrounding time interval from 900 to 700 ka, which is based on 37 independently dated paleomagnetic sediment records. We will discuss if the longitudinal distributions of transitional VGPs and of field intensity minima found for this time interval resemble the findings for the past 100 ka and in particular for the Laschamps excursion, and if they lend further support to indications of mantle control by global paleomagnetic field reconstructions.

Keywords: core-mantle boundary; paleomagnetic field model; Matuyama-Brunhes reversal;

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The first non-zonal time-averaged field model of the geomagnetic field during the Miocene, MTAM1, suggests a persistent reversed flux patch in the South Atlantic.

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Abstract

Reconstructions of the long-term time-averaged geomagnetic field (TAF) are important to identify the scale and longevity of non-dipolar field morphology. This poster presents MTAM1, the first non-zonal TAF model for the Miocene era (5.3 – 23 Ma). This model shows remarkable similarities to the features in TAF models of the last 5 Myrs (e.g. LN3, Cromwell et al., 2018), and shows a persistent reversed flux patch (RFP) under the South Atlantic region. Our inverse model is based on PSVM (Engbers et al., 2022), a directional data compilation comprised of 1454 sites from 44 different localities. We separate the data into normal ($PSVM_N$) and reversed ($PSVM_R$) datasets, yielding two corresponding models $MTAM1_N$ and $MTAM1_R$. Allowing for the different sign, no substantial differences were found between the models, giving no evidence for the often discussed "memory" of the field after a reversal and suggesting symmetry between the morphology for the normal and reversed field. Therefore, we compute MTAM1, a TAF model for the complete Miocene dataset (PSVM) using normalized polarities, enhancing the data distribution and thus the robustness of the model. All models include a reversed flux patch (RFP) under the South Atlantic. The broad structure of the models matches previous TAF models for the past 5 Myrs, but with some clear differences, particularly in the South Atlantic. To investigate whether this difference is well defined, or could result from differences in modelling methodology or data distribution, we invert the data of the last 5 Myrs with our new model as a prior constraint, in effect testing whether the data are consistent with the new model. For an equivalent fit, we find only small increases in modelling complexity (consistent with requiring more detail, particularly in the southern hemisphere). We find no evidence that the more recent data is inconsistent with our Miocene model, suggesting an overall stability in the geomagnetic field morphology for the past 23 Myrs, which is consistent with long-term mantle control on geomagnetic field morphology.

Keywords: Geomagnetic field, Time-Averaged Field Model, Miocene

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Electromagnetic boundary conditions at the Core-Mantle Boundary: a not so trivial problem

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Abstract

The derivation of the electromagnetic junction conditions between two continuous dielectric media is a staple exercise in textbooks on classical electromagnetism. When the two materials are in sliding contact with relative velocity, **v**—typically at the interface between the free stream at the top of the Earth's fluid core and the weakly conducting mantle—the condition on the electric field, **E**, becomes ambiguous. While most studies use the continuity of the tangential part of **E** to constrain the shape of the velocity field near the interface, theoretical considerations contend that it is instead the tangential part of the combination $\mathbf{E} + \mathbf{v} \times \mathbf{B}$, where **B** is the magnetic field, which should be continuous. Combined with Ohm's law, this condition implies the existence of surface currents in order to satisfy charge conservation near the boundary. The dynamics of hypothetical currents at the core-mantle boundary has been an object of attention in early studies of geophysical magnetohydrodynamics. Here we review some of the arguments of these studies and how they concur to resolve the above-mentioned ambiguity in the boundary condition for a realistic fluid core model with small but finite viscosity and resistivity, satisfying the no-slip boundary condition.

We discuss some practical implications for numerical simulations using the alternative stress-free boundary condition, as well as for the electromagnetic coupling at the core-mantle boundary.

Keywords: Boundary conditions, MHD, Electromagnetism, Core-Mantle Boundary

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Investigating regional heterogeneity at the core-mantle boundary and its impact on outer core flow by applying spherical Slepian functions

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Abstract

Currently, there is relatively poor understanding of how the magnetic field is affected by heterogeneity on the core-mantle boundary (CMB) despite increasing evidence of heterogeneity from geochemical, seismic tomography, geomagnetic, and geodynamics studies. An example of heterogeneity are the Large Low seismic Velocity Provinces (LLVPs) that have been identified at the base of the mantle. LLVPs have been proposed to indicate topographic features, thermal variation, regional stratification, or chemical exchange between core and mantle, all of which would affect the flow at the surface of the core and the magnetic field it generates. If spherical harmonic separations are conducted to investigate heterogeneity, a boundary is enforced at the region edge and large amounts of ringing are generated.

One way to investigate regional potential fields on a sphere is to use spherical Slepian functions which convert spherical harmonic data into a new localized basis. These functions are constructed by maximizing the power of a function within a specified region where it is orthogonal in both the region and the complementary part of the sphere. This allows for the preferential ranking and selection of a subsection of the functions to be constrained in the region of interest. Spherical Slepian functions are the only functions that achieve a regional separation expressed as a finite sum of spherical harmonics, and in an easily computable framework, depending only on the geometry of the region and maximum spherical harmonic degree.

The key contribution of this work is using spherical Slepian functions during the inversions for SV at the core-mantle boundary. Slepian functions provide a novel application of geomagnetic virtual observatory datasets, which allows 20 years of magnetic data from Swarm, CHAMP, and Cryosat to be treated as an even spread of data points in time and space, similar to ground observatory data. We apply altitude-cognizant Slepian functions to core surface SV models by directly inverting from satellite virtual observatory secular variation data into regions of interest. We successfully demonstrate the technique and current short comings by investigating the influence of LLVPs on the movement of liquid iron at the core surface over time. Unwanted spatial leakage is generated at the region edges in the separated SV but to less of an extent than when using spherical harmonic separations.

Keywords: spherical Slepian functions, regional core surface flow, LLVPs

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True polar wander and heat flux patterns at the core-mantle boundary in a mantle convection simulation

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Abstract

The heat flux at the core-mantle boundary (CMB) is an important variable of the Earth's thermal evolution and dynamics. The CMB heat flux notably plays a key role in the dynamics of the core and the geodynamo. Tomographic studies reveal more and more complex structures near the CMB, providing some insights on the present-day heat flux, which are however limited by the difficulty to resolve both thermal and chemical heterogeneities. Mantle convection models can also be used to provide estimates of the CMB heat flux by applying past plate motion history or using self-consistent models without prescribed surface velocities. Mantle convection modifies the Earth's moments of inertia which creates a rotation of the Earth relative to its spin axis called true polar wander (TPW). This TPW has to be considered to obtain relevant CMB heat flux maps for the outer core.

This work aims at describing the TPW and CMB heat flux produced by a realistic mantle convection simulation that exhibits plate-like behavior (Coltice et al., 2019), and at providing representative CMB heat flux maps to be used in geodynamo simulations. Our model is not anchored to any specific plate reconstruction, we rather explore what kind of CMB heat flux can be produced by a freely-evolving and physically realistic mantle convection simulation on a 1 Ga timescale. This model includes chemical piles at the base of the mantle to account for the observed LLSVPs. The representative CMB heat flux maps are obtained using a Principal Component Analysis (PCA) to bring out the dominant heat flux patterns at the CMB. Because we aim to obtain heat flux patterns useful for geodynamo studies, we compute the geoid and correct the TPW before computing the PCA.

We obtain TPW velocities in agreement with observations and previous modelizations. The computed geoid is largely controlled by the subducted slabs in the upper mantle, which produce geoid highs as observed on Earth. On the contrary, the lower mantle chemical piles produce no significant signal in the geoid. This leads to a strong equatorial CMB heat flux, due to the effect of subducted slabs, which control the position of the equator, cool the core, and push the hot lower mantle piles towards high latitudes. These equatorial subductions eventually lead to the formation of an equatorial supercontinent above this high CMB heat flux.

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Keywords: Heat flux, CMB, geoid, TPW

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Extracting spatial-temporal coherent patterns in geomagnetic secular variation using dynamic mode decomposition

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Abstract

Observations of the geomagnetic field offer a wealth of information about the dynamics of Earth's deep interior. Recent measurements of the geomagnetic field and its first time derivative, often called secular variation, are commonly used to model large fluid motions near to the core mantle boundary. Other contributions include magnetic diffusion and the effects of unresolved small-scale flow. Modern data-driven methods help to identify and characterize patterns of change in the observations with different types of wave motions. Dynamic mode decomposition (Schmid, 2022) is a well-suited technique to analyze and decompose the geomagnetic data into modes (waves). Modes recovered using the DMD serve as the starting point for a physical interpretation of the observations. Each mode has a well-defined spatial structure and frequency, which allows us to draw inferences about the physical properties, like the wave speed or the damping rate. We use this approach to quantify the time dependence and spatial patterns of the geomagnetic radial field and the secular variation simultaneously using data from the CHAOS-7 model (Finlay et al, 2020).

We applied the DMD technique to the entire north pole between latitudes 30° and 90°, where evidence of wave motions has been reported in previous studies (Chi-Durán et al, 2020). Decomposing the geomagnetic signal in 5 modes, we identify 2 pairs of waves (corresponding to 4 DMD modes) with periods of T1 = 19.21 and T2= 65.14 years and quality factors of Q1 = 21.96 and Q2 = 1.22, respectively. The 60-year period wave is consistent with a l = 4 MAC wave proposed by Buffett et al (2016) to explain a 60-year fluctuation in the geomagnetic field and length of day. Predictions for the l=4 MAC wave provide a good fit to the spatial structure of the DMD mode. The period and damping are compatible with a thin layer of stratified fluid in the outer 143 km of the core. The required strength of the stratification is 0.83$\boldsymbol{\Omega}$ (where $\boldsymbol{\Omega}$ is Earth's rotation frequency). A 20-yr wave had previously been reported in the same location (Chi-Durán et al, 2020, Chi-Durán et al, 2021), although the corresponding DMD mode does not appear to correspond to a shorter period MAC wave (with spherical harmonic degree l=6 or l=8, for example). The predicted spatial pattern of the MAC wave is not compatible with the spatial structure of the DMD mode. Further analysis is needed to understand the nature of this wave and to establish the underlying wave mechanics.

Keywords: geomagnetism, dynamic mode decomposition, secular variation,

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Dynamic pressure estimates at the core-mantle boundary

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Abstract

Flows in the fluid outer core of Earth push and pull on the core-mantle boundary (CMB) via a dynamic pressure. Depending on the strength of such a pressure the CMB could be deformed dynamically, or it could influence the chemical interactions between core and mantle material. It is therefore crucial to have a realistic estimate of the pressure associated to flows within the fluid core. In a commonly utilized approximation, it is assumed that the flow tangent to the CMB is in balance between Coriolis and pressure gradient forces, i.e., tangentially geostrophic.

A static pressure field is thereby associated kinematically to the flow field at the core's surface. Direct numeric simulations of the magnetohydrodynamic equations in the anelastic approximation solve for the pressure field explicitly. This allows for a comparison of a fully dynamic solution to the tangential geostrophic pressure estimate. Further, a comparison of the tangential geostrophic pressure to numerically calculated hydromagnetic modes, that operate at the inter-annual time scale, is made. The pressure of the modes is approximated by representing the velocity by a subset of inertial modes, whose pressure field is known.

Keywords: Core-mantle boundary, Core flows, dynamic pressure

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Experimental determination of thermal conductivity and Lorenz number of solid iron up to 176 GPa and 2900 K

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Abstract

Thermal conductivity of Earth's outer core controls thermal evolution and dynamics of deep Earth such as inner core birth and growth, changing of strength of magnetic field, convention style of mantle and outer core. It is widely accepted that the main carrier of heat transport of iron, which is the main component of the core, is an electron. The thermal conductivity of iron and iron-alloy(s) under the pressure-temperature (*P*-*T*) conditions of the planetary core and the relationship between the conductivity and electrical resistivity have been actively investigated for decades. However, there is a large range of the predicted values for the thermal conductivity of iron under the core *P*-*T* conditions, and various Earth evolution scenarios are possible.

Here, we measured thermal conductivity of solid iron up to 176 GPa and 2900 K using the pulsed light heating thermoreflectance technique in a laser-heated diamond anvil cell. We found that the temperature derivative of thermal conductivity of hcp iron changes negative to positive above 40 GPa. According to Wiedemann–Franz law, the value obtained by dividing the product of thermal conductivity and electrical resistivity of a metal by absolute temperature is called the Lorenz number. We calculated the Lorenz number of iron from the previously reported electrical resistivity and the present thermal conductivity. At the *P*-*T* conditions of the top of the core, the thermal conductivity and Lorenz number of iron are found to be about 200 W/m/K and lower than the ideal value of 2.44×10^{-8} WΩ/K^2.

Keywords: Thermal conductivity, iron, Earth's outer core, laser heated diamond anvil cell

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Self-consistent models of Earth's mantle and core from long-period seismic and tidal constraints

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Abstract

We have inverted a large set of normal-mode centre frequencies and attenuation factors, including geodetic data (mass, moment of inertia and tidal response), for the radial anelastic seismic structure of the Earth. The mantle models are constructed using petrologic phase equilibria in combination with a laboratory-based visco-elastic model that connects dissipation from seismic to tidal periods, whereas seismic properties for a well-mixed and homogeneous core are computed using equations-of-state. Relative to PREM, we find that mantle P- and S-wave velocities have to be slightly faster and slower, respectively, while outer-core P-wave velocity is slower on account of a different velocity gradient, whereas inner-core velocity structure is similar, within the uncertainties of the inferred model parameters. In terms of density, we find that the mantle is less dense and the outer core more dense than PREM, while the inner core is similar to PREM. These changes are partly driven by the geodetic data. We further computed P- and S-wave travel times and compared these to the observations of globally-averaged P- and S-wave travel times from the reprocessed ISC catalog. The comparison resulted in an excellent match and is superior to that of PREM. To further refine the outer-core P-wave velocity structure, we also considered multiple core- mantle-boundary underside-reflected body wave travel time data. While the match to the underside reflections clearly improves as a result of a steeper velocity gradient in the outer core, differences nevertheless persist that support a change in velocity gradient in the outermost core, evocative of a stably stratified layer. As a means of constraining core composition, we considered the density contrast across the inner-core boundary (ICB). The most probable ICB density difference found here ranges between 0.3-0.5 g/cm^3, which is less than earlier body-wave- and normal-mode-based predictions. This suggests that the compositional heterogeneity associated with light-element partitioning may be less effective than previously thought, calling for exsolution of solids from the liquid outer core as a possible additional source for driving the geodynamo.

Keywords: Surface waves and free oscillations, Body waves, Tides, Seismic attenuation, Mantle and core composition, Structure of the Earth

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CCMOC: A New View of the Earth's Outer Core Through the Global Coda Correlation Wavefield

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Abstract

Increasing seismic evidence has suggested that the Earth's outer core consists of distinct layers of low P-wave velocities relative to the Preliminary Reference Earth Model (PREM) in the top and bottom of the liquid core. Seismically detected low velocity in the outer core could be linked with the stratification, essential for understanding the geodynamo and thermochemical evolution of the fluid outer core. However, a consistent globally-averaged radial structure of the outer core has not been obtained due to the incomplete seismic data coverage. To remedy this problem, we explore the seismic structure of Earth's outer core by employing a relatively new observational and theoretical concept termed coda correlation wavefield, which was recently utilized to construct a new reference Earth model, CCREM. We first construct a global coda correlogram in the 15-50 second wave-period range by stacking cross-correlation functions of the long-duration late-coda waves from the selective ten large earthquakes. We then assemble a dataset of prominent correlation features from the global correlogram sensitive to the outer core structure. The waveforms of these features are fit by computing synthetic correlograms through various outer-core models. The optimal outer-core model displays reduced P-wave velocities in both the top and bottom relative to PREM. The low wave speeds at the top of the outer core could imply the formation of a thermal and/or chemical stratification.

Keywords: outer core, coda correlation wavefield, late coda, thermal/chemical stratification

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Observability of the Earth's core signals in GRACE-based gravity field

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Abstract

The GRACE and GRACE Follow-On (GRACE-FO) missions have been providing monthly time-variable gravity field estimates since 2002 with an one-year gap between 2017 and 2018. GRACE satellites monitor mass variations in the Earth system. GRACE products enable to study continental hydrology, oceanic and atmospheric loading, post-glacial rebound, glaciers, earthquakes and other phenomena that involve mass variations. The Earth's interior, particularly the Earth's fluid outer core possesses a broad dynamics of processes involving mass variations. Theoretical modeling indicates that low degrees of the gravity field might indeed contain some inter-annual signals of core origin. We can mention for instance dynamic pressure changes at the Core Mantle Boundary (CMB) associated with core flows reconstructed from geomagnetic observations, reorientation of the Inner Core controlled by a gravitational coupling with the mantle and some dissolution/crystallization at the CMB introducing a time-varying roughness of the interface.

To verify the capacity of detecting Earth's core signature into GRACE time series, we propose to generate some synthetic core signals that we incorporate into GRACE gravity products. Then, we aim to retrieve these synthetic signals through different analysis methods. We test correlations with the geomagnetic field observations and decomposition methods such as wavelet and Empirical Orthogonal Function (EOF) analyses. We then discuss the needed amplitudes for a possible detection with respect to the predicted amplitude and in regards with other sources of mass variations that were originally present in GRACE data.

Finally, we identify the correct methods to search for the Earth's core signature and their current limitations.

Keywords: Gravimetry, Earth's core, GRACE, simulations, EOF, correlations

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Recurrent geomagnetic field asymmetries linked to millennial-scale variations in the dipole moment

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Abstract

The strength of the axial dipole part of the geomagnetic field has been decreasing at an average rate of 16nT/year over the past two centuries. The dipole decay has coincided with an increasing field asymmetry associated with the growth of the South Atlantic Anomaly (SAA). Here we present a new geomagnetic field model based on archaeomagnetic and sedimentary palaeomagnetic data over the past 9000 years and identify potential ancient analogues. The model is constructed using a novel probabilistic approach that addresses key challenges related to the (i) sparse data distribution, (ii) chronological data uncertainties and (iii) temporal smoothing due to the gradual process by which sediments acquire a magnetization. We find evidence for recurrent east-west hemispherical geomagnetic field asymmetries linked to weak field anomalies at Earth's surface, similar to the SAA, and quasi- periodic fluctuations in the dipole moment over the past 9000 years. We propose that the period around 600 BCE, characterized by a strongly asymmetric field, could provide an analogue to the present-day field, implying that the SAA will likely disappear in next few hundred years. We discuss potential underlying mechanisms and possible links to previously identified high-latitude westward drift at the core- mantle boundary.

