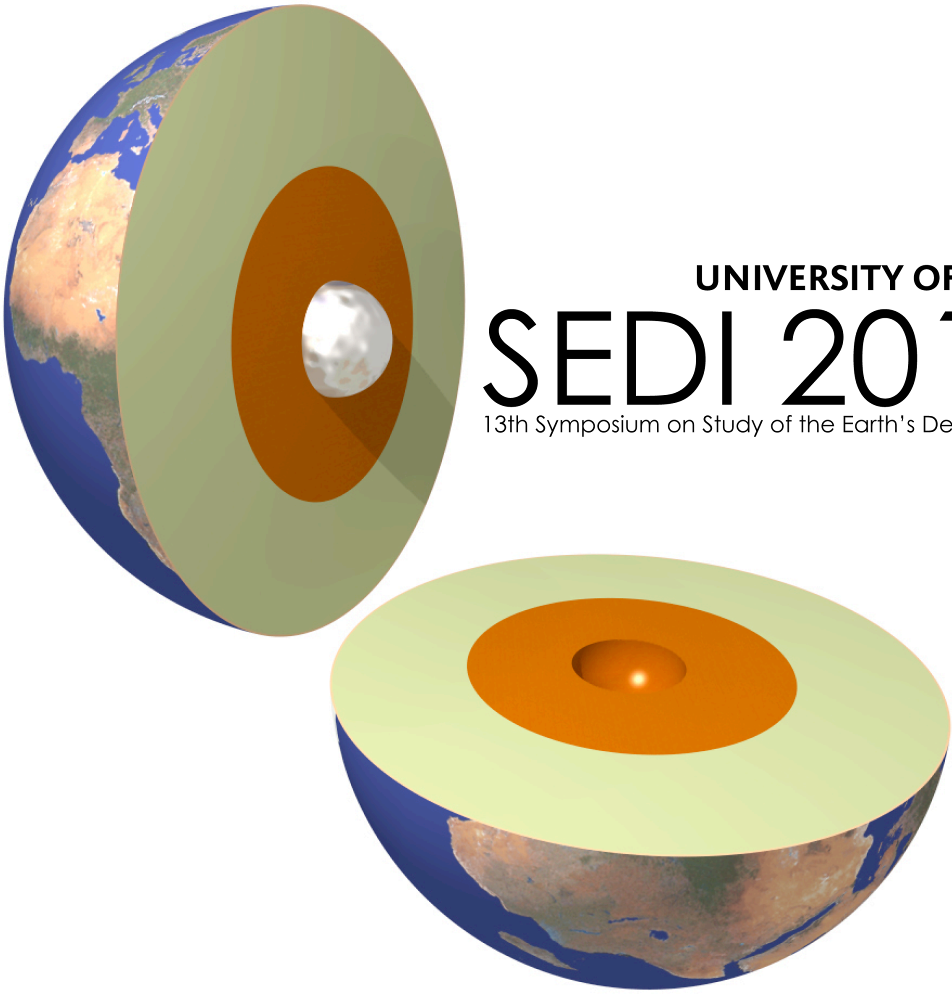

UNIVERSITY OF LEEDS

SEDI 2012

13th Symposium on Study of the Earth's Deep Interior

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Contents

Foreword

Welcome to Leeds and the 13th Symposium on Study of the Earth's Deep Interior. The scientific sessions will be held on the University of Leeds campus, just northwest of Leeds city centre. On Wednesday afternoon there will be an outing to the historic city of York, culminating in the conference dinner at the National Railway Museum. The olympic flame recently passed through Leeds in the lead up to the London summer olympics, and we also recently celebrated the Queen's diamond jubilee. In many ways, the SEDI meeting is then the third highlight of the year! Indeed, it is a special year for SEDI, the 25th anniversary of being a union committee of the IUGG. During these last two and a half decades, the SEDI symposia have been an important international gathering of scientists from all disciplines to meet, discuss, debate and collaborate.

Advancing our understanding of the deep Earth, and the interior of other planets, requires the integration of results from multiple disciplines and multiple approaches. We have generally organised the meeting into sessions focussed on contributions to understanding the composition, structure and dynamics of a given region. A small number of invited talks will provide overviews for each session, including some recent results. Posters will be on display all week, which in combination with the general discussion sessions represent the heart of the meeting; we hope that everyone will contribute to these opportunities for open and wide-ranging discussion.