Keywords: Geomagnetism, South Atlantic Anomaly, Paleomagnetism

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Magnetic boundary layers in numerical dynamos with heterogeneous outer boundary heat flux

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Abstract

It has been proposed that magnetic flux expulsion due to outer core fluid upwellings may affect the geomagnetic secular variation on the core-mantle boundary (Bloxham, 1986). In this process intense horizontal field lines are concentrated below the outer boundary, introducing small radial length scales and consequently strong radial diffusion. Here we explore such magnetic boundary layers in numerical dynamo simulations with heterogeneous outer boundary heat flux inferred from a tomographic model of lower mantle seismic shear waves velocity anomalies. Our scheme associates magnetic boundary layers to peak horizontal magnetic fields at the top of the shell. In our models mean magnetic boundary layer thickness ranges $\approx 200 - 400$ km and decreases with increasing magnetic Reynolds number. Extrapolation or interpolation to Earth's core conditions based on total core flow amplitude or its poloidal part gives mean magnetic boundary layer thickness of ≈ 220 and $\approx 260 - 330$ km, respectively. We find magnetic boundary layers associated with the azimuthal field at the equatorial region, whereas magnetic boundary layers associated with the meridional field are found at mid latitudes. Negative outer boundary heat flux anomalies yield preferred locations of expulsion of azimuthal field below Africa and the Pacific, while positive outer boundary heat flux anomalies yield preferred locations of expulsion of meridional field below the Americas and East Asia. Furthermore, we find a tendency of the azimuthal field to low latitudes of the Northern Hemisphere. Our results suggest that the local diffusion time is on the order of several kyr and the local magnetic Reynolds number is on the order of ≈ 10, both much smaller than classical estimates.

Keywords: Magnetic field, magnetic boundary layer, magnetic diffusion, core-mantle boundary heat flux, core upwelling.

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Preferred locations of weak surface field in numerical dynamos with heterogeneous core–mantle boundary heat flux: consequences for the South Atlantic Anomaly

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Abstract

The present-day geomagnetic field is characterized by a region of weak surface intensity, the so-called South Atlantic Anomaly (SAA). We identify the locations of surface intensity minima in modern, historical and archeomagnetic field models. We then investigate whether lower mantle thermal heterogeneity may explain the location of the SAA. We run numerical dynamos with heterogeneous core–mantle boundary (CMB) heat flux inferred from a lowermost mantle tomography model, varying dynamo internal control parameters as well as the amplitude of the CMB heat flux heterogeneity. Histograms of the longitude and latitude of surface intensity minima show the persistence of different locations. We find two preferred longitudes of surface intensity minima, one close to the present SAA minimum longitude. In contrast, in the dynamo models and in the archeomagnetic field models the surface intensity minima are often close to the equator, whereas the present-day SAA is at mid-latitudes. We demonstrate that the determining ingredients in dynamo models to reproduce the SAA latitude are related to north–south asymmetries of reversed and normal geomagnetic flux on the CMB. The imposed heterogeneous heat flux leads to more convective and magnetic activities in the Northern Hemisphere. Large time-average upwelling structure below the South Atlantic in the dynamo models correlates well with the present-day SAA region. Scaling laws analysis indicates that the persistence of surface minima longitudes is favored by slow rotation, strong convection and large heat flux heterogeneity. Furthermore, increasing mantle control yields two preferred longitudes and southern surface minima, the latter indicating that the present-day southern location of the SAA is mantle controlled. However, the rareness of mid-latitude minima in dynamo models and archeomagnetic field models leads us to speculate that the SAA mid-latitude value at present is possibly unusual.

Keywords: Magnetic field, South Atlantic Anomaly, core-mantle boundary heat flux, core flow.

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Secular variation signals in magnetic field gradient tensor elements derived from *Swarm* satellite observations

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Abstract

We present an approach to estimate local time series of the gradient tensor elements of the geomagnetic field at satellite altitude. These time series are derived from magnetic observations collected by the *Swarm* satellite constellation via the Geomagnetic Virtual Observatory (GVO) local potential field modelling method. Construction of GVO time series on an approximately equal area grid enables global investigations of spatial-temporal variations in the gradient tensor elements. We find that the orbital configuration of the *Swarm* satellite constellation has significant benefits for deriving GVO gradient series compared with single satellite missions. Our results support previous findings that gradient information helps to better resolve the Secular Variation (SV) at spherical harmonics above degree 6. We find evidence for a regional SV impulse (jerk) event in 2017 in the gradient tensor elements. This event is located at low latitudes in the Pacific region, and its signature is independent of adopted data selection criteria. We find that the field acceleration change has a distinctive localized form in maps of the gradient tensor elements. Our investigations show that GVO gradient tensor series provide an effective way of compressing spatio-temporal information regarding geomagnetic field variations gathered by the *Swarm* satellites. Such gradient tensor series may therefore be useful for future studies of geomagnetic jerks, for core flow inversions, and for geodynamo data assimilation systems.

Keywords: Geomagnetic Secular Variation - Rapid Core Dynamics – Satellite Observations

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Localized origin at the core-mantle boundary of the 1969 geomagnetic impulse

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Abstract

We present a new model of the geomagnetic field from 1960 to 1980, designed to investigate field changes around the time of the famous 1969 geomagnetic impulse. Results are compared to recent patterns of field changes measured by the *Swarm* satellites in the Pacific region between 2014 and 2020. Our new model of the 1969 impulse is derived from scalar field intensity measurements collected by the POGO satellites, and their along-track differences, along with three component vector field measurements from ground observatories. We apply data selection, processing and modelling techniques similar to those used to derive the CHAOS series of field models (Olsen et al., 2006; Finlay et al., 2020).

Our new field model suggests that the 1969 geomagnetic impulse originated primarily in a localized dipolar pattern of radial field acceleration change at core-mantle boundary under Central and North America. Due to the form of Green's function that links the core-mantle boundary radial field and the various components of the surface field this change is capable of explaining both the classic signature of 1969 impulse in the eastward field component in European observatories, and striking secular variation trend changes observed in radial and southward field components in Central and North American stations. The same dipolar pattern of field acceleration change under Central and North America in 1969 is seen in field models built only from POGO satellite data, or if key ground observatories are omitted.

The recent episode of rapid field change observed in the Pacific region in 2017 also involved a localized dipolar pattern of field acceleration change, with amplitude comparable to that seen for the 1969 impulse. However the dipolar pattern associated with the 1969 event was oriented north-south compared to east-west for the 2017 event, and it was associated with a rapid poleward rather than westward displacement of the field acceleration pattern. A more fundamental difference is that the 1969 impulse was associated with a localized surge in the core-mantle boundary secular variation in the years leading up to the impulse event; this was not seen for the 2017 event. A possible explanation for some of these differences can be found in the numerical dynamo simulations of Aubert et al., (2022) where secular variation surges happen along with geomagnetic impulses only when the responsible hydromagnetic waves are triggered at shallow depths beneath the core-mantle boundary.

Keywords: Rapid Core Dynamics – Geomagnetic Observations – Global Field Models

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Improving monitoring of the fast changing core magnetic field with the future NanoMagSat 16U nanosatellite constellation high-precision magnetic project

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Abstract

The geomagnetic field has been continuously monitored from low-Earth orbit (LEO) since 1999, complementing ground-based observatory data by providing calibrated scalar and vector measurements with global coverage. The successful 3-satellite ESA Swarm constellation is expected to remain in operation up to at least 2025. Further monitoring the field from space with high-precision absolute magnetometry beyond that date is critical for improving our understanding of dynamics of the multiple components of this field, in particular that of the core field. Here, we will report on the latest status of the NanoMagSat project, which aims to deploy and operate a new constellation concept of three identical 16U nanosatellites, using two inclined (approximately 60°) and one polar LEO, as well as an innovative payload. This will include an advanced Miniaturized Absolute scalar and self-calibrated vector Magnetometer (MAM) combined with a set of precise star trackers (STR), a compact High-frequency Field Magnetometer (HFM), a multi-needle Langmuir Probe (m-NLP) and dual frequency GNSS receivers. Data to be produced will include 1 Hz absolutely calibrated and oriented magnetic vector field, 2 kHz very low noise magnetic scalar and vector field, 2 kHz local electron density and 1 Hz electron temperature, as well as precise timing, location and TEC products. The constellation design is such that all local times at all geographic locations between 60°N and 60°S will be covered in a little more than one month, much faster than Swarm, which the NanoMagSat is also designed to complement for even faster local time coverage, should Swarm still be in operation at the time of launch. We will present the latest status of the mission, which started an 18 months ESA funded phase of risk retirement activities in January 2022. We will also more specifically focus on the expected ability of NanoMagSat to recover fast core field signals at mid and low latitudes that no previous mission could detect so far, but which numerical simulations of the dynamo strongly suggest are very likely produced within the Earth's core.

Keywords: Core Field, Core dynamics, Nanosatellites

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Quasi-Geostrophic Magneto-Coriolis waves in Earth's core

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Abstract

Reanalysis of geomagnetic field changes over the satellite era have unveiled Magneto-Coriolis (MC) waves in Earth's core, with a period close to 7 years [1]. These are responsible for a large part of the rapid field changes recorded over the past two decades. Such motions are Quasi-Geostrophic (QG), i.e. invariant along the rotation axis due a dominating Coriolis force. QG MC modes were previously thought to be detectable only on centennial and longer periods [2]. However, an eigenmode study has recently revealed the existence of QG MC solutions on interannual time- scales, presenting a low azimuthal complexity [3]. The dispersion relation for these very dispersive waves indeed indicates that a short period is associated with a shear much stronger along the cylindrical radial direction, and a low azimuthal wavenumber. Their reconstruction is easier in the vicinity of the core equator because there small radial length-scales project onto large horizontal patterns. Our analysis of geophysical observations suggests that (i) their detection is facilitated by the advent of the continuous satellite era since 2000 and (ii) similar waves also exist at decadal periods. This scenario is supported by the reanalysis of synthetic magnetic data computed from geodynamo simulations run at extreme parameters [4], where modulated QG MC waves are triggered over a large range of periods.

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High latitude jets in Earth's core inferred from Swarm

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Abstract

Observations from the Swarm mission have made possible imaging of the magnetic field generated inside Earth's core to unprecedented detail. These data, along with physics-based assumptions concerning the dynamics of the liquid iron within the core, permit us to construct new data-constrained models of the direction and speed of flow at the edge of the Earth's core. Such maps of the flow lie at the heart of understanding how the Earth's magnetic dynamo operates some 3000km beneath the surface.

The unique constellation configuration of Swarm's polar orbiting satellites has provided new insights into magnetic field change at high latitude. Of particular interest is the behaviour of a cluster of localised patches of magnetic field at the core surface, located at around 70 degrees latitude, which serve as a powerful indicator of core dynamics. The movement and change in structure of these patches was recently explained by an accelerating jet, inferred to be localised on the region of core surface at high-latitude stretching beneath Siberia to Canada. Such behaviour of the flow has not yet been identified elsewhere. We will present new images and models of the dynamics of this phenomenon which is apparently unique to the north polar region, based on the most recent data from Swarm and ground-based observatories. Because this high-latitude region forms an important component of the core's general circulation pattern, the eccentric *gyre*, changes at high latitude may indicate changes in the flow elsewhere in the core.

Keywords: Core dynamics, geomagnetism

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Intradecadal variations in length of day: coherency with core flow models

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Abstract

The variations of the Earth's length of day (LOD) exhibit several interannual oscillations. First, a 5.9- year periodic oscillation, better seen after removing the atmospheric contribution, is now widely admitted to originate from the Earth's core. The physical mechanism behind this 5.9-yr signal is still uncertain but a possibility is from torsional waves propagating in the fluid core. Second, a ~8.5-year oscillation was proposed to be explained by fast equatorial waves propagating at the Earth's core surface. Torsional waves could indeed explain both periodic signals. The recently detected interannual quasi-geostrophic magneto-Coriolis modes could also have a zonal component that carries angular momentum and couples with the mantle. Finally, a 7.3-year fluctuation was also detected in LOD data but no physical mechanism was proposed. We show using a continuous wavelet transform analysis of synthetic oscillators embedded into a random noise, the limits of detecting damped signals in time series of limited duration. In particular, we emphasize the possibility that the 7.3-year oscillation could originate from an artefact due to the restricted time series of LOD data. Finally, we perform a wavelet coherency analysis between geodetically observed LOD variations and predicted LOD changes from geomagnetically inferred core flow models. Observed coherency at 5.9-year and ~8.5-year periods most probably confirms the fluid outer core origin for these two oscillations.

Keywords: length of day, core flows, auto-regressive process, wavelet coherency

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Imaging inner core seismic structure using normal mode and body wave data

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Abstract

The Earth's inner core displays strong seismic heterogeneity, which are most likely formed as a result of growth processes and post solidification deformation. Thus, accurately resolving seismic anomalies is key to understanding the formation and dynamic mechanisms of the inner core. Our ultimate aim is to improve current constraints on seismic anomalies in the inner core by combining normal mode data and body wave data in a joint tomographic inversion. While the body wave data is sensitive to regional scale seismic P-wave velocity anomalies in the inner core, normal modes provide long wavelength information on density, P-wave velocity and S-wave velocity.

We recently produced a high resolution 3D seismic model of inner core isotropic and anisotropic velocity variations using a transdimensional methodology with body waves. In the transdimensional approach, the inversion itself determines the parameterization. It is encouraging to find many well know features, such as a hemispherical difference between a slow and strongly anisotropic western region and a fast and only weakly anisotropic eastern hemisphere, without a priori imposing those in our parameterization. We are now interested to see if the features seen using body waves are consistent with those seen by normal modes. We measure inner core sensitive normal modes using the splitting function approximation in a way which thoroughly explores the splitting function measurement model space. This then allows us to quantify the uncertainty in individual splitting function coefficients for each mode. We then combine these new normal mode measurements and uncertainty estimates with our body wave data in a joint probabilistic inversion for seismic structure in the inner core.

Keywords: InnerCore, Seismology, Anisotropy, Tomography, MCMC

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A Search for Large-scale Variations in the Fine-Scale Structure of Earth's Inner Core

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Abstract

A hemispherical pattern in inner core attenuation (Q) has been observed from the apparent Q of inner core transmitted waves (PKPDF). How the elastic scattering (QS) originating from kilometer-scale inner core heterogeneities relates to large-scale apparent Q variations remains elusive. Such inner core scattered energy (ICS) is characterized by emergent, long-lasting, high-frequency (1–4 Hz) coda immediately following pre-critical reflections (*PKiKP*) from the inner core boundary (ICB). In this study, we develop a framework to systematically investigate ICS and examine its hemispherical pattern using data from two arrays that sample opposing sides of the Pacific quasi-hemispherical boundary. We use all the viable data from earthquakes (M_W>5.7) within the past 2–3 decades recorded at distances of 50°–75° by YKA and ILAR—small-aperture (~10–20 km) seismic arrays situated in northwestern North America. Two independent waveform stripping methods are applied to extract ICS from the background energy, and various stacks are performed to identify ICS and its spatial pattern. We found that individual beams lacking clear evidence of *PKiKP* coda waves reveal ICS characteristics when stacked together, implying that ICS is ubiquitous. We used a modified phonon-based simulation to reinforce the idea that ICS is primarily created by volumetric heterogeneity within the inner core as opposed to ICB topography. With simplified two-layer ICS models, our results suggest that ICS within the eastern quasi-hemisphere is slightly stronger than in the western quasi-hemisphere, although intra-hemispherical variations are as significant and our sampling is limited to patches of the northern hemisphere.

Keywords: fine-scale inner core heterogeneity, hemispherical pattern, inner core scattering, *PKiKP* coda

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Excitation of Earth's Inner Core Rotational Oscillation During 2001–2003 Captured by Earthquake Doublets

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Abstract

The nature of any differential rotation between Earth's inner core and mantle is important for understanding Earth's magnetic field and intradecadal variations in the length-of-day; however, a consensus on the existence and rate of differential rotation is still lacking after 25 years. The reported model for inner core differential rotation from seismic body waves is controversial and might be explained by non–rotational processes. Here, we explore inner core differential rotation using the decorrelation of inner-core sensitive coda waves from 123 earthquake doublets recorded during 1991– 2017. We find that the inner core was nearly locked to the mantle before 2001 and after 2003 with relatively small motion about an equilibrium position. During 2001–2003 the inner core experienced a burst of differential rotation, possibly in response to a magnetic torque induced by the expulsion of light elements from the inner core. We suggest that this fleeting bit of differential rotational helped excite an inner core rotational oscillation, consequently exciting the six-year-oscillation in the length-of-day.

Pang and Koper (2022)

Keywords: inner core rotation, length-of-day oscillation, coda wave interferometry

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Anisotropically distinct innermost inner core revealed by seismic records of exotic podal and antipodal reverberating body waves

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Abstract

P-wave anisotropy of the Earth's inner core characterizing the variation of seismic wave speed with sampling orientations remains a topic of heated debate mainly because of the limited volumetric sampling by high-frequency body waves (PKIKP). The coverage of the centermost inner core is worse because the near-antipodal epicentral distances are required. Here, we stack waveforms from global seismic stations and observe a gallery of "exotic phases" by large earthquakes, which reverberate along the entire Earth's diameters multiple times. The examples of our new observations include PKIKP waves reverberating up to five times (I5). Opportunistically, the differential travel times between the exotic arrival pairs complement the current coverage of PKIKP waves, especially its centermost region. In a cylindrically anisotropic model, the new measurements place additional constraints on the centermost ~600 km ball having P wave speeds traveling along the Earth's rotation axis ~5% faster than at the slowest direction, ~50° from the fast axis. Our findings supply complementary evidence for the anisotropically distinct innermost inner core because the properties differ from the outer shell of the inner core. The outer shell displays much weaker cylindrical anisotropy with a fast direction along the Earth's rotation axis and a slow direction at the equator.

Keywords: exotic phases, body waves, anisotropy, the inner core

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Seismological observation of innermost inner core anisotropy from the Earth's correlation wavefield

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Abstract

Anisotropy in seismic velocity is the directional dependence of seismic waves. Under inner core (IC) pressure and temperature conditions, different phases of iron – the core's main mineral constituent can stabilize and form elastic anisotropy. Thus, improved constraints on its strength and distribution are required to understand the crystallographic structure of iron in the IC, which is linked to the evolution of its solidification and deformation processes. However, the volumetric sampling of the IC with body waves is poor, especially in its innermost part, also known as the innermost IC (IMIC). Here, we devise a new method based on the global earthquake coda-correlation wavefield to investigate the anisotropic structure of the Earth's inner core (IC).

We calculate cross-correlation functions of the late-coda seismic wavefield (the correlation wavefield) that reverberates within the Earth up to 10 hours after large earthquakes. We analyse the travel times of the I2* correlation feature, a mathematical manifestation of similarity among IC seismic phases with the same slowness detected in global correlograms at small interstation distances. This feature can be formed by the similarity between the pair of seismic phases, e.g., I6 and I4, I12 and I10, etc. The I2* spatial sampling offers unprecedented data coverage of the IMIC, which overcomes the shortage of the traditional approach using PKIKP ray paths sampling. By comparing the time residuals of different paths of I2* propagating through the IC, we confirm the presence of a deep IC structure with distinct anisotropy, although we cannot resolve the depth at which the change occurs. Our observations, using the new class of data, support an IMIC cylindrical anisotropy with a slow direction of propagation oriented 55° from the Earth's spin axis. This new evidence reinforces previous inferences on the existence of the IMIC structure, with implications for our understanding of the core's geodynamical evolution. The correlation wavefield offers a new way to sample the deep Earth, with the sensitivity of the periods between 15 and 50 s, placing it between the body waves and normal mode studies.

Keywords: anisotropy; inner core; correlation wavefield.

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Observations of Inner Core Shear Waves with AlpArray

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Abstract

Although the solidity of Earth's inner core is evidenced by normal mode data, the direct observation of inner core shear waves (J-waves) has remained challenging for decades due to their small amplitudes. Nevertheless, some studies have presented evidence for J phases in different seismic datasets using regional arrays (e.g., *Okal and Cansi Y, 1998*; *Cao et al., 2005*; *Wookey and Helffrich, 2008*), as well as global stacks (*Deuss et al., 2000*; *Waszek and Deuss, 2015*) and global correlation wavefield (*Tkalčić and Phạm, 2018*). However, most of the previous observations require specific ray paths/windows and a much higher inner-core Q_β than current earth models. Therefore, searching the J arrivals systematically and in higher frequencies would help determine their observability, their dependence on distance and the location of the source and receiver, and other factors that might influence the observation.

To further improve phase identification and discrimination, we use an approach that combines the array method of slant stacking and polarization filtering to enhance linearly polarized signals with the expected slowness and incident angle. We apply this technique on the data of the AlpArray Seismic Network, a large-scale seismic network in Europe that consists of over 600 broadband stations with a mean station spacing of 30-40km. We find arrivals consistent with PKJKP (in reference travel time, slowness, and polarization) in several events in the source region reported by *Cao et al.* (2005) but not every event with similar distances during the course of AlpArray (2016-2019).

To investigate whether the signal observed in these events can be explained by a PKJKP phase, we review all candidate events in the epicentral distance range 125-150° from the Central European stations in the past 20 years and present a systematic overview of conditions to observe PKJKP.

Keywords: Core; Inner core; PKJKP; AlpArray; Polarization filtering

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Investigating the uppermost inner core with 30 years of high quality measurements of PKIKP/PKiKP amplitude ratio and delay time residuals

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Abstract

The inner core is widely thought to have a hemispherical structure, often associated with lopsided growth or melt, and specific combinations of translation and possible super-rotation. Investigating the boundary between the solid inner core and the liquid outer core is crucial to understanding how the core grows, with fundamental importance for the operation of the geodynamo. We investigate the seismic structure (P-wave velocity, apparent attenuation and cylindrical anisotropy) of the uppermost inner core (top ~100 km) using the highest signal-to-noise ratio global records of PKIKP and PKiKP phases generated by earthquakes recorded globally between 1987 and 2021. These waves have similar propagation paths and low angular separation when they enter the inner core, making them the best candidates to image uppermost inner core properties with minimum bias. We estimate the amplitude ratios and delay times between the two phases relative to synthetic waveforms calculated using normal mode summation for each source-station configuration and CMT moment tensor solutions. We invert our measurements for the variation of P-wave velocity anomalies and quality factors relative to ak135 using a hyper-planar inversion algorithm. Our results indicate the presence of strong heterogeneities in both delay time residuals and relative amplitude ratios that are incompatible with a simple hemispherical dichotomy. Moreover, our data does not show any significant variation with the angle between the propagation path and the Earth's rotation axis, implying there is virtually no cylindrical anisotropy in the uppermost inner core.

Attenuation slightly changes with depth possibly implying an increase in melt degree or a change in inner core growth rate with time. These 3-D heterogeneities are inconsistent with simple models of core translation or lopsided growth, indicating that more intricate processes are needed to explain inner core structure and evolution.

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Illuminating the Earth's Deep Interior with Global Coda Correlations

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Abstract

Global coda correlations, the cross-correlation of seismic recordings many hours after an earthquake's origin, is a relatively new paradigm in seismology. As a new type of observation and method, it complements the seismic wavefield and places additional constraints on the deep Earth structure. Here, we present theory and applications to illuminate the Earth's deep interior with global coda-correlations. We first show how to obtain coda-correlation features based on the formation theory of coda correlations, and we demonstrate how to "dissect" these features in terms of their constituents. Our approach circumvents distortions of relevant correlation features due to a mixture of various constituents and inaccuracies that could possibly be introduced in the data processing. We then derive the relationship between the obtained features and Earth's structure. The relationship allows inference of Earth's structure based on the timing of coda correlation features and their constituents in a similar way seismic tomography works for the direct seismic wavefield. Finally, we demonstrate applications for constraining shear-wave anisotropy in the Earth's inner core. We argue that coda correlation will be indispensable in advancing fine-resolution illumination of the Earth's and deep planetary interior in the coming decades.

Keywords: The Earth's deep interior, Global coda correlations, Inner-core shear-wave anisotropy

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Probing the nucleation of iron in Earth's core using molecular dynamics simulations of supercooled liquids

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Abstract

Earth's inner core nucleation paradox states that for the Earth to have been sufficiently supercooled to freeze, it would be larger than is seismically observed. Classical nucleation theory describes the formation of the first solids from supercooled liquids and predicts an average waiting time for a system to freeze as it is cooled below the melting temperature. When only moderately supercooled, a system will not freeze for considerable time, longer than is practical to observe through experiment or simulation. Instead, the thermodynamic properties of the system must be used to extrapolate observable waiting times at greater supercooling. In the case of crystallizing Earth's solid iron inner core, these thermodynamic parameters are not well known and directly observed waiting times from simulations must be extrapolated over approximately 60 orders of magnitude. In this work, we develop a new approach negating the need for freezing to be observed. We collect statistics on solid-like particles in molecular dynamic simulations of supercooled liquids at 320 GPa. This allows estimation of waiting times at temperatures closer to the melting point than is accessible to other techniques and without prior thermodynamic insight or assumption. Our method describes the behaviour of nucleation at otherwise inaccessible conditions such that the nucleation of any system at small undercooling can be characterized alongside the thermodynamic quantities which define the first formed solids.

Keywords: Inner core, nucleation, core formation

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Two-phase slurry model of the F-layer at the base of Earth's core

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Abstract

Seismic observations suggest that a stably stratified layer, known as the F-layer, 150–300km thick exists at the bottom of Earth's liquid outer core. At the same time, there is a consensus that light material is expelled from the inner core and rises through the outer core. This raises an apparent juxtaposition: how can the F-layer be stably stratified if lighter material passes through it from underneath? A plausible and elegant hypothesis is that matter in the F-layer exists in the form of slurry – a region of mixed phase, where the condensed phase exists in the form of fine grains. Thus, solid can freeze out of the liquid and fall due to its high density, with the lighter liquid buoyantly rising towards the top of the F-layer. The presence of such a region has potentially far-reaching consequences since the F-layer mediates the power input to the bulk core where the magnetic field is generated. It is therefore important to understand the dynamics of two-phase slurries to assess its impact on the global dynamics of the Earth's core. Here, we describe a mathematical model of a two-phase slurry and investigate one-dimensional solutions and their dependence on various physical parameters.

Keywords: two-phase flow; slurry, Earth's core

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A model of Earth's F-layer as a non-equilibrium slurry

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Abstract

We describe a model of the formation of the seismically observed F-layer, a 150-400 thick zone of unexpectedly low p-wave velocity at the base of Earth's outer core. We assume the F-layer consists of a slurry. Specifically we assume the F-layer consists of a low volume fraction of solid iron crystalising out of the outer core alloy and settling onto the inner core through a stably stratified fluid. Similar "iron snow zones" have been proposed to be present in other planetary cores and their presence has implications for the long timescale thermal evolution of planets and on the generation of internal magnetic fields. In contrast to most previous descriptions, we focus on modelling the physics controlling the growth and sinking of individual iron crystals and do not assume that the slurry layer is in phase equilibrium. This means that our model does not require the temperature and solid volume to be linked through a liquidus relation and yields a size distribution of solid grain sizes and their falling velocities throughout the layer. We consider the layer as a liquid iron-oxygen alloy cooled below the liquidus temperature such that microscopic solid iron crystals can form. Each crystal sinks because it is denser than the surrounding liquid. As the crystal sinks it also grows because of the chemical potential difference between iron in the solid and liquid phases. Growing crystals reject oxygen, moving the system towards equilibrium, but this equilibration is limited by the intrinsic growth kinetics of iron and by the need for iron to diffuse through an oxygen enriched boundary layer around the falling crystal. We model the layer as a collection of independently falling crystals which form throughout the layer and only interact by collectively changing the composition and temperature of the liquid. Assuming the layer is in steady state and imposing a suitable parameterisation of classical nucleation theory allows us to solve for the volume fraction of solid in the layer, the temperature and composition of the liquid, the size distribution of crystals. We also recover the growth rate of the Earth's inner core that is attributable to sedimentation.

Keywords: F-layer, outer core, inner core boundary, slurry

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Growth of a chemically stratified layer due to chemical exchanges between mantle and core

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Abstract

The presence of a stratified layer has been proposed at the top of the cores of the Earth and Mars. Buffett & Seagle (2010) and O'Rourke & Shim (2019) proposed that such a layer could be the result of chemical exchanges between the mantle and core. The mantle would deliver light elements at the top of the core, which would then migrate downward owing to chemical diffusion. This would gradually suppress convection in the outermost core and form a chemically stratified layer over long time scales. This scenario has not yet been assessed using numerical simulations. I present the results obtained by Mathis Pinceloup (student in 1st year of Master at the university of Nantes) during his 2 months- internship. Using the code NEK5000, Mathis performed numerical simulations in a 2D Cartesian box with Rayleigh-Bénard convection. A constant flux of light elements is injected at the top of the box. Two regimes were obtained when systematically varying the light elements injection rate and diffusivity. In the first one, light elements are entrained and mixed in the convective region. In the second, entrainment is not efficient enough so that a chemically stratified layer grows and eventually fills up the entire box. We characterise both regimes and the transition between them. Future work will be conducted in a 3D rotating shell for more direct planetary applications.

Keywords: core structure and composition, stratified layer, core/mantle processes, numerical simulations

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Internal waves in a stratified layer atop a convecting liquid core

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Abstract

Seismic and magnetic observations have suggested the presence of a stably stratified layer atop Earth's core. Such a layer could affect the morphology of the geomagnetic field and the evolution of the core, but the precise impact of this layer depends largely on its internal dynamics. Among other physical phenomena, stratified layers host internal gravity waves, which can be excited by adjacent convective motions. Internal waves are known to play an important role on the large scale dynamics of the Earth's climate and on the long- term evolution of stars. Yet, they have received relatively little attention in the Earth's outer core so far and deserve detailed investigations in this context. Here, we make a first step in that direction by running numerical simulations of internal gravity waves in a non-rotating spherical shell in which a stratified layer lies on top of a convective region. We use a non- linear equation of state to produce self-consistently such a two-layer system. Both propagating waves and global modes coexist in the stratified layer. We characterise the spectral properties of these waves and find that energy is distributed across a wide range of frequencies and length scales, that depends on the Prandtl number. For the control parameters considered and in the absence of rotational and magnetic effects, the mean kinetic energy in the layer is about 0.1% that of the convective region. Gravity waves produce perturbations in the gravity field that may fall within the sensitivity limit of present-day instruments and could potentially be detected in available data. Finally, we show preliminary simulations including rotation/magnetic field and discuss possible implications for the dynamics of the core and the structure of the geomagnetic field.

Keywords: core structure and composition, stratified layer, internal waves

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Sustaining Earth's magnetic dynamo

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Abstract

Earth's magnetic field originates from flow motions in the outer core. This geodynamo has operated for at least 3.4 billion years. However, the mechanism that has sustained the geodynamo for over 75% of Earth's history remains debated. Here, we assess the candidate mechanisms and their ability to match geomagnetic and palaeomagnetic observations.

The most accepted candidate is convection. The Earth formed very hot and is now cooling. This cooling drives convective flows in the outer core. However, evidence suggest that the thermal conductivity of Earth's core could be as high as 250 W m^{-1} K^{-1}. Such high values call the ability of convection to maintain the dynamo for over 3.4 billion years into question. Yet, we show that convection could supply enough power to sustain a long-lived geodynamo if the thermal conductivity is lower than 100 W m^{-1} K^{-1} [1]. The exsolution of light elements from the core increases this upper conductivity limit by only 15% and up to 200%, based on the exsolution rates reported so far.

Precession, which is a slow variation of the orientation of Earth's rotation axis, and tides are other candidates to drive flow motions in Earth's core. We show that the flow driven by precession is too weak to sustain the geodynamo. In contrast, the flows driven by tides could have been strong enough in the early Earth, before 1.5 billion years ago, when tidal deformation and Earth's spin rate were larger than they are today [1].

Keywords: Geodynamo, driving mechanisms, thermo-chemical convection, cooling of the Earth, precession, tides, exsolution, thermal conductivity, early Earth.

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Generation of planetary core zonal flows by orbital forcings or fingering convection

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Abstract

Zonal flows generation is a long-standing issue in rotating fluids, which can be key in the dynamics of planetary fluid layers (e.g. planetary cores). They are indeed believed to play a significant role in angular momentum exchanges between liquid layers and surrounding solid domains (e.g. Roberts & Aurnou 2012). Moreover, mean flows could be unstable (e.g. Sauret et al. 2014, Favier et al. 2014), which could sustain space-filling turbulence and mixing. Therefore, understanding the formation of mean flows is essential to model the fluid dynamics of many rapidly rotating systems.

Zonal flows of planetary liquid cores are usually studied as originating from convection in rotating spheres. In the frame of the ERC THEIA (grant agreement no. 847433), we consider here two alternative origins. First, zonal flows can be generated by orbital forcings (e.g. tides, precession) via nonlinear effects within the Ekman layer (Cébron et al. 2021). These flows survive in the relevant regime of vanishing forcings and viscosity. Their competition with bulk driven zonal flows are then considered for various planets and moons. Second, zonal flows can emerge from double-diffusive convection (DDC) in stratified cores (Monville et al. 2019). Applying our results to the early Earth, we obtain that double diffusion can reduce the critical Rayleigh number by four decades, suggesting that its core was prone to turbulent DDC, with large-scale zonal flows.

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Keywords: rotating flows, zonal flows, fingering

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Finite element analysis of a topographic core-mantle coupling mechanism and implications on LOD variations

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Abstract

Minute fluctuations of the length of day (LOD) on the order of milliseconds are observed on decadal timescales and are believed to be caused by interactions of the outer core with the mantle. In addition to the magnetic field, LOD fluctuations are an additional resource for gaining a fundamental understanding of the processes inside the Earth's outer core. Apart from core-mantle coupling models, core angular momentum and torsional wave models were explored regarding an explanation of LOD variations. The question of how the angular momentum is exactly transferred between core and mantle is still open and is the subject of core-mantle coupling models. This study explores a previously proposed core-mantle coupling model that accounts for a stratified fluid layer below the core-mantle boundary (CMB) and deviations of the CMB shape from a perfect sphere. A first-order perturbation analysis in Cartesian geometry has shown that the average traction acting on the CMB depends non-linearly on the stratification strength, velocity and magnetic field. This yields a variation of the average traction by several orders of magnitude and raises the question whether nonlinear effects play an important role in the proposed model. Specifically, physical and geometric nonlinearities will be analyzed by means of a finite element program, which is customized for solving stationary nonlinear magnetohydrodynamic problems. Results of a parameter study will be presented and a comparison with the previous linear analytical model is made. This allows to re-assess and improve results of a synthetic model that combines the core-mantle coupling model with numerical dynamo simulations to predict LOD fluctuations of the Earth. Moreover, efforts to develop a finite element software package computing transient magnetohydrodynamic flows in domains of arbitrary shape will briefly outlined.

Keywords: LOD variations, core-mantle coupling, CMB topography, stratification, nonlinear model, FEM

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Triadic resonances driven by thermal convection in a rotating sphere

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Abstract

We report for the first time on triadic resonances in a rotating convection system. Using direct numerical simulations, we find that convective modes in a rotating spherical fluid can excite a pair of inertial modes whose frequencies and wavenumbers match the triadic resonance conditions. Depending on the structures of the convective modes, triadic resonances can lead to the growth of either a pair of modes with lower frequencies and wavenumbers, or a pair of modes with higher frequencies and wavenumbers, providing a possible mechanism for the bi- directional energy cascade. Increased thermal forcing leads to fully developed turbulence, which also exhibits wave-like motions, and is reminiscent of the energy spectrum of inertial wave turbulence. Our results suggest that the interaction of inertial waves plays an important role in rotating convection, which is of great importance in understanding the dynamics of planetary and stellar interiors.