A number of organisations have provided funding towards this conference. Much of this support has been used to support young scientists (PhD students and early-career post-docs) attending this meeting. We would like to take this opportunity to thank the international bodies of: the International Union of Geodesy and Geophysics, the National Science Foundation (US), le Centre National de la Recherche Scientifique - Institut National des Sciences de l'Univers (France) and the Worldwide Universities Network; and from the UK: the Royal Astronomical Society (RAS), the British Geophysical Association, and the Mineralogical Society of Great Britain and Ireland - Mineral Physics Group for their generous support. Funding from the RAS has also supported a public lecture by Ed Garnero given in conjunction with SEDI2012; our thanks to Ed for agreeing to deliver this lecture.

Welcome again, we hope you have an enjoyable and intellectually stimulating week.

The Local Organising Committee:

Chris Jones
Phil Livermore
Jon Mound
Sebastian Rost
Stephen Stackhouse

Timetable

Sunday, July 1st

12:00 Registration until 19:00 (Parkinson Court)
18:00 Welcome Reception until 20:00 (School of Earth & Environment Lobby)

Monday, July 2nd

S1: Other Planets (Rupert Beckett)
9:00 Sabine Stanley: New insights into planetary deep interiors
9:50 Catherine Johnson: MESSENGER observations of Mercury's magnetic field
10:15 David Bercovici: Generation of plate tectonics on Earth & other planets
10:40 Posters, Tea & Coffee (Parkinson Court)
11:30 General Discussion (Rupert Beckett) Led by: Dave Stegman

12:15 Lunch (The Refectory)

S2: Inner Core - Structure, Dynamics & Composition (Rupert Beckett)
13:45 Bruce Buffett: Evolution and dynamics of the Earth's inner core
14:35 Thierry Alboussiere: Asymmetric dynamics of the inner core
15:00 Dario Alfe: Thermal and electrical conductivity of the Earth's outer core
15:25 Posters, Tea & Coffee (Parkinson Court)
16:15 General Discussion (Rupert Beckett) Led by: Renaud Deguen

17:00 Posters & Refreshments (Parkinson Court)

Tuesday, July 3rd

S3: Outer Core - Observations of Structure & Composition (Rupert Beckett)
9:00 Chris Finaly: Observational constraints on the dynamics of the outer core
9:50 Ingo Wardinski: Modelling Earth's magnetic field variation
10:15 George Helffrich: Evidence for and consequences of outer core stratification
10:40 Posters, Tea & Coffee (Parkinson Court)
11:30 General Discussion (Rupert Beckett) Led by: Andy Jackson

12:15 Lunch (The Refectory)

S4: Outer Core - Modelling & Dynamics (Rupert Beckett)
13:45 *Zatman Lecture* Nicolas Gillet: Stochastic core flow reconstruction over the observatory era
14:35 Julien Aubert: Imaging flow throughout the Earth's core
15:00 Peter Olson: Coupling between geomagnetic reversal frequency and mantle convection in the Phanerozoic: results from numerical dynamos
15:25 Posters, Tea & Coffee (Parkinson Court)
16:15 General Discussion (Rupert Beckett) Led by: Rainer Hollerbach

17:00 Posters & Refreshments (Parkinson Court)

19:00 *Public Lecture* (Rupert Beckett) Ed Garnero: A seismological journey to the center of the Earth

Wednesday, July 4th

S5: Experiments & Measurements in Deep Earth Research (Rupert Beckett)

9:00 Andreas Tilgner: Low frequency magnetic field fluctuations in dynamos
9:25 Stephane Fauve: Hemispherical and reversing dynamos
9:50 Michael Walter: Melting phase relations at lower mantle conditions in the laser-heated diamond anvil cell
10:15 Maxwell Brown: Assessment of palaeointensity methodologies using historical lava flows
10:40 Posters, Tea & Coffee (Parkinson Court)
11:30 General Discussion (Rupert Beckett) Led by: Jon Aurnou

12:15 Packed Lunch & Departure for York

18:00 Reception & Conference Dinner (National Railway Museum)

Thursday, July 5th

S6: CMB - Structure, Dynamics & Composition (Rupert Beckett)

9:00 Stephane Labrosse: News from the core mantle boundary region
9:50 Laurence Koot: Constraints on the structure and dynamics of the core-mantle and inner core boundaries inferred from nutation observations
10:15 Daniel Frost: The composition of the base of the mantle and reactions with the outer core
10:40 Posters, Tea & Coffee (Parkinson Court)
11:30 General Discussion (Rupert Beckett) Led by: Ed Garnero