Keywords: rotating flows, convection

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The influence of inertial modes on planetary rotation

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Abstract

Rotating fluids are the hosts of internal oscillations known as inertial waves, which are restored by the Coriolis force. When the fluid is confined into a finite volume— such as is the case for the liquid cores of terrestrial planets like Earth, or the global oceans of icy satellites like Enceladus—these wave motions can be represented as the superposition of global oscillations called inertial modes. When the fluid is taken as incompressible and inviscid, angular momentum transfer between the fluid and the container is entirely mediated by the pressure torque on the aspherical *Core-Mantle boundary* (CMB). In which case, it can be shown that the only flow component contributing to the torque has uniform vorticity. When the rotation of the model is kept steady, such as happen in laboratory experiments, this flow corresponds to the inertial mode known as the *Spin-Over Mode* (SOM), and can be excited by a constant precession of the spin-axis. When the container can rotate freely in space, as is the case for real planets, this flow is associated with the rotational mode of the whole planet known as the *Free Core Nutation* (FCN). Due to the proximity in shape and frequency between these two modes, they have often been equated to one another.

In this work, we examine the differences and the relation between the SOM and the FCN in details, and show that the former retains some significance in the freely rotating planetary model. We also examine how viscosity and stratification affect the coupling of planetary rotation to inertial modes other than the SOM.

Keywords: Earth Rotation, Inertial Modes, Free Core Nutation, Planetary Science

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Topographic effects in magnetized and stratified fluid cores

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Abstract

The interactions between planetary fluid layers and their solid boundaries are a key aspect when studying flow dynamics and planetary motions. These couplings are not straightforward to calculate and can originate from pressure, gravity, viscous, or electromagnetic forces. Earth and Moon's rotations are tracked accurately, and these data are inverted with rotation models, providing the coupling between the liquid core and the solid layers (mantle, inner core). Despite these well constrained values, the coupling mechanisms are still disputed.

Here, we focus on the small-scale topographic effects which give rise to pressure forces, or increase the electromagnetic coupling. To explore these questions, we develop a local model based on plane wave perturbations, following the work of Jault (2020) and Glane & Buffett (2018). Relying on symbolic and arbitrary precision calculations, our code ToCCo unlocks several limitations of previous calculations. With our "higher-order" solutions, we go beyond the forced wave linear regime, investigating non-linear effects and improving previous results. With this new approach, we explore a large range of parameters and boundary conditions for arbitrary topography shapes. We also take into account the spherical geometry in a better way, via spatial integrations that considers physical fields variations. To do so, we have implemented the "improved beta-plane" approximation of Dellar (2011), for both the magnetic and the rotation vectors.

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S. Glane, B. Buffett, Frontiers in Earth Science 2018, 6.

P. J. Dellar, Journal of Fluid Mechanics 2011, 674, 174.

Keywords: topography, waves, rotation

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Turbulent Boundary-Layer at Core-Mantle Boundary

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Abstract

Turbulence in the boundary layer at core-mantle boundary (CMB) is one hypothesis to explain for the inferred coupling from nutation observations. The conditions for a turbulent boundary layer were examined by Buffett (2021). In this study, we further quantify the turbulent effect on CMB coupling. Since the flow driven by nutation is too small to trigger turbulence, we focus on precession-driven flow. The result obtained here is only applicable for nutation if the nutation-driven flow is affected by the turbulence triggered by precession-driven flow. We develop a local Cartesian model to simulate the flow near CMB. The simulation is based on the Navier-Stokes equation in a rotating frame for an incompressible fluid. We consider pure hydrodynamic case, where there is no electromagnetic force nor stratification. Our result shows that the boundary layer is marginally turbulent, with a coupling increase of only a factor of two. If we apply the same increment to the nutational coupling, it is still insufficient for the observed coupling. This finding suggests that the story is not finished yet. We still need to explore other mechanisms, such as topographic or electromagnetic coupling.

Keywords: turbulence; core-mantle boundary; nutation; precession

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Topographic excitation of Inertial waves

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Abstract

In planetary cores, inertial waves contribute to the maintenance of quasi geostrophic motions or to the formation of elongated structures in rotating turbulence. An astonishing property of inertial waves is that they can only occur in a frequency range between zero and twice the rotation rate of a planet. Motivated by the evidence for topography at the core-mantle boundary in both geodynamic and seismological studies, we focus on inertial waves excited by topography.

We present results of experimental investigations of inertial waves over the entire frequency range of their existence and beyond. Inertial waves are generated by topography of varying complexity, and we focus on the transport of kinetic energy at different length scales and on the interactions between direct and reflected inertial waves.

Keywords: Iner'al waves, Core Mantle Boundary Topography

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A taxonomy of simulated geomagnetic jerks

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Abstract

Geomagnetic jerks - abrupt changes in the acceleration of Earth's magnetic field that punctuate geomagnetic records - have been richly documented over the past decades by taking advantage of the complementary strengths of ground observatory and satellite measurements. It has recently been proposed that these events originate from the interplay and time scale separation between slow convection and rapid hydromagnetic wave propagation in Earth's outer core, with these latter waves playing a key role in the generation of jerk signals. To assess the generality of this explanation, here we analyse a catalog of 14 events obtained during a 14000 year long temporal sequence from a numerical geodynamo simulation that is the closest to date to Earth's core conditions regarding time scale separation. Events are classified according to their dynamical origin and the depth at which they are triggered in the outer core. The majority of jerk events are found to arise from intermittent local disruptions of the leading-order force balance between the pressure, Coriolis, buoyancy and Lorentz forces (the QG-MAC balance), that leads to an inertial compensation through the emission of rapid, non-axisymmetric, quasi-geostrophic Alfvén waves from the region where this force balance is disrupted. Jerk events of moderate strength arise from the arrival at low latitudes at the core surface of hydromagnetic wave packets emitted from convective plumes rooted at the inner core boundary. As in an earlier simulation, these account well for jerk features that have recently been documented by satellite and ground observations. The more realistic timescales in the simulation reported here allow further details to be distinguished, such as multiple temporal alternations of geomagnetic acceleration pulses at low latitudes, long-range synchronisation of pulse foci in space and rapid longitudinal drift of these foci at the core surface. The strongest events in the catalog arise from disruption of the leading-order force balance near or at the core surface, from the combined influence of the arrival of buoyancy plumes and magnetic field rearrangement. The hydromagnetic waves that are sent laterally and downwards generate signals that clearly illustrate the presence of nearly synchronous 'V-shaped' magnetic variation patterns over a wide portion of Earth's surface and also at mid to high latitudes, despite the source being confined to low latitudes at the core surface. Other well-known characteristics of strong geomagnetic jerks such as surges in the intensity of the secular variation and inflexions in the length-of-day variations are also reproduced in these events. Irrespectively of the event strength, our results support the hypothesis of a single physical root cause - the emission of magneto-inertial waves following a disruption of the QG-MAC balance - for jerks observed throughout the geomagnetic record.

Keywords: Rapid geomagnetic variations, satellite magnetism, geodynamo simulations

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Inference of quasi-geostrophic motions from the geomagnetic secular variation

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Abstract

Fluid motions in the outer core of the Earth generate the largest part of the magnetic field and of its time variations. The classical view on the core flow inverse problem provides surface motions from the knowledge of the radial field and its rate of change at the top of the core. Meanwhile, the dynamical assumption of quasi-geostrophy (QG) couples the core surface flow to the flow throughout the outer core. Based on the radial induction equation, calculations of the velocity of the flow were classically performed via the toroidal and poloidal representation of the horizontal velocity field at the core-mantle boundary (CMB). Here, we propose a new approach that involves the two-dimensional stream function, which describes the QG velocity field in the whole volume, and a complex basis constructed upon generalized spherical harmonics. This method allows us to derive in a concise manner two physical constraints at the CMB: on the core side, the induced field should present no toroidal component, and should attach to a potential field. We assume these constraints hold on time scales (1-10 years) on which the background magnetic field is approximately steady. These decrease the number of degrees of freedom while solving the inverse problem for QG motions. The above constraints have been partly implemented in a new code. Correctness of the calculation for the radial component of the secular variation incorporating a new formalism, has been benchmarked by comparing with the classical approach. We present the importance of developing and implementing the new constraints for the reconstruction of the core dynamics, and for a better understanding of the part played by Magneto-Coriolis waves in the Earth's dynamo mechanism.

Keywords: geomagnetic secular variation, quasi-geostrophy, core dynamics, Earth's core, inverse problem

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Millennial axisymmetric Magneto-Coriolis modes in Earth's fluid core

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Abstract

Magneto-Coriolis (MC) modes in Earth's fluid core involve oscillations sustained by the combined effect of the Lorentz and Coriolis forces. The characteristics of MC modes have been investigated in a few recent theoretical studies, with a focus on modes involving non-axisymmetric motions. Here, we investigate axisymmetric MC modes. We show that for reasonable magnetic field strength and electrical conductivity inside the core, the gravest modes have millennial periods and a quality factor above 1. We investigate whether such modes could be tied to observed millennial changes in Earth's magnetic field and Length-of-day.

Keywords: Earth's core, geomagnetic field variations, Magneto-Coriolis modes, core-mantle coupling

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Comparison of Quasi-Geostrophic, Hybrid and 3D models of planetary core convection

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Abstract

We present investigations of rapidly-rotating convection in a thick spherical shell geometry relevant to planetary cores, comparing results from Quasi-Geostrophic (QG), 3D and hybrid QG-3D models. The Quasi-Geostrophic (QG) model is based on the open-source pizza code. We extend this in a hybrid approach to include the temperature field on a 3D grid. The 70 reported calculations span Ekman numbers, Ek, between 10^{-4} and 10^{-10}, Rayleigh numbers, Ra, between 2 and 150 times supercritical, and Prandtl numbers, Pr, between 10 and 10^{-2}. The default boundary conditions are no-slip at both the ICB and the CMB for the velocity field, with fixed temperatures at the ICB and the CMB.Cases driven by both homogeneous and inhomogeneous CMB heat flux patterns are also explored, the latter including lateral variations, as measured by Q^*, the peak-to-peak amplitude of the pattern divided by its mean, taking values up to 5.

In general, we find convection is dominated by zonal jets at mid-depths in the shell, with thermal Rossby waves prominent close to the outer boundary when the driving is weaker. For the thick spherical shell geometry studied here the hybrid method is best suited for studying convection at modest forcing, $Ra \leq 10\ Ra_c$ when $Pr=1$, and departs from the 3D model results at higher Ra displaying systematically lower heat transport characterized by lower Nusselt and Reynolds numbers. We find that the lack of equatorially anti-symmetric and z-correlations between temperature and velocity in the buoyancy force contributes to the weaker flows in the hybrid formulation. On the other hand, the QG models yield broadly similar results to the 3D models, for the specific aspect ratio and range of Rayleigh numbers explored here. We cannot point to major disagreements between these two datasets at $Pr \geq 0.1$, although the QG model is effectively more strongly driven than the hybrid case due to its cylindrically-averaged thermal boundary conditions. When Pr is decreased, the range of agreement between the Hybrid and 3D models expands, *e.g.* up to $Ra \leq 15\ Ra_c$ at $Pr=0.1$, indicating the hybrid method may be better suited to study convection in the regime $Pr \ll 1$.

We effectively observe two regimes: (i) at $Pr \geq 0.1$ the QG and 3D models agree in the studied range of Ra/Ra_c while the hybrid model fails when $Ra \geq 10\ Ra_c$; (ii) at $Pr=0.01$ the QG and 3D disagree above $Ra/Ra_c = 10$ while the hybrid and 3D models agree fairly well up to $Ra \sim 20\ Ra_c$. Models that include laterally-varying heat flux at the outer boundary reproduce regional convection patterns that compare well with those found in similarly forced 3D models. Previously proposed scaling laws for rapidly-rotating convection are tested; our simulations are overall well described by a triple balance between Coriolis, inertia and Archimedean (CIA) forces with the length-scale of the convection following the diffusion-free Rhines-scaling. The Prandtl number, Pr, affects the number and the size of the jets with larger structures obtained at lower Pr; higher velocities and lower heat transport are also seen on decreasing Pr. The scaling behaviour of the convective velocity shows a strong dependence on Pr.

Keywords: Core dynamics – Thermal convection – Numerical simulations

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QG-3D Hybrid convection-driven dynamo models

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Abstract

We report progress on a numerical dynamo model in a thick spherical shell geometry relevant to planetary cores, using an hybrid QG-3D method. The hydrodynamic part of the model is based on the open-source pizza quasi-geostrophic convection code (Gastine, 2019) that is discretised using a Fourier decomposition in longitude and Chebyshev polynomials in cylindrical radius. We have extended this in a hybrid approach to include the temperature and magnetic fields, along with their associated heat transport and magnetic induction equations on a 3D grid. This 3D grid is discretised using spherical harmonics horizontally and Chebyshev polynomials in radius, based on the implementation of the MagIC code (Wicht 2002). The default boundary conditions at both the ICB and the CMB are no-slip for the velocity field, with fixed temperatures, and magnetically insulating boundaries.

We present here benchmark tests of the different elements of the method, specifically of the terms of the 3D Lorentz-force that have to be added to the *z*-averaged vorticity and the axisymmetric flow equations. The terms are validated against analytical solutions when possible and against independently coded functions otherwise. The comparison with the analytical solutions gives an overall accuracy of order 3 for the whole process which test compared to the independent code converge towards the same solution. A computationally faster method has also been benchmarked and is available but it leads to a disappointing accuracy for the Lorentz-force terms of order ~ 1. In addition we present several simple example dynamos obtained with our method computed at $Ek=3\text{x}10^{-5}-10^{-5}$, $Pr=1-0.1$, $Ra\sim10-20$ xRac and $Pm=2.5-0.9$. Including 3D-temperature effects, we find self-sustained multipolar dynamos where magnetic energy is one or two order of magnitude lower than the kinetic energy such that they can be categorised as weak field dynamos. We find that a lack of magnetic poloidal energy and, by construction, a lack of equatorially anti-symmetric components in the Lorentz-force leads to configurations where the velocity field is weakly affected by the magnetic field, similar to dynamos found in 3D simulations where zonal flows and the omega effect dominate. Using a simpler 2D-temperature equation, as used in classical QG convection models, we have so far been unable to find a configuration with a self-sustain dynamo. However, the addition of parametric alpha effect have produced results with a self-sustained field, suggesting additional source of alpha effect may be needed in these models.

This study is a first step towards an effort to study dynamo action at lower *Ek*, in the case where *Pr* and *Pm* are small, so coarser grids can be used for the 3D velocity and magnetic fields.

Keywords: Core dynamics – Dynamo models – Numerical simulations

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Torsional wave propagation in the Earth's core

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Abstract

The Earth's core is made of a solid inner core and a liquid outer core. In the Earth's outer core, a dominant Coriolis force causes the fluid to form columnar structures aligned with the rotational axis. With a large-scale background magnetic field, a small disturbance may cause oscillations of these fluid columns, which then form torsional waves travelling perpendicular to the rotational axis. Inverse models have shown that the variation of the day length is correlated with the period of torsional oscillations due to the angular momentum transport. Since 1999, monitoring of the Earth's magnetic field from satellites (e.g. CHAMP and the Swarm constellation) has provided us with a detailed description of the changes in the geomagnetic field. Over more than 20 years of satellite observations are now very much appropriate to the study of torsional oscillations as these waves have periods of about 6 years. An accurate description of torsional waves is therefore essential for the interpretation of geomagnetic data. Many past studies on torsional waves have assumed a simple 1D profile, and did not distinguish the region above and below the inner core. Recent observations and analytical models of the outer core have suggested that this is not necessarily the case. In this study, we consider the realistic geometry of the outer core, and include the effects of conductivity and equatorial symmetry of the background field. We run 3D numerical simulations to quantify how much an initial Gaussian torsional wave pulse can be modified as it propagates, particularly at the tangent cylinder (a special location where the geostrophic cylinder intersects the inner core) where an inward propagating wave splits into two—above and below the inner core. We find that the width of the wave pulse is important in determining how the wave reflects. The wider the pulse, the more effects it feels from the presence of the inner core. The conductivity also plays a role: a conducting inner core generates more reflection compared with an insulating one. The combined effect is likely both geometrical and conductivity-dependent. On the contrary, the asymmetry in the background field only strongly affects the torsional wave in limited cases. Given that the inverted Earth's torsional wave signal has a relatively wide wavelength with respect to the core radius, and the inner core has a conductivity close to that of the outer core, we need to carefully consider these features for future torsional wave modelling.

Keywords: Earth's core dynamics, torsional waves

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Liquid Core Convection without Large Scale Vortices

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Abstract

An asymptotically reduced model for Rayleigh-B`enard convection in a planar geometry is numerically investigated up to reduced Rayleigh numbers ($\widetilde{Ra} = Ek^{4/3}Ra$) of 280. This model is believed to represent the convection in the liquid core, where convection is constrained by the rapid rotation of the Earth. At each time-step, the barotropic (depth averaged) components of the flow are zeroed out in order to remove the effects of domain-sized vortices. The results are compared to cases where the barotropic component is not removed. Without the large-scale vortices, a linear scaling between the reduced Reynolds number $\widetilde{Re} = Ek^{1/3}\,Re$ and $\widetilde{Ra}$ is reported as well as a $\widetilde{Ra}^{2/3}$ scaling for the Nusselt number. In addition, it is found that the Taylor microscale is approximately constant with increasing $\widetilde{Ra}$, despite the increase in global $\widetilde{Re}$. The kinetic energy spectra are not found to follow a Kolmogorov −5/3 law, which suggests the absence of a traditional inertial range. We interpret these results as evidence that energy in rapidly rotating convection is generated at small (viscous) length scales; kinetic energy cascades to both larger and smaller length scales, the former of which is responisble for the appearance of large scale vortices.

Keywords: Geostrophic turbulence, convective turbulence, quasi-geostrophic flows, numeri-cal turbulence

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Asymptotic models of rotating flows in ellipsoidal planets

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Abstract

Global spherical models of convection have succeeded in reproducing the main features of the large-scale magnetic field observed at the Earth's surface (e.g. Schaeffer et al, 2017). Planetary magnetic fields are thus often believed to be generated by turbulent convection in planetary liquid interiors. However, the recorded paleomagnetic fields of both the Early Earth and the Moon (which were generated billions years ago) may be incompatible with the convection scenario for the possible planetary conditions at that time (e.g. Weiss & Tikoo, 2014; Landeau et al., 2022). Other dynamical scenarios are thus considered to explain such puzzling observations, notably in the framework of the ERC THEIA (grant agreement no. 847433). In particular, turbulent flows driven by large-scale planetary deformations are worth investigating. Planetary core boundaries are indeed rather ellipsoidal at the leading order (due to the combined action of global rotation and tidal deformation), but the effects of large-scale topography have been largely overlooked in current models. Motivated by such planetary applications, reduced models of rotating flows (i) enclosed in ellipsoidal geometries and (ii) asymptotically valid in the low-viscosity planetary regime are presented. The compressible eigenmodes of the rotating fluid are first explored (Vidal & Cébron, 2020), since they could provide physical insights into the planetary flow dynamics, and then pioneering dynamo computations in non-spherical geometries are discussed (Vidal & Cébron, 2021).

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Keywords: rotating flows, dynamo, ellipsoids

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Plesio-Geostrophy for Earth's Core: Onset of Thermal Convection

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Abstract

The dynamics of Earth's core is believed to display phenomenology on an extremely wide range of spatial and temporal scales. This has led to difficulties in simulating the dynamics of the core on modern supercomputers. State-of-the-art 3-dimensional numerical simulations are incapable of reaching the extreme parameter regimes that characterize the geophysical reality, leading one to question whether their predictions truly apply to Earth's core.

One strategy to overcome this limitation is to simplify the fundamental equations governing the dynamics of Earth's core, resulting in numerical models that are computationally cheaper than fully 3-dimensional geodynamo models. On inerannual-to-decadal timescales, Earth's rotation is believed to constrain the fluid flows in the core to be highly invariant along the direction parallel to the rotation axis. This allows for a reliable 2-dimensional, *columnar* description of 3-dimensional flows. The description of magnetic fields in a similar 2-dimensional manner has proven itself mathematically challenging, and a fully 2-dimensional, columnar model of the dynamics of the core is not currently available.

In Jackson & Maffei (2020), a novel mathematical description of the magnetic field, called *plesio-geostrophic* (or PG) overcomes the limitations of previous columnar (or *quasi- geostrophic*, QG) formulations, and work is currently under way to validate the new PG set of equations on a suite of fundamental problems of significance to the dynamics of the core. Here we focus on the calculation of the onset of thermal convection and present the first results that will pave the way to the development of a fully non-linear model for the description of strongly forced thermal convection and, eventually, of the full magneto-hydrodynamics of Earth's core. Previous QG formulations have been successfully applied to the study of thermal convection in the core, and this problem represent therefore an important validation exercise for the new PG model equations.

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Keywords: Earth's core, thermal convection, plesio-geostrophy, quasi-geostrophy, columnar models

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A local model to study precessing turbulence

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Abstract

Rotating turbulence is a ubiquitous phenomenon in several geophysical and astrophysical objects that is often characterized by geostrophic vortices invariant along the rotation axis. Precession driven flows have been shown to present this tendency too [1], however several open questions still remain, e.g, wheter the geostrophic structure is due to precession instabilities or to nonlinear transfers.

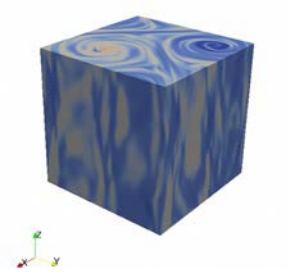


Figure: Three dimensional contours of the vertical vorticity highlighting two geostrophic vortices., under the influence of precession.

While global simulations and experimental campaigns are devoted to observe large scale structures and parametric instabilities, the use of a local model (i.e periodic cube box) allows to focus on turbulence features. We use therefore a spectral code [2], [3] showing the interplay of energy injection due to precession instability and nonlinear transfers for both 2D vortical structures and 3D turbulent perturbations (which are essentially inertial waves). We also analyze energy fluxes to understand the cascade directions founding that as typical for rotating turbulence, cascade in the presence of precession also exhibits dual - direct and inverse - nature at the same time. This study will serve to understand the turbulence mechanisms driven by precession dynamics and it will be useful for the upcoming DRESDYN precession experiment [4].

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Keywords: Rotating turbulence, precession driven flows, local model

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A statistical description of the kinematic dynamo equation using the MSRJD formalism

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Abstract

Geomagnetic field variations occur on a wide range of time scales, from milliseconds to millions of years. The advent of satellite measurements has allowed for detailed studies of short timescale behaviour, but understanding the long timescale magnetic field evolution remains a challenge due to the relative paucity of magnetic field observations older than ~400 years.

While it is well accepted that large-scale fluid motions exist in the outer core, the nature of the underlying convective motions is inherently turbulent. This turbulent nature manifests itself in the unpredictable behaviour of the geodynamo, the most extreme examples of which are magnetic reversals, occurring at seemingly random intervals. Given these phenomena, it appears justifiable to use stochastic models for studying the evolution of the Earth's magnetic field over long timescales.

Starting from the kinematic dynamo equation, we present a simple stochastic model for the geodynamo. The fluid velocity acts as a random forcing, obeying Gaussian statistics. Using the Martin- Siggia-Rose-Janssen-de Dominicis (MSRJD) formalism, we compute the statistics of the magnetic field, in particular the average response function. This allows us to determine a theoretical minimum velocity fluctuation strength required to sustain magnetic field growth against dissipation. The formalism can also be used to compute the spatial correlations of the magnetic field. Finally, we consider ways of connecting the results from our simple model to physically measurable parameters that can be extracted from the paleomagnetic record.

Keywords: Geodynamo, Statistical dynamos

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Towards Parallel-in-time integration of Dynamo Simulations: Kinematic Dynamos and Rayleigh-Bénard convection

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Abstract

The precise mechanisms responsible for the natural dynamos in the Earth and Sun are still not fully understood. Numerical simulations of natural dynamos are extremely computationally intensive, and are carried out in parameter regimes many orders of magnitude away from real conditions. Parallelization in space is a common strategy to speed up simulations on high performance computers, but eventually a scaling limit is reached. Additional directions of parallelization are desirable to utilise the high number of processor cores now available. Parallel-in-time methods can deliver speed up in addition to that offered by spatial partitioning but have not yet been applied to dynamo simulations.

We investigated the potential of parallel-in-time methods to speed up dynamo simulations using two simple analogous models, and the Parareal algorithm. We performed simulations of kinematic dynamos and Rayleigh-Bénard convection, analogues for the generation of magnetic field, and the generation of convective flows, in geo- and astro- physical dynamos. Speed ups of up to 300 were obtained for the Galloway-Proctor kinematic dynamo using 1600 processors in space and time, while limited speed ups were obtained for Rayleigh-Bénard convection for Rayleigh numbers up to 10^7.

Keywords: Dynamo, spectral methods, Parallel-in-time, Parareal, HPC, convection

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Towards high resolution fully spectral whole sphere dynamo simulations

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Abstract

In the study of planetary dynamos, a spherical geometry provides a very good approximation. In this setting, a whole sphere represents the canonical problem as well as model for Earth's core before the nucleation of the inner core. A numerical solution of the dynamo equation can be computed efficiently using a fully spectral method based on spherical harmonics and the Jones-Worland polynomials as implemented in our CFD framework QuICC. When large resolution is required, with spherical harmonic truncation $O(10^3)$, the memory footprint of Gaussian quadrature based algorithms becomes prohibitive. Furthermore, in order to fully utilize the computational power of modern HPC systems, the algorithms need to be adapted in order to efficiently use heterogeneous nodes built from multi-core processors and accelerators (GPU). We will present our ongoing work on the spectral transform algorithms and the refactoring of QuICC.

Keywords: planetary dynamo, numerical simulation, spectral method

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Exploiting GPU in the fully spectral MHD code QuICC

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Abstract

QuiCC is a code designed to solve the equations of magnetohydrodynamics in a full sphere and other geometries. The aim is to provide understanding of the dynamo process that sustains planetary magnetic fields for billions of years by thermally-driven convective motion of an electrically-conducting fluid. It also aims to provide the first clues as to how and why the magnetic fields can undergo reversals. The code must solve the coupled equations of conservation of momentum (the Navier Stokes equation), Maxwell's equations of electrodynamics and the equation of heat transfer. For accuracy and to facilitate imposition of boundary conditions, a fully spectral method is used in which angular variables in a spherical polar coordinate system are expanded in spherical harmonics, and radial variables are expanded in a special polynomial expansion in Jones-Worland polynomials. As a result the coordinate singularities at the north and south poles and at the origin disappear. The code is designed to run on upward of 10^4 processors using MPI and shows excellent scaling.

At the heart of the method is the ability to move between physical and spectral space by a variety of exact transforms: these involve the well-known Fast Fourier Transform (FFT) and the Associated Legendre Transform and Jones-Worland Transform.

In this talk we will focus on the latest advancements in the field of fast GPU algorithms for these types of discrete transforms. We present an extension to the publicly-released VkFFT library - GPU Fast Fourier Transform library for Vulkan, CUDA, HIP, OpenCL and Level Zero, that allows the calculation of the Discrete Cosine Transforms of types I-IV. This is a very exciting addition to what VkFFT can do as DCTs are often used in image processing, data compression and numerous other scientific tasks. So far, this is the first publicly available optimized GPU implementation of DCTs. We also present our progress in creating efficient Spherical Harmonic transforms (SHTs) and radial transforms using GPU implementations. This talk will present Jones-Worland and Associated Legendre Polynomial Transforms for modern GPU architectures, implemented based on the VkFFT runtime kernel optimization model. Combined, they can be used to create a new era of full-sphere models for planetary simulations in geophysics.

Keywords: GPGPU, FFT, DCT, SHT, QuICC, VkFFT

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Geodynamo reversals simulated with a rare event algorithm

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Abstract

Geomagnetic reversals are rare events. Simulations must run for long times to catch such events. Long simulations can only be performed at unrealistic parameters, which questions their relevance to the Earth. Here, we use a rare event algorithm called AMS (Bouchet+ 2019) to simulate many reversals at a small fraction (1/25) of the cost of a naive simulation. Although we are still not able to reach fully realistic parameters, we operate at high magnetic field strength, vigorous convection, and large magnetic Reynolds number (Rm ≈600).

Invariably, the simulated reversals imply a collapse of the dipole amplitude together with the total magnetic energy in the core. The dipole may then grow in the opposite direction.

With many simulated reversals, we can hope for a statistically significant description of the typical reversal behaviour and mechanisms. However, using the AMS algorithm efficiently at low viscosity is still challenging as it requires simulations of many advective time-scales.

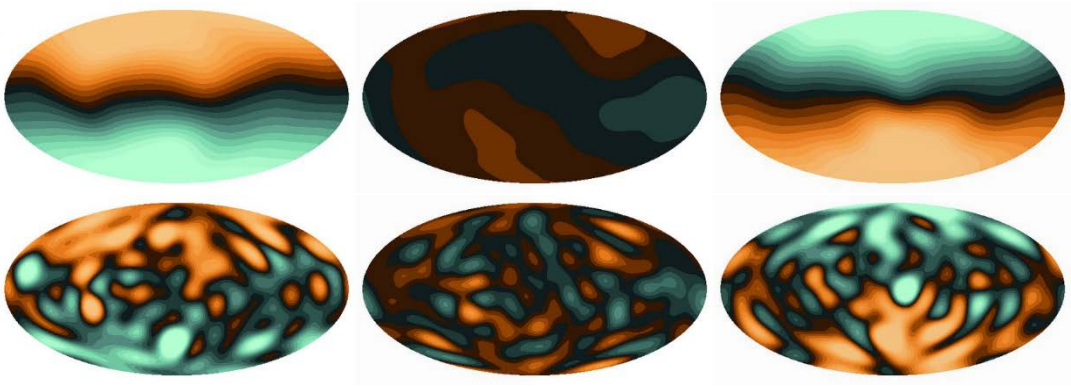


Figure: radial magnetic field before (left), during (middle) and after (right) a reversal, at the Earth's surface (top) and at the core surface (bottom).

Bouchet+ 2019: https://doi.org/10.1103/PhysRevLett.122.074502

Keywords: Dynamo, Magma Ocean, Early Earth, Planetary magnetism, Convection, Turbulence

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Effect of heat flux heterogeneities at the core-mantle boundary on geodynamo simulations

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Abstract

The heat flux at the core-mantle boundary (CMB) is a key parameter for core convection and the geodynamo. Both the mean value and the lateral variations of the CMB heat flux affect the behavior of the geodynamo and notably the stability and strength of the magnetic dipole in numerical simulations. A strong heat flux at the equator has notably been shown to increase the reversal frequency. Inside the Earth, the CMB heat flux is controlled by mantle convection, with possibly large lateral variations. This could thus be a significant parameter influencing the dynamo.

This work aims at acquiring a more complete understanding of how lateral heterogeneities of CMB heat flux affect the geodynamo. For this purpose we ran geodynamo simulations with degree 1 and 2 spherical harmonic patterns of heat flux at the CMB. We especially focus on the heat flux repartition between the poles and the equator. We use the *XSHELLS* code to run the simulations, and adopt a codensity approach with a fixed flux at both inner and outer boundaries. The half peak-to-peak amplitude δq_o of the heat flux patterns is varied from $\delta q_o/q_i = 0$ to $\delta q_o/q_i = 0.29$ with q_i the fixed flux at the inner core surface. A mean CMB heat flux is also added in some cases. Most of our simulations are performed at an Ekman number $E = 10^{-4}$, but we also perform simulations with $E = 10^{-5}$ to extend the results to smaller Ekman number.

Most of the explored patterns tend to decrease or have little effect on both the magnetic energy and the dipolar fraction of the magnetic field. However, a positive heat flux near the equator strongly decreases the magnetic energy and dipolarity, while the magnetic energy and dipolarity increase for moderate positive heat flux near the poles. These effects are especially strong for moderate heterogeneities amplitudes, up to $\delta q_o/q_i = 0.029$. The kinetic and magnetic energy maps show that strong heat flux near the equator and near the poles tend to promote convection outside and inside the tangent cylinder, respectively.

Keywords: Geodynamo, Magnetic field, Heat flux, CMB

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Searching for precursors of geomagnetic reversals with machine learning

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Abstract

While it is well documented that the axial dipole component of Earth's magnetic field can reverse polarity, the conditions leading to reversals are not well understood. Specifically, it is unknown whether there exist precursors to reversals, i.e., patterns of behavior which precede a reversal. We study whether machine learning (ML) can identify reliable precursors to reversals within time series of the axial magnetic dipole. To do this, we train ML algorithms (support vector machines and long short-term memory networks) to classify segments of time series according to whether they precede a reversal. Because reversals are rare, a modification to standard ML training is made to avoid classifiers that always predict that no reversal is imminent.

Given the shortness of the usable observational record (covering the last 2 Myr and containing only five reversals), we carry out our investigation using paleomagnetic reconstructions (PADM2M and Sint-2000), as well as a hierarchy of numerical models (from scalar models of the axial dipole to 3-D geodynamo simulations). It is found that the ability of ML to identify precursors varies across the models and paleomagnetic reconstructions. We present evidence that this is not the result of our chosen methodology but instead reflects varying levels of "predictability" among the models and observations. The ML classifiers therefore highlight shortcomings and advantages among various numerical models. For the magnetic field of the Earth, we demonstrate that the ability of ML to reliably identify precursors is limited, in part, by the shortness and low-frequency resolution of the data.

Keywords: Magnetic field; Polarity reversals; Machine learning.

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Energetics of equatorially anti-symmetric flow during polarity reversals in a geodynamo simulation

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Abstract

It is widely accepted that the geomagnetic field is sustained by fluid motion in the Earth!s outer core, so-called the dynamo action. Paleomagnetic measurements have revealed that the geomagnetic field has reversed its polarity frequently. Many examples of such polarity reversals have been found in geodynamo simulations since Glatzmaier and Roberts (1995). The equatorially anti-symmetric flow is suggested to play an important role in polarity reversals (Olson *et al.*, 2004), while convective motions in a rotating spherical shell are dominated by the equatorially symmetric flow due to the effect of rotation. Consequently, any mechanism for growth of anti-symmetric flow is required when a polarity reversal occurs. In the present study, we aim at clarifying the mechanism that would work before and during polarity reversals.

We have performed a geodynamo simulation in a rotating spherical shell modeled on the Earth!s outer core. Dimensionless numbers are set to the Ekman number $E = 6\times10^{-4}$, the Prandtl number $Pr = 1$, the magnetic Prandtl number $Pm = 5$, and the modified flux Rayleigh number $Ra_f = 2000$. We have obtained numerical results producing 10 polarity reversals for 80 magnetic diffusion time.

We have analyzed energy fluxes transferred between the equatorially symmetric and anti- symmetric flows. The buoyancy flux for the anti-symmetric flow is found to be almost one-third of that for the symmetric flow when the axial dipole magnetic field is stable. Toward polarity reversals, the following processes have been observed. (i) The energy flux from the equatorially symmetric flow to the magnetic field decreases, (ii) the energy flux from the symmetric flow to the anti-symmetric flow by the advection increases, and (iii) the energy injection by the buoyancy into the anti-symmetric flow increases. As a result, the energy of the equatorially anti-symmetric flow increases during polarity reversals. The largest energy flux transferred to the anti-symmetric flow is found to be the energy flux due to the advection in 9 of 10 observed polarity reversals.