12:15 Lunch (The Refectory)

S7: Mantle - Observations of Structure & Composition (Rupert Beckett)

13:45 Thorne Lay: Reserach frontiers in the deep Earth
14:35 Rita Parai: Early planetary differentiation recorded in deep mantle Xenon isotopes
15:00 Vedran Lekic: A re-analysis of lower mantle tomographic models
15:25 Posters, Tea & Coffee (Parkinson Court)
16:15 General Discussion (Rupert Beckett) Led by: Guy Masters

17:00 Posters & Refreshments (Parkinson Court)
18:00 SEDI Business Meeting (Rupert Beckett)

Friday, July 6th

S8: Mantle - Modelling & Dynamics (Rupert Beckett)

9:00 Lars Stixrude: Geophysics of chemical heterogeneity in the mantle
9:50 Tilman Spohn: Thermal and transport properties of the deep interiors of super-Earth planets
10:15 Robert Moucha: Seismic tomography and mantle convection - a window into the past
10:40 Posters, Tea & Coffee (Parkinson Court)
11:30 General Discussion (Rupert Beckett) Led by: Louis Moresi

12:15 Packed Lunch & Departure

S1: Other Planets

Invited Talk

New insights into planetary deep interiors

SABINE STANLEY[1]

[1] Department of Physics, University of Toronto, Toronto, CA
(stanley@physics.utoronto.ca)

Recent spacecraft observations, along with advances in experiments and numerical simulations have provided new insights into the deep interiors of planets. In this talk I will review some of the latest results for both terrestrial and giant planet interiors. For planetary dynamos, alternative driving mechanisms and/or core-mantle interactions may be required to explain magnetic field observations for Mercury, Moon, Mars and Saturn. For terrestrial planet mantles, the presence of metals in the deep mantle has consequences for magnetic field observations and planetary thermal evolution. In Uranus and Neptune, new phases of water at high pressure and temperature may also influence planetary evolution and dynamos. In addition, extra-solar planets with more extreme physical properties, such as super-Earths and Hot Jupiters, provide us with investigations of phase spaces not seen in our solar system. The sheer number of extra-solar planets will eventually result in a test-bed for planetary interior studies not possible with the limited number of large bodies in our own solar system. Upcoming missions, such as Juno, also have the potential for unprecedented resolution of planetary magnetic fields and interior properties.

Invited Talk

MESSENGER Observations of Mercury's Magnetic Field

CATHERINE L. JOHNSON[1,2], MICHAEL E. PURUCKER[3], HAJE KORTH[4], BRIAN J. ANDERSON[4], REKA M. WINSLOW[1], MANAR M. AL ASAD[1], JAMES A. SLAVIN[5], IGOR. I. ALEXEEV[6], ROGER J. PHILLIPS[7], MARIA T. ZUBER[8], SEAN C. SOLOMON[9]

[1]Department of Earth and Ocean Sciences, University of British Columbia, Vancouver, British Columbia, Canada. Email: cjohnson@eos.ubc.ca
[2]Planetary Science Institute, Tucson, Arizona, USA.
[3]NASA Goddard Space Flight Center, Greenbelt, Maryland, USA.
[4]The Johns Hopkins University Applied Physics Laboratory, Laurel, Maryland, USA.
[5]Department of Atmospheric, Oceanic and Space Sciences, University of Michigan, Ann Arbor, Michigan, USA.
[6]Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia.
[7]Planetary Science Directorate, Southwest Research Institute, Boulder, Colorado, USA.
[8]Department of Earth, Atmospheric and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, Massachusetts, USA.
[9]Department of Terrestrial Magnetism, Carnegie Institution of Washington, Washington, D.C., USA.

Mercury is the only inner solar system planet other than Earth to possess a large-scale magnetic field. The field is primarily dipolar, of the same polarity as Earth's field, but has a surface strength about 1% that of Earth. The high solar wind pressure of the inner heliosphere combined with Mercury's weak dipole moment and time variations in the solar wind and interplanetary magnetic field result in a small, dynamic magnetosphere. Satellite magnetic field observations contain substantial contributions from fields due to magnetospheric current systems that can vary on timescales of seconds to a Mercury year (88 Earth days). Thus, understanding Mercury's magnetic environment requires knowledge of both the internal and external large-scale fields.