Keywords: Dynamo simulation, dipole reversal, energy balance

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Effects of the latent heat at the inner core boundary at ICB on the thermal structure in geodynamo simulations

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Abstract

Recent seismic observations suggest that inner core has a seismic anisotropy. These studies suggest aspherical growth of the inner core, and slow viscous deformation of the inner core and latent heat distribution by flow motion are expected to be the origin of the aspherical growth of the inner core. To explain inner core anisotropy and aspherical growth of the inner core, dynamo simulations have been performed with prescribed aspherical boundary conditions at ICB to take into account the inner core heterogeneity. In the present study, we investigate the effects of the latent heat on the thermal structure on the ICB using numerical simulations with a simple model.

We assume that the change of the position of ICB is proportional to the given radius of the average radius of the ICB. Under the present condition, the latent heat at ICB makes the thermal diffusivity at ICB smaller than that in the other area. Consequently, we perform dynamo simulations with changing the thermal diffusivity at ICB to be from 1.0 (no latent heat) times to $1x10^{-4}$ times of that in the other area. We started simulations from a snapshot in the quasi-steady state in a dynamo simulation with fixed homogeneous temperature condition to compare behaviors of Y_0^2 components of temperature at ICB due to the latent heat.

First, we compare responses by changing the ICB conditions at the beginning of the simulations. The Y_0^2 component of the temperature rapidly increases and decreases to the quasi-steady state in the all cases. There is only at most 2% of differences from the case without the latent heat.

We also compare the effects of the latent heat at the quasi-steady state with results without latent heat case and with fixed heat flux case. The average amplitude of Y_0^2 component in no latent heat case is approximately 0.78 times of that fixed heat flux cases. After introducing the latent heat, the Y_0^2 component of the temperature variation increases between 0.83 times 1.09 times of that of the fixed heat flux cases in the cases with less than 0.1 times of the thermal diffusivity at ICB.

Keywords: Dynamo simula-on, inner core boundary, latent heat

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Geomagnetic semblance and dipolar–multipolar transition in top-heavy double-diffusive geodynamo models

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Abstract

Convection in the liquid outer core of the Earth is driven by thermal and chemical perturbations. The main purpose of this study is to examine the impact of double-diffusive convection on magnetic field generation by means of 3-D global geodynamo models, in the so-called 'top-heavy' regime of double-diffusive convection, when both thermal and compositional background gradients are destabilizing. Using a linear eigensolver, we begin by confirming that, compared to the standard single-diffusive configuration, the onset of convection is facilitated by the addition of a second buoyancy source. We next carry out a systematic parameter survey by performing 79 numerical dynamo simulations. We show that a good agreement between simulated magnetic fields and the geomagnetic field can be attained for any partitioning of the convective input power between its thermal and chemical components. On the contrary, the transition between dipole-dominated and multipolar dynamos is found to strongly depend on the nature of the buoyancy forcing. Classical parameters expected to govern this transition, such as the local Rossby number—a proxy of the ratio of inertial to Coriolis forces—or the degree of equatorial symmetry of the flow, fail to capture the dipole breakdown. A scale-dependent analysis of the force balance instead reveals that the transition occurs when the ratio of inertial to Lorentz forces at the dominant length scale reaches 0.5, regardless of the partitioning of the buoyancy power. The ratio of integrated kinetic to magnetic energy E_k / E_m provides a reasonable proxy of this force ratio. Given that $E_k / E_m \approx 10^{-4}$–$10^{-3}$ in the Earth's core, the geodynamo is expected to operate far from the dipole–multipole transition. It hence appears that the occurrence of geomagnetic reversals is unlikely related to dramatic and punctual changes of the amplitude of inertial forces in the Earth's core, and that another mechanism must be sought.

Keywords: Composition and structure of the core; Core; Dynamo: theories and simulations;Magnetic field variations through time; Numerical modelling.

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Salt fingers and jets in non-rotating spherical shells

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Abstract

Convection in planetary fluid interiors is often driven by buoyancy sources of thermal and chemical origins. When chemical and thermal background gradients have opposing contributions to the stability of the fluid, the latter is prone to instabilities such as semi-convection or salt fingering. The main purpose of this study is to investigate the so-called 'salt fingers' regime, in which the potential energy is released from the chemical component, by means of 3D global non-rotating spherical shell models. To do so, we carry out a systematic parametric survey by computing 107 direct numerical simulations. We vary the Prandtl number (Pr) between 0.03 and 7, the Lewis number (Le) between 3 and 33, and the density ratio over the entire theoretical range of instability for salt fingering, i.e $1 \leq R_\rho \leq Le$. The first part of the study is focused on the primary instability triggered in this regime. In our model, the emergence of boundary layers leads to the attenuation of thermal and chemical contrasts in the fluid bulk. The spherical geometry induces an asymmetry between the upper and lower boundary layers, implying that physical diagnostic quantities such as the effective density ratio have to be defined on the fluid bulk. Considering the equilibrium between buoyancy sources and viscous dissipation, we derive scaling laws for the mean convective lengthscale and for the convective velocity which accurately describe the numerical data. By defining two asymptoticities close to the two edges of the instability range for salt fingering, we derive refined end-members scaling laws for convective velocity and transport of heat and chemical composition. In the second part of the study, we attempt to characterise a large-scale secondary instability observed in 43 of our models. In these simulations, we observe either the formation of a single jet or multiple jets of alternated directions. On longer times, we frequently observe a gradual merging of the multiple jets, possibly implying that the single jet solution would be the ultimate faith of the system. Even though we are not able to formally prove the instability conditions by means of a dedicated linear stability analysis, the jet formation is very much alike the instability put forward by Holyer (1984) in her analysis conducted in periodic plane layers. This implies that for a subset of parameters delimited by convective Reynolds number $Re > 20$ and ranges of density ratio which depend on Pr the formation of jets is the spontaneous way of saturating the salt finger primary instability.

Keywords: Numerical modelling, convection double-diffusive, salt finger regime, spherical shell

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Influence of the Prandtl number on geodynamo models

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Abstract

Convective motions that sustain the Earth magnetic field by dynamo action are driven by density perturbations of thermal and compositional origins. Depending on the relative fraction of buoyancy power coming from those two sources, the effective Prandtl number of the fluid outer core ranges from 0.1 to values larger than 100. To ease the numerical computations, the vast majority of geodynamo models have been conducted with a Prandtl number of unity. To explore the influence of this dimensionless number on dynamo action, we have carried out a systematic parameter survey changing the convective forcing -the Rayleigh number- from onset of convection to more than 200 times supercritical and the magnetic Prandtl number from 10^{-2} to 50 for a fixed Ekman number of 10^{-5} and Prandtl numbers equal to 0.1 and 10.

We show that for Pr = 0.1, onset of dynamo action leads to multipolar magnetic fields. An increase of the magnetic Prandtl number and/or the supercriticality leads to a parameter window of dipole-dominated solutions with magnetic energy exceeding kinetic energy. For Pr=10, inertia is much less influential and dynamo action sets in as dipole-dominated magnetic fields. Much larger supercriticalities are required to obtain multipolar dynamos and the ratio of magnetic to kinetic energy reach much larger values than for Pr=0.1. For both values of Pr, the dipole-dominated region of the parameter space is bounded at large convective forcing by a maximum Rayleigh number which increases with the magnetic Prandtl number. The dipole-multipole transition is controlled by the respective role of inertia and Lorentz force in the governing force balance, a quantity which can be approximated by the ratio of magnetic to kinetic energy. Measuring the Earth-likeness of the dynamo models in terms of their morphological semblance to the Earth magnetic field at the CMB, we show that Earth-like numerical models can be achieved for both Pr values though with a larger number of compatible solutions for Pr=0.1.

Keywords: Dynamo: theories and simulations -- Core -- Numerical modelling

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Extreme direct numerical simulation of dynamo action in a spherical shell

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Abstract

We report on a direct numerical simulation of rotating Boussinesq dynamo action in a spherical shell in which the flow is driven by an imposed temperature contrast between the outer and inner boundaries. The radius ratio is equal to 0.35, the boundaries are rigid, and the solid inner core is free to rotate in response to magnetic and viscous torques. Using the shell depth as length scale, the control parameters of the simulation are the following: Prandtl number = 0.2, magnetic Prandtl number = 0.03, Rayleigh number = 3×10^{11} (about 200 times critical) and Ekman number = 10^{-7}. The magnetic field is dipolar, maintained by a "strong-field" dynamo, in the sense that the magnetic energy is larger than the kinetic energy by an order of magnitude. The flow is highly turbulent (hydrodynamic Reynolds number ~ 15,000), with substantial activity occurring inside and near the rims of the so-called tangent cylinder. The force balance is of the QG-MAC type, noting that inertia becomes sizeable in the outer part of the fluid domain.

Upon time rescaling using the secular variation timescale of the non-dipole field, the simulation spans approximately ~ 5000 years. From a static morphological standpoint, the simulated field exhibits on average a marginal compatibility with the recent geomagnetic field. The compatibility is good over a time window of width ~ 1000 years. Taylorisation is sufficiently strong for torsional waves to propagate from the tangent cylinder outward.

Keywords: Dynamo:theories and simulations; Magnetic field variations through time; Rapid time variations; Numerical modelling

We acknowledge GENCI for access to the Irene resource (TGCC) under grants "Grand Challenge" GCH0315, A0060407382, and A0080402122.

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Dynamos in a Rapidly Rotating Full Sphere

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Abstract

The Earth's magnetic field has existed for 4 Gyr. Before the onset of crystallisation of the solid inner core, and for possibly 90% of Earth history, the relevant geometry was that of a full sphere. Numerical studies of the geodynamo in a full sphere are thus critical for understanding the paleomagnetic field. However, direct numerical simulations of the dynamo problem in a whole sphere has been rare, partially due to the difficulty of proper treatment of the singularity at the sphere centre. Using a fully spectral method with basis functions which are smooth everywhere, we run a series of numerical simulations to investigate dynamos in a whole sphere. For various Ekman numbers E, measuring the effect of viscosity compared to the Coriolis force, the dynamo regime dependence on the Rayleigh number Ra (measuring thermal forcing) and the magnetic Prandtl number Pm (controlling electrical conductivity) was determined, and we find it to be different from that of dynamos operating in a spherical shell. The regime of stable dipolar magnetic field seems to be narrower compared to the spherical shell case. We also report scaling analysis of the input/output quantities of our simulations.

Keywords: Earth's magnetic field, dynamo, full sphere

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Dynamos driven by inertial and columnar convection in spherical shells

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Abstract

We investigate the thermochemical convection and hydromagnetic dynamos in a spherical shell using the so-called codensity formulation. When the Ekman numbers are large, then inertial convection is preferred, while the large-scale columnar convection with prograde propagating modes is preferred for lower viscosity. Unlike the columnar convection, the inertial convection is found to be almost independent of the nature of the driving buoyancy source. Wall-attached modes are not developed for our parameters. For non-magnetic convection, not only retrograde propagating inertial modes are developed, but also prograde propagating ones. The existence of prograde propagating inertial modes is a new result not previously observed in previous analyses of inertial convection. For less overcritical convection the prograde flows occur rather at larger values of the Prandtl number while when convection gets more overcritical, the prograde flows exist for all the investigated values of the Prandtl number. Both prograde and retrograde flows are independent of the nature of the driving buoyancy source and in a given group also of the Rayleigh and Prandtl numbers as the codensity and velocity fields look similar. Only prograde flows (both inertial and columnar) drive hydromagnetic dynamos. Thus, the effect of Lorentz force is evident and it manifests in the preference of prograde inertial and columnar modes over retrograde ones. The generated magnetic fields are dipolar, strong-field and for the inertially driven dynamos, independent of the nature of the driving buoyancy source and also of the Prandtl numbers.

Keywords: inertial waves, spherical shell, dynamo, prograde flow, retrograde flow, Prandtl number

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Penetrative convection with heat sources in a spherical shell model of the Earth's core

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Abstract

The effect of stable stratified layer near the Earth's core-mantle boundary (CMB), on the outer core convection is investigated using a numerical model in spherical shell geometry with various thermal profiles. A radially varying heat source is incorporated to generate thermal profiles with the stable stratified layers. The thickness of stable stratified layers range from 200km-700km with varying intensities and boundary heat flux. Both the onset of convection and strongly driven convection is simulated for various control parameters such as the rotation rate and material properties. As the Ekman layer thickness becomes comparable with that of the stable layer the onset wave number changes to a higher value. As the thickness of stratified layer exceeds that of the Ekman layer, it is observed that the radial velocity profiles are restricted to deeper part of the spherical shell. And these restrictions is found to be latitudinally and longitudinally invariant.

Keywords: Stable stratified layer, Outer core convection, Wave number, Radial Velocity

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The effect of a thermally stratified layer in the outer core of Mercury on its internally generated magnetic field

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Abstract

The low intensity and lack of small-scale variations in Mercury's magnetic field can be explained by a thermally stratified layer overlying its convective liquid core. Its present-day existence is supported by thermal evolution studies that show that a sub- adiabatic heat flow at the core-mantle boundary can occur during a significant fraction of Mercury's history. The requirements for both the likely long-lived Mercury dynamo and the presence of a stable layer place important constraints on the interior structure and evolution of the core and planet.

We couple mantle and core thermal evolution to investigate the necessary conditions for a long-lived and present-day dynamo inside Mercury's core by taking into account an evolving stable layer overlying the convecting outer core. Events such as the cessation of convection in the mantle may strongly influence the core-mantle boundary heat flow and affect the thickness of the thermally stratified layer in the core, highlight the importance of coupling mantle evolution with that of the core. We employ interior structure models that agree with geodesy observations and make use of recent equations of state to describe the thermodynamic properties of Mercury's Fe-S-Si core for our thermal evolution calculations.

Keywords: Mercury, dynamo, interior structure

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The internal structure of Mercury's core inferred from magnetic observations

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Abstract

Previous models of Mercury's core magnetic field based on high altitude data from first MESSENGER flybys revealed an axisymmetric structure of the field. Here, we use low altitude MESSENGER data covering the entire mission period to construct spherical harmonic models based on various spatial norms. Although we find a dominantly axisymmetric field, our models nevertheless include detectable deviations from axisymmetry. These non-axisymmetric features appear at high latitudes, resembling intense geomagnetic flux patches at Earth's core-mantle boundary. Based on this core field morphology, we then attempt to infer Mercury's internal structure. More specifically, assuming that Mercury's high- latitude non-axisymmetric features are concentrated by downwellings at the edge of the planet's inner core tangent cylinder, and accounting for the presence of a stably stratified layer at the top of Mercury's core, we establish a relation between the inner core size and the thickness of the stratified layer. Considering plausible ranges, we propose that Mercury's inner core size is about 500–660 km, which corresponds to a stratified layer thickness of 880–500 km, respectively.

Keywords: Magnetic field, Mercury, dynamo, inner core tangent cylinder.

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Seismology on Mars: Analysis and identification of body-waves with implications for Martian structure

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Abstract

The InSight (Interior Exploration using Seismic Investigations, Geodesy and Heat Transport) mission has been collecting high-quality seismic data on Mars for over 1200 Martian solar days (sols), providing the first direct observations of its interior structure. In this study, we report on a complete analysis of low-frequency (LF) seismic events (main energy below 1 Hz), that have proven essential for understanding the deep interior of Mars [1], [3]–[5]. As Martian seismograms are generally characterized by a low signal-to-noise ratio and strong scattering, data selection and processing is central for the identification and consistent picking of body-wave arrivals. To this end, we employ complementary approaches, including: 1) narrow-band-filtered time-domain envelopes; 2) polarised waveforms and their time-domain envelopes; 3) polarisation analysis; and 4) waveform matching. The careful application of this 4-step processing scheme to each LF event has resulted in a significant increase in body wave phase picks, encompassing direct, reflected, and converted body waves, relative to earlier analyses [1]. With our method, all phases are obtained through iterative refinement, which relies on inverting an initial set of phase picks for models of interior structure, event distance, and depth, while predicting travel times for additional seismic phases. Based on the predictions, we re-pick (every pick is subject to our 4-step processing scheme), thereby enlarging our differential travel-time data set (all picks are relative to the main P- or PP-wave arrival), and subsequently re-invert for an updated set of interior structure models, event distances, and depths. Through application of iterative refinement to new seismic data, we continuously update information on radial velocity models of the crust, mantle, and core, as well as source parameters, and phase picks. The recent identification of the most distant marsquakes recorded by the InSight mission and the first core-diffracted P-wave [2] allow constraints on the P-wave velocity structure of the lower mantle that hitherto could not be constrained because of lack of lower-mantle-traversing P-waves. In addition, on sol 1222, InSight detected the largest event ever recorded on Mars, providing a unique opportunity to understand the interior of Mars through the identification of waves that could not be identified in earlier events because of their low signal-to-noise ratio. Our iterative refinement procedure demonstrates that through continued analysis of new events, our knowledge and understanding of the interior of Mars will steadily improve.

Keywords: Marsquakes, Mars' interior structure, Body waves, Receiver functions, Inversion

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Scanning for Planetary Cores with Single-Station Inter-Source Correlations

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Abstract

Global seismic imaging of the Earth's interior has come a long way in exploring and understanding the Earth's internal structure and dynamics with the worldwide proliferation of seismographs. However, investigating planetary interiors, especially their deep structures on a global scale, remains challenging due to the limited number of seismographs that will be deployed in the foreseeable future. Besides, the existing methods based on direct seismic wave observations require the presence of unambiguous seismic phases in seismograms. That restricts the seismic station locations to a limited angular distance range from the source in order to record reflecting and refracting seismic wavefields from internal planetary interfaces.

Here, we explore a new way to image deep planetary interiors using a single seismograph, especially scanning for the existence of the cores. We first develop a novel procedure for constructing global inter-source correlograms and show that they contain many prominent features sensitive to the Earth's and internal planetary structures. We show that a single station is sufficient to produce a global correlogram, in which all observed features exist due to the similarity of the seismic phases. We then utilize a single-station correlogram to demonstrate the steps for detecting and quantifying the Earth's and Mars' core interface. This provides a new way of imaging deep planetary interiors on a global scale.

Keywords: Planetary interiors, Cores, Single station, Global inter-source correlations

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Sublimation driven convection in Sputnik Planitia on Pluto

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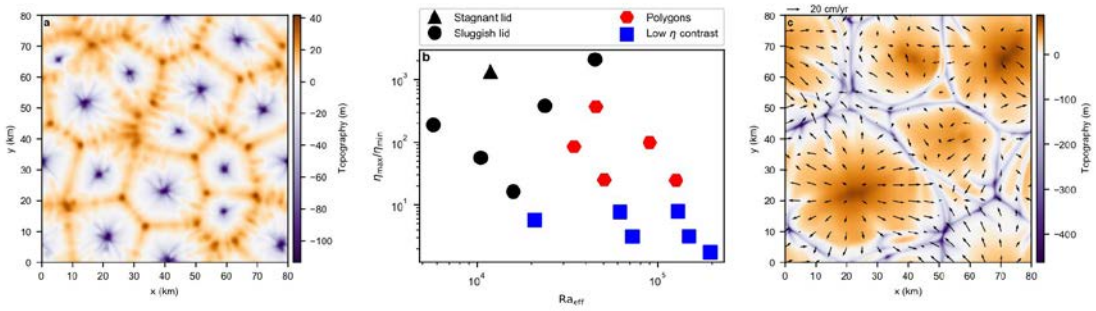
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Abstract

The flyby of Pluto by the New Horizons spacecraft in 2015 revealed stricking features in a nitogen ice filled basin named Sputnik Planitia (SP). On the large (few 10 km) scale, irregular polygons [1] have been interpreted as resulting from solid-state convection [2, 3], with down- welling currents at the polygons' edges [4]. It was first proposed that convection was driven by heating from below, associated with radioactivity in Pluto's core but it produces a flow that is opposite to the observations with upwelling currents at polygons' edges [5] (fig. 1a). At the small scale, we can observe pits that have been explained as produced by sublimation of nitrogen ice. The development of this pattern when getting toward the polygons' sides has been used to estimate the flow velocity on several polygons, of the order 10 cm yr^{-1} [4]. We proposed [6] that sublimation is also at the origin of convection by cooling the surface: sublimation consumes latent heat which results in the surface of SP being ~ 5 K colder than the surroundings [7].

We developed a theory to take into account sublimation in a convection model and showed that it leads to a mixed-type (Robin) thermal boundary condition which, in the case of SP is close to that of a fixed temperature. Starting from a uniform temperature in the ice layer, imposing a colder surface value leads to cooling and convection. With the best estimates of the various parameters for SP, a Rayleigh number of order 10^5 can be obtained, justifying the possibility of convection. We used a mantle convection model to explore systematically the effect of surface cooling on convection in a temperature-dependent viscosity solid. Depending on the Rayleigh number and the viscosity contrast, we obtain different regimes (fig. 1b), including one with polygons that match the observations of SP (fig. 1c). The five cases that we obtained in that regime can be used to explore the relationships between observed quantities, like the polygonal sizes, and unconstrained ones, like the thickness of the ice layer or the amplitude of topography [6]. Such large-scale dynamics of a solid state layer driven by climate is unprecedented in the knowledge of planetary bodies but might also operate on other volatile rich moons and Trans-Neptunian objects.

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Keywords: Pluto, nitrogen ice, convection.

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The tidal-thermal evolution of the Pluto–Charon system

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Abstract

The existence of subsurface oceans on the satellites of the giant planets and Trans-Neptunian objects has been predicted for some time. Liquid oceans on icy worlds, if present, exert a considerable influence on the dynamics of the ice–ocean system and, because of the astrobiological potential, represent an important objective for future missions to the outer solar system. The Pluto–Charon system is representative of an icy moon orbiting a dwarf planet that is believed to have formed from the remnants of a giant impact. The evolution of icy moons is primarily controlled by the mode and efficiency of heat transfer through the outer ice shell, which is influenced by the presence of impurities, by tidal dissipation in the ice shell, and by the radioactive element budget in the silicate core. Previous studies on the evolution of the Pluto–Charon system generally considered either only the thermal or the tidal evolution, and in the cases where both were considered, the important effect of the presence of impurities in the liquid oceans was not addressed. Here, we consider the joint tidal– thermal evolution of the Pluto–Charon system by combining a comprehensive tidal model that incorporates a viscoelastic description of the tidal response with a parameterized thermal convection model developed for icy worlds. This approach enables an extensive analysis of the conditions required for the formation and maintenance of subsurface liquid oceans up to the present. Our results show that because of relatively fast circularization and synchronization of the orbits of Pluto and Charon, tidal heating is only important during the early stages of evolution (<1 Myr). As part of our study, we test the sensitivity of our results to a number of parameters that pertain to the orbital and thermal history. In all the studied cases, oceans on Pluto are always predicted to remain liquid to the present, ranging in thickness from 40 km to 150-km, whereas oceans on Charon, while in-place for approximately 4 Gyr, have solidified. This is supported by New Horizons observations of primarily extensional faults on Pluto and both extensional and compressional faults on Charon.

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Cooling patterns in rotating thin spherical shells — Application to Titan's subsurface ocean

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Abstract

We use rotating convection simulations in a thin spherical shell to study fluid dynamics in subsurface oceans of icy moons. We find two types of persistent results, characterized by larger outer boundary heat flux either at polar regions or at the equatorial region. Simulations corresponding to larger Rossby numbers result in polar cooling with moderate lateral heterogeneity in heat flux, whereas lower Rossby numbers give equatorial cooling with more pronounced heat flux heterogeneity. The polar cooling scenario is in agreement with inferences for the heat flux at the top of Titan's ocean, which may provide a dynamical constraint for the vigor of convection in this layer. Our results may help unraveling the internal dynamics and the interactions among the different layers within the hydrosphere of Titan. Possible implications for the deep interiors of other icy moons are envisaged.

Keywords: Icy moons, subsurface ocean, convection, rotation, heat transfer.

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Heat transfer in the ocean of Enceladus: connecting unconsolidated core and surface ice shell

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Abstract

Observations from the Cassini spacecraft imply the presence of a global salty ocean underneath Enceladus' ice shell, with ongoing hydrothermal activity at its seafloor. Previous numerical simulations showed that convection in Enceladus' unconsolidated core generates enough dissipation to sustain the ocean and produces a strongly heterogeneous heat flow pattern at the seafloor that looks promising for explaining the surface ice topography. Yet, how the ocean in-between connects the deeper core to the surface ice shell is unknown. The dynamics of the ocean is thus the missing piece of the Enceladus puzzle towards a fully self-consistent model of the heat transfer in this moon. We fill this gap by performing 3D numerical simulations of the buried ocean of Enceladus. We show that, for the strongly heterogeneous heat flow pattern expected at the seafloor from the unconsolidated core model, azimuthal deflection of strongly localized plumes by the Coriolis force inhibits the heat transfer at low latitudes. The resulting heat flow pattern at the ocean/ice interface is qualitatively consistent with the surface ice topography and in decent quantitative agreement with an ice shell model derived from observations. Using passively advected tracers particles, we predict rising times for hydrothermal products of the order of 1-2 months, in line with previous observations-based predictions. We are thus now able to draw a complete self-consistent model of the heat transfer in Enceladus, explaining the global characteristics of this moon: global ocean, strong dissipation, reduced ice-shell thickness at the south pole and seafloor activity.

Keywords: Enceladus, oceanic convection, heat transfer, heterogeneous boundary conditions

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Thin-Shell Dynamos with Underlying Solid Superionic Layers

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Abstract

Fluid turbulence and vigorous convection in an electrically-conducting liquid region, called the dynamo region, drives magnetic field generation from inside a planet. While the magnetic fields of the other planetary bodies in our Solar System are dipolar, Voyager 2 observations revealed that the magnetic fields of Uranus and Neptune are multipolar. My work attempts to understand the origins of the multipolar shape. Prior studies inferred that the dynamo regions in Uranus and Neptune are very thin and near the planetary surface. Interior structure models for water-rich planets suggest that the thickness of the dynamo shell may be between r_{io} = 0.70 to r_{io} = 0.85 (r_{io} is the ratio between the inner and outer radii of the thin shell). Studies have suggested that the "superionic" material is up to 100 times more electrically conductive than the dynamo shell. It is uncertain whether the superionic material behaves like a solid, stably- stratified liquid, or convecting liquid at the pertinent planetary depths. Using the code MagIC, we have run numerical magnetohydrodynamic simulations of thin-shell dynamos above a superionic layer as a proxy for observations of Uranus/Neptune-like magnetic fields. We assumed that the superionic layer behaves like a solid and tested what happens to the simulated magnetic field when we vary the dynamo shell thickness and increase the electrical conductivity of the superionic layer up to 100 times that of the dynamo region.

Keywords: magnetohydrodynamics, dynamo, superionic, thin-shell, Uranus, Neptune

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An assessment of implicit-explicit time integrators for the pseudo-spectral approximation of Boussinesq thermal convection in an annulus

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Abstract

We analyze the behavior of an ensemble of time integrators applied to the semi-discrete problem resulting from the spectral discretization of the equations describing Boussinesq thermal convection in a cylindrical annulus. The equations are cast in their vorticity-streamfunction formulation that yields a differential algebraic equation (DAE). The ensemble comprises 28 members: 4 implicit-explicit multistep schemes, 22 implicit-explicit Runge-Kutta (IMEX-RK) schemes, and 2 fully explicit schemes used for reference. The schemes whose theoretical order varies from 2 to 5 are assessed for 11 different physical setups that cover laminar and turbulent regimes. Multistep and order 2 IMEX- RK methods exhibit their expected order of convergence under all circumstances. IMEX-RK methods of higher-order show occasional order reduction that impacts both algebraic and differential field variables. We ascribe the order reduction to the stiffness of the problem at hand and, to a larger extent, the presence of the DAE. Using the popular Crank-Nicolson Adams-Bashforth of order 2 (CNAB2) integrator as reference, performance is defined by the ratio of maximum admissible time step to the cost of performing one iteration; the maximum admissible time step is determined by inspection of the time series of viscous dissipation within the system, which guarantees a physically acceptable solution. Relative performance is bounded between 0.5 and 1.5 across all studied configurations. Considering accuracy jointly with performance, we find that 6 schemes consistently outperform CNAB2, meaning that in addition to allowing for a more efficient calculation, the ac- curacy that they achieve at their operational, dissipation-based limit of stability yields a lower error. In our most turbulent setup, where the behavior of the methods is almost entirely dictated by their explicit component, 13 IMEX-RK integrators outperform CNAB2 in terms of accuracy and efficiency.

Keywords: Boussinesq convection; Pseudo-spectral methods; Sti*ff* ODE/PDE/DAE time marching; IMEX time integrators; Stability; Turbulence

Gopinath, V., Fournier, A., & Gastine, T., 2022. An assessment of implicit-explicit time integrators for the pseudo-spectral approximation of Boussinesq thermal convection in an annulus, *J. Comp. Phys.*, 110965 (34 pp). doi : 10.1016/j.jcp.2022.110965

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An experimental anisotropic dynamo called Fury

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Abstract

We have built an experimental dynamo with 40 kg of copper, that can be human powered with a minimum of 230 Watt. It consists in a rotor/stator setup and produces an axisymmetric magnetic field. These apparent violations of Cowling's theorems have been made possible by cutting grooves in the copper pieces, so that their electrical conductivity can be considered as anisotropic. This experiment is an illustration of recent theoretical models we have developed with materials of anisotropic conductivity. Explicit analytical solutions of the critical rotation rate or of the growth rate of the magnetic field can be obtained with anisotropic conductivity and localized shear velocity, making it the simplest dynamo solution. In the deep interior of the Earth, it is definitely possible that the electrical conductivity of the inner core possesses some degree of anisotropy. In plasmas (stars, galaxies, …), such an anisotropic model could be suitable, either because of oriented small scale heterogeneities or because of the magnetic field itself. Another purpose of this experiment is to get a direct feeling of dynamo action. It is a rather small setup and we hope we can bring it to the SEDI conference so that anybody interested can produced her or his own "green", "sustainable", magnetic field. The name Fury– thanks to Andy Jackson for the suggestion – makes reference to a property of that dynamo in a regime that is certainly difficult to access. Suppose all parameters of the dynamo are kept constant (rotation rate, size) except for its electrical conductivity that could hypothetically be increased as much as desired, then the growth rate of the self-generating magnetic field would increase without upper bound compared to the growth rate. We called this property 'very fast' or 'furious', while in the existing terminology a 'fast' dynamo would have a non- zero limit for the growth rate and a 'slow' dynamo would have a growth rate converging toward zero, still compared to the rotation rate.

Keywords: Dynamo, anisotropy, experimental setup

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A drunk man's walk amidst measurement techniques used in MHD experiments

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Abstract

This poster accompanies the keynote lecture on experiments that I will present on the last day of our Symposium. The idea is to list and illustrate some of the numerous measurement techniques that have been developed or used in MHD experiments. I will highlight the pros and cons of these techniques, and provide some examples of their fruitful use in recent publications.

I thus hope to clarify for the non-specialists what acronyms such as UDV, PIV, MAV and others mean, while fostering exchange and debate among the specialists.

Keywords: MHD; UDV; PIV; MAV; lab experiments; geophysical fluid dynamics

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Thermoelectric Liquid Metal Magnetoconvection

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Abstract

Thermoelectric (TE) properties at the core-mantle boundary (CMB) and TE-induced core flow dynamics remain poorly understood. TE currents have long been proposed to drive dynamos in the interior of planets (e.g. Stevenson, 1987; Giampieri & Balogh, 2002), and generate toroidal field that potentially explains inclination asymmetry in paleomagnetic data between normal and reversed fields (Runcorn, 1954; Merrill et al. 1979, 1990). However, pre-vious estimates of TE-induced field strength is simply too small, and TE-induced dynamics in the vicinity of CMB (or ICB) has yet been discussed in depth. Thus, we have developed a two-metal laboratory experimental model to simulate TE effect at the core-mantle interface.

We conducted a series of laboratory surveys in a turbulent Rayleigh-B´enard convec-tion system with a vertical imposed magnetic field. Two sets of boundaries, one electrically conducting and one electrically insulating, are used to investigate the TE effects on the sys-tem. We performed thermal measurements at a fixed buoyancy forcing and varying magnetic forces in a cylindrical cell filled with liquid gallium. A tank-scale overturning circulation de-velops in most of the experiments. This large-scale circulation slowly precesses in azimuth in the subcases which have electrically conducting boundaries, as magnetic Lorentz forces be-come comparable to buoyant inertial forces. This novel magnetoprecessional mode reverses its orientation when the magnetic field reverses its polarity. We develop a simple analytical model that predicts the TE magnetoprecession frequency.

Extrapolating our results to the Earth's core, we provide estimates of the material properties based on up-to-date thermal and electric conductivity of the CMB that needed to generate TE dynamics. In particular, we postulate mega-ULVZs are well-suited to drive TE core dynamics. Further, should thermoelectric processes drive core flows in the vicinity of the CMB (or ICB), TE currents will alter the velocity field and thus change the magnetic field via u × B term in the induction equation. Such TE-drive flows should reverse their direction when the geomagnetic field reverses, providing a natural symmetry breaker between normal and reversed geomagnetic field orientations. This new mechanism is more efficient in explaining the polarity asymmetry in paleomagnetic data than toroidal field generated by the TE current loop. A better understanding of Seebeck coefficient, lateral thermal gradients, electric and thermal conductivity at the CMB will help better characterize the TE dynamics in future studies. This study is reported in our latest paper: Xu, Y., Horn, S., & Aurnou, J. M. (2022). Thermoelectric precession in turbulent magnetoconvection. Journal of Fluid Mechanics, 930.

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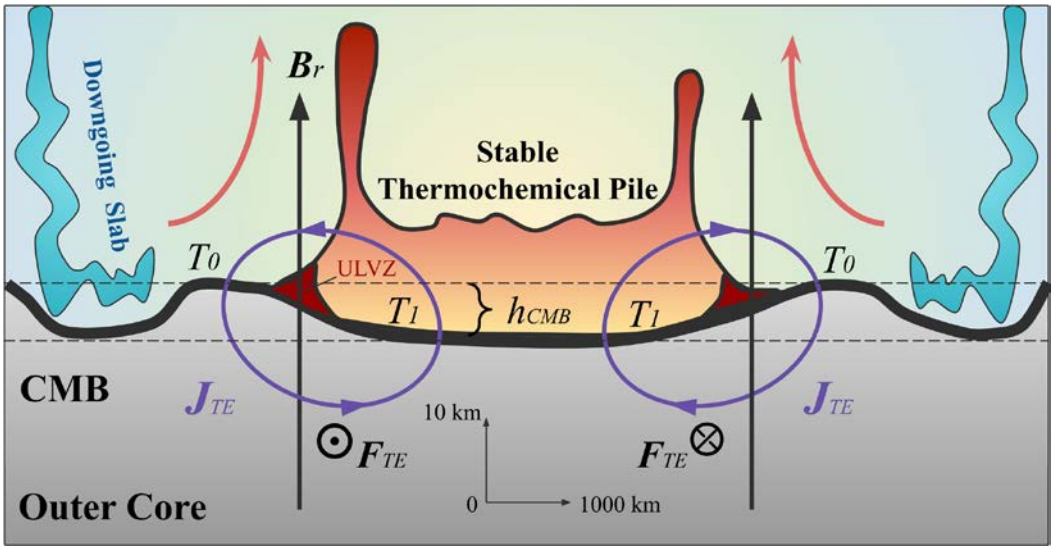


Figure 1: Schematic adapted from Garnero *et al.* 2016 and Deschamps *et al.* 2018 showing thermoelectric currents $\boldsymbol{J}_{TE}$ and forces $\boldsymbol{F}_{TE}$ in the vicinty of the core-mantle boundary (CMB). The vertical scale is considerably exaggerated. The black arrows are radial magnetic field, $B_r \sim 19$ gauss. The temperature contrast between the thermochemical pile or the ULVZs and the surrounding mantle is denoted by $T_1 - T_0 = \Delta T_p$.

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Liquid metal convection experiments

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Abstract

The flow in the Earth's outer core consists of liquid metal and consequently has a very low Prandtl number (Pr). The very high thermal conductivity of liquid metals quickly vanishes out any small-scale temperature gradient. The flow behavior of convective systems thus differs significantly from fluids such as air or water. Experiments and numerical simulations at very low Prandtl numbers are extremely demanding, but can be a helpful tool to learn more about the flow processes in the liquid Earth's core. We present two liquid metal experiments at Pr =0.03 that demonstrate that the flow dynamics at such low Prandtl-numbers differ significantly from moderate Pr fluids under comparable physical conditions.

In a recent experiment with strongly turbulent liquid metal convection, we found a surprising collapse of the coherent large scale flow. The reconstruction of the three-dimensional flow pattern by 17 ultrasound Doppler velocimetry sensors detecting the velocity profiles along their beam lines in different planes reveals a clear breakdown of coherence of the large-scale circulation for $\Gamma = 0.5$. As a consequence, the scaling laws for heat and momentum transfer inherit a dependence on the aspect ratio. We show that this breakdown of coherence is accompanied with a reduction of the Reynolds number Re. The scaling exponent β of the power law $Nu \propto Ra\beta$ crosses eventually over from $\beta = 0.221$ to 0.124 when the liquid metal flow at $\Gamma=0.5$ reaches $Ra \gtrsim 2\times10^8$ and the coherent large-scale flow is completely collapsed.

In an experiment with rotating liquid metal convection we found strongly inertial, thermal wind flows, with velocities reaching those of non-rotating cases. Oscillatory bulk convection and wall modes coexist across a wide range of our experiments, along with strong zonal flows that peak in the Stewartson layer, but that extend deep into the fluid bulk in the higher supercriticality cases. The flows contain significant time-mean helicity that is anti-symmetric across the midplane, demonstrating that oscillatory liquid metal convection contains the kinematic components to sustain system-scale dynamo generation.

Keywords: Liquid metal, Experiments, Convection

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Experiments on penetrative convection

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Abstract

Penetrative convection regards the interaction between a convective and a stable density stratified layer and is relevant in various astrophysical and geophysical applications, such as the excitation of waves in the stably stratified upper atmosphere by the convective lower troposphere. In the context of Earth's interior dynamics, the core is known to be in a convective state that sustains the Earth's magnetic field by dynamo action. Although seismology does not yet bring a definite answer, a stably stratified layer on the top of the core may exist since the Earth's origin, as current estimations of the core thermal conductivity would lead to an excessive heat flux coming out of the core to sustain a fully convective region. Against this background, it is important to understand what kind of motion can exist in a potentially stable layer excited by a convective region. To help answer key questions relative to penetrative convection, an experimental setup was built to investigate the interaction of a stably stratified layer with a convective region. Salty stratification was used with concentration increasing in the direction of gravity. Lighter fresh water is then slowly introduced from the bottom of the cavity, creating the convective region. The velocity of the convective interface advancing in the stable regions was investigated. The presence of gravity waves in the stable region was also observed using Schlieren technique, and will also be presented. These investigations are the first step before looking at these phenomena on a rotating experimental setup, that is now in its final phase of construction. The experimental task is made more difficult in a rotating frame but is important to be performed in a planet's interior context due to Coriolis forces in the core, that become strong when compared to the ocean or atmosphere applications, for example. These future investigations on a rotating frame will also create a rich environment in terms of physical processes, such as rotating convection, and the presence of Inertial-gravity waves due to the stratification and rotation.

Keywords: Penetrative convection; Buoyancy-driven instability; Internal waves; Stratified flows

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Turbulent super-structures in Rayleigh-Bénard convection: a new laboratory experiment at very large aspect ratio

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Abstract

Thermal convection caused by temperature difference across a fluid layer has been proposed to be one of the forcing behind many of geophysical flow dynamics such as in the Earth outer core, other planetary fluid cores or atmospheres or in the Sun. Rayleigh-Bénard convection is one of the classical problem that allows to approach natural systems subject to temperature difference. The classical problem consists of a fluid layer heated from below and cooled from above at given constant temperatures. When thermal forcing is strong enough, as defined by the Rayleigh number, flow occurs, first in roll-like structures and then can become turbulent, reorganizing itself in large-scale structures.

We are building a new experimental setup to study coherent structures in turbulent Rayleigh-Bénard convection. The setup is a square box of 1m x1m x 4cm, filled with the metallic eutectic alloy GaInSn, to match the high thermal conductivity (low Prandlt numbers) found in the geophysical systems of interest. Both top and bottom enclosures are made of copper to optimize heat distribution while lateral walls are made from polymere plastic for thermal insulation. The overall size is chosen so that the aspect ratio ($\Gamma = L/H$) is large enough to ensure minimum influence from the lateral boundaries, in our case Γ =25. In order to follow and characterise the emerging structures, the setup is then instrumented for temperature and velocity measurements with thermocouples and ultrasound transducers respectively.

Keywords: Thermal convection, turbulence, laboratory experiment, liquid metal

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Paraboloidal free-surface experiments for planetary core-style convective flows

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Abstract

We present a novel experimental platform for modeling turbulent convection outside the tangent cylinder of fluid planetary cores. Our device, the Coreaboloid, uses an imposed thermal gradient and a rotating paraboloidal free surface to produce the key features of planetary core hydrodynamics: rotational forces, convective turbulence, and topographic β effects. As proof of concept, we conducted three experimental cases at 35, 50, and 60 revolutions per minute (rpm). Using ultrasonic Doppler velocimetry and thermographic imaging, we identify thermal Rossby waves and multiple zonal jets, which extend in radius in proportion to the Rhines scale and migrate outwards in accordance with prior scaling estimates. The agreement of these results with models of rapidly rotating convection further demonstrates Coreaboloid's efficacy as an experimental platform for studying core flow. Our next steps include quantifying the thermal wind flow via axisymmetric models and implementing a thermal image velocimetry system. These improvements to both our theoretical and observational framework will facilitate our future studies with Coreaboloid.

Keywords: Turbulent convection, experiments, zonal jets

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Effect of Prandtl number on rotating convective turbulence

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Abstract

Rotating convective turbulence is ubiquitously found across geophysical settings, such as surface and subsurface oceans, liquid planetary cores, magma chambers, magma oceans, and basal magma oceans. Depending on the thermal and material properties of the system, buoyant convection can be driven thermally or compositionally, where a Prandtl number ($Pr = \nu/\kappa i$) defines the characteristic diffusion properties of the system, with $\kappa i = \kappa T$ representing thermal diffusion and $\kappa i = \kappa \xi$ representing chemical diffusion. These numbers vary widely for geophysical systems; for example, the liquid iron experiencing thermal-compositional convection in Earth's core is defined by $PrT \approx 0.01$ and $Pr\xi \approx 100$, while a thermally-driven liquid silicate magma ocean is defined by $PrT \approx 100$. Currently, most numerical and laboratory data for rotating convective turbulent flows exists at $Pr \leq O(1)$, which can explore the pure thermal end-member of liquid metal convection relevant to planetary cores. However, large Pr rotating convection relevant to compositionally-driven core flow and other systems is not commonly studied. Here, we seek to address this deficit by carrying out experiments in water and silicone oil (Pr = 7, 40, 210, and 1000) and comparing the results to those done in liquid gallium (Pr = 0.025). Using measurements of flow velocities (Reynolds, Re) and heat transfer efficiency (Nusselt, Nu), we find that a thermal wind balance dominates the turbulence regardless of Pr number as long as Re is sufficiently large ($Re \gtrsim 10$). As many planetary flow systems are expected to have a large Reynolds number, we also present Pr-dependent scaling arguments for rotating and non-rotating convection that can be utilized in studies of geophysical systems existing at any Pr number.

Keywords: Turbulence, convection, experiment

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A laboratory model for iron snow in planetary cores

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Abstract

Top-down solidification has been suggested in the liquid cores of small planets, moons, and large asteroids. An iron snow is then thought to exist, consisting of the crystallization of free iron crystals at the top of these cores and of their settling in a stably stratified ambient, until they remelt in a hotter, deeper region. This inward crystallization and associated buoyancy flux may sustain dynamo action by convection below the remelting depth. However, thermal evolution models are up-to-now oversimplified, assuming a constant-in-time and homogeneous-in-space buoyancy flux at the bottom of the snow zone. We have shown from analog experiments that the buoyancy flux is heterogeneous in time and space, with intense snow events, corresponding to an explosion of frazil-ice, separated by quiescent periods when the snow zone supercools. The presence of supercooling during the growth phase challenges the thermodynamic equilibrium hypothesis underlying the evolution models. We also found that a wide range of crystal sizes exists, with large crystals overshooting the convection region. The contributions from all crystals sizes to the mass flux seem to be important. Therefore, the spatiotemporal variability of the buoyancy flux, providing energy source for the dynamo action, would impacts the shape and intensity of the generated magnetic field. It may provide alternative explanations for the observed and surprising features of Mercury's and Ganymede's magnetic fields.

Keywords: inward crystallization, iron snow regime, magnetic field, lab experiments

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Mixing in a turbulent thermal and implications for metal-silicate equilibrium during Earth's formation

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Abstract

During the differentiation of terrestrial planets, the metal phase from the impactor core segregates from the silicate phase of the magma ocean. This buoyant mass forms a turbulent thermal and settles toward the proto-core. During this descent, thermal and chemical exchange occurs at the boundary between the metallic and silicate phases. Turbulent motions induce stirring of the metallic phase and entrainment of silicates. However, homogenization between the two phases only occurs when the metallic phase reaches the diffusive length scale, where mass or heat transfer became irreversible. Based on laboratory fluid dynamic experiments and on 3D direct numerical simulations mimicking the settling of the metallic thermal turbulent, we develop a Lagrangian approach of the mixing from the velocity field. 3D simulations strengthen the results obtained from the experimental dataset which is only 2D. We can track the evolution of the material elongated as lamellae by the turbulent stirring. We have characterized the elongation rate, the aggregation of lamellae, and the probability density function of the elongation and concentration, which are not accessible from direct measurements in the experiments. We have also investigated the effect of the Reynolds number on these quantities. These results will allow us to develop a new predictive model of mixing and chemical transfer in turbulent thermals to better understand the equilibrium between metals and silicates during the accretion of terrestrial planets.

Keywords: mixing, Lagrangian approach, metal-silicate equilibrium, Earth's accretion

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Experiments on oblique planetary impacts

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Abstract

The basic structure of the terrestrial planets - an iron-rich metallic core surrounded by a silicate mantle - has been set during the accretion of the planets, when the high temperature has allowed the metal and silicate phases to melt and separate. The transfer of chemical elements and heat between the metal and silicates that occurred during the differentiation is critical for the composition and initial temperature of the core and mantle. Most of the chemical and heat transfer probably occurred in magma oceans following the impact of large planetary bodies onto the Earth; we focus here on quantifying the dispersion of the impactor material induced by its impact onto the growing planet.

We have developed an experimental set-up designed to model oblique planetary impacts, using liquids of different densities (aqueous solutions of various salts) to model the impactor and magma oceans. Our set-up allows to vary the impact angle from ~15 degrees (grazing impacts) to near vertical.

We have carried out experiments at various impact angle, Froude numbers, and density ratios, to explore and quantify the effect of the impacting angle on the shape of the impact crater, and on the dispersion of the impacting material. The range of Froude numbers explored here ($5<Fr<50$) is relevant for the modelling of the impact of large planetary bodies. Our experiments show that the effect of impact angle is significant, low angle impacts resulting in a higher amount of dispersion than vertical impacts. The trajectory and dispersion of the impacting material are well described by a model of turbulent thermal with an initial velocity having a non-zero horizontal component. The model allows to propose a parametrization of the dispersion as a function of impact angle and Froude number.

Keywords: planetary formation, core/mantle differentiation, impact, dispersion

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Metal fragmentation by large Earth-forming impacts

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Abstract

The fragmentation of metal during Earth-forming impacts controlled the chemical equilibration between metal and silicates, and hence the composition of the core and mantle. Knowing the degree of fragmentation of the impactor core is important to date the formation of the Earth's core from isotopic data.

The final stage of Earth's accretion involved high-energy collisions between planetary embryos. During each collision, the metallic core of the impacting embryo fell in a molten silicate magma ocean. Recent fluid dynamics investigations showed that, as it fell in the ocean, the impactor core fragmented into subcentimetric drops. However, previous studies on this fragmentation process lack an impact stage. Hence, it is unclear whether the impactor core can fragment during the impact, prior to its fall in the magma ocean.

To answer this question, we conduct a series of experiments on the impact and fragmentation of a liquid volume into a lighter immiscible liquid. The liquid volume represents the impactor core while the liquid target represents the magma ocean. In our experiments, the impact produces a crater which collapses into a jet, as observed in numerical simulations of impact cratering.

We vary the impactor velocity and size to investigate the conditions under which the impactor fragments into drops during the collapse of the crater. When the impact inertia is comparable to gravity, the impactor remains coherent during the impact. In contrast, when inertia is large compared to gravity, the impactor fragments into droplets prior to its fall in the liquid target.

Applied to planetary impacts, these results suggest that the core of impactors less than 100 km in diameter fully fragmented into droplets, whereas the core of giant Moon-forming impactors fragmented only partially.

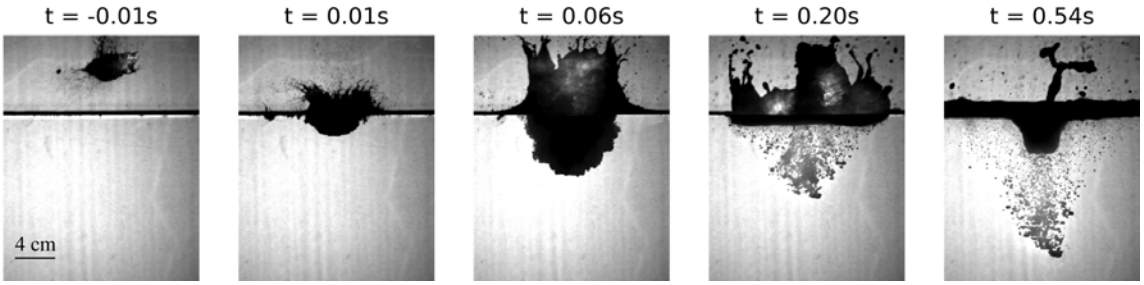


Figure 1: Experiment on the impact of a liquid volume into a lighter immiscible target pool modelling the large impacts that formed the Earth.

Keywords: Giant impacts, core formation, metal-silicate equilibration, liquid fragmentation, laboratory experiments, fluid dynamics.

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The fragmentation and drop size of liquid metal in magma oceans during Earth's formation

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Abstract

The formation and differentiation of the Earth set the initial temperature and composition for its later evolution. The Earth formed by high-energy collisions. Following each impact, the metallic core of the impactor fell in a molten silicate magma ocean. Previous fluid dynamics experiments showed that, in this ocean, the impactor core fragmented into a cloud of iron drops at depths $2-4$ times the impactor radius. However, what controls the size of these metal drops remains unclear. This drop size controlled the chemical equilibration of metal and silicates, and hence the composition of Earth's core and mantle.

To investigate the size of metal drops in magma oceans, we use laboratory experiments where a piston injects a volume of aqueous solution (representing the impactor core) into a pool of silicone oil (representing the magma ocean). We vary the Weber number, which measures the importance of inertia to interfacial forces, reaching values nearly two orders of magnitude larger than previous studies. We observe that the released liquid entrains ambient fluid into a ring, inside which it fragments into drops. We obtain a scaling law for the drop size as a function of the Weber number. This scaling agrees with theoretical predictions in a turbulent flow. Applied to planet formation, our results predict that the impactor core fragments into millimeter-sized drops, implying that the metal drops fully equilibrate with the silicates that they entrain.

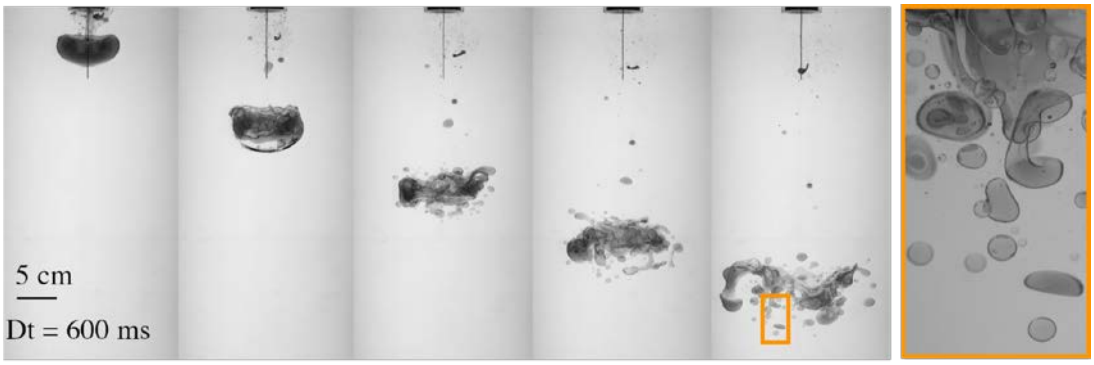


Figure 1: *Fragmentation of a liquid into a lighter immiscible liquid to model the frag- mentation of liquid metal into a magma ocean.*

Keywords: core-mantle differentiation, core formation, metal drop size, liquid fragmentation, magma ocean, metal-silicate equilibration.

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New technical concepts for the laser heated DAC

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Abstract

We present a few new concepts and recent developments in two laser heating systems for the generation of extreme temperature and its measurement in diamond anvil cell experiments. These concepts are based on the 90° off-axis mirror parabolic mirror, whose potential as reflective imaging objective has been demonstrated one year ago (Spiekermann et al. 2021, High Pressure Research).

With the here presented concepts, CO2 laser heating becomes more accessible and temperature measurements in the laser heated diamond anvil cell become more reliable.

Keywords: diamond anvil cell, high pressure, laser heating, mantle conditions

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