Vector magnetic field observations have been acquired from the Magnetometer (MAG) on the MErcury Surface, Space ENvironment, GEochemistry, and Ranging (MESSENGER) spacecraft, in orbit about Mercury since 18 March 2011. MESSENGER's orbit is highly eccentric, with a period of 12 (8) hours during the first (second) Earth year of operations. MESSENGER's altitude variations present challenges to analyzing the internal field but have the advantage that every orbit transits into, and out of, the magnetosphere, allowing identification of the bow shock and magnetopause on each orbit. After one Mercury year, MAG measurements sampled the northern magnetosphere at all local times and sampled the nightside southern lobe of the magnetotail to distances of almost 5 R_M (where R_M Is Mercury's radius, or 2440 km). The 88-day timescale and associated Mercury solar orbital coordinate system govern the geometry of the large-scale external (magnetopause and magnetotail) current systems at Mercury. With the exception of induction, the Mercury body-fixed coordinate system governs the geometry of internally generated fields at Mercury.

The structure of Mercury's internal and external fields have been determined from MAG data. The internal field is dominantly dipolar and symmetric about the planet's rotation axis, with a moment of 190 nT-R_M^3 or 2.8×10^{19} Am^2. The magnetic equator is identified directly from the MAG data and is offset 479 km northward along the rotation axis, equivalent to an axial quadrupole term that is 40% of the axial dipole term. Observations of the magnetotail current sheet confirm that its position is controlled by this internal field geometry: the current sheet is offset northward from the planetary equator. We present a time-averaged model of Mercury's magnetosphere, constructed under the approximation that the magnetospheric shape can be represented as a paraboloid of revolution. The model includes magnetopause and magnetotail current systems and an internal dipole field and allows for reconnection. It provides an excellent first-order fit to the MESSENGER observations, with a root-mean-square misfit of less than 20 nT globally.

We analyze residual signatures to this baseline model. Globally, these are dominated by the results of magnetospheric processes, confirming the dynamic nature of Mercury's magnetosphere. Upper bounds on static internal fields determined from the residuals indicate that contributions from spherical harmonic degree 3 and higher are less than a few percent. We determine limits on crustal remanent magnetization; the remanence is geographically associated with the northern rise region of the northern volcanic plains. Changes in the magnetopause boundary position and in the dipole moment are correlated with changes in solar wind pressure, and we explore induction as a possible explanation for these observations. The internal field structure provides new constraints for dynamo models.

Invited Talk

Thermal and Transport Properties of the Deep Interiors of Super-Earth Planets

TILMAN SPOHN[1]

[1]DLR Institute of Planetary Research, Berlin, Germany

Models of the temperature- and pressure-dependent transport and thermal properties, i.e., viscosity, phonon thermal conductivity, thermal expansivity and heat capacities, as well as electronic and radiative thermal conductivities, are discussed for the mantles of super-Earths. It is assumed that the mantles consist of $MgSiO_3$ perovskite (pv), but we discuss the effects of the post-perovskite transition, and we elaborate on an addition of periclase MgO and incorporated Fe. MgO is found to significantly influence the phonon thermal conductivity – but the viscosity, heat capacity and thermal expansivity of pv and MgO remain comparable. We use the Keane theory of solids, which takes into account the behavior of solid matter at the infinite pressure limit, adopt the Keane equations of state, and adjust for pv and MgO by comparison with experimental high-pressure and high-temperature data. To calculate the melting curve, we use the Lindemann–Stacey scaling law and fit it to available experimental data. The best data fitting melting temperature for pv reaches 5700 K at 135 GPa and increases to 20,000 K at 1.1 TPa, the pressure at the core-mantle boundary of a 10 Earth mass super-Earth (10MEarth). We find the pv adiabatic temperature (with a potential temperature of 1700 K) to reach 2570 K at 135 GPa and 5000 K at 1.1 TPa. The thermal expansion coefficient decreases by about an order of magnitude and the thermal conductivity increases by almost an order of magnitude. Using the semi-empirical homologous temperature scaling to relate enthalpy change, and hence viscosity, to the melting temperature we find that the resulting activation volume of pv decreases from 2.8 cm3/mol at 25 GPa to 1.4 cm^3/mol at 1.1 TPa-resulting in a viscosity increase by _15 orders of magnitude through the adiabatic mantle of a 10MEarth planet. Convection is being supressed under these circumstances for the deep layers of the super-Earth, the effective Rayleigh numbers of mantle convection become small and the time scales for the thermal evolution of the planets large. We compare these models with models that use lower values of the activation volume and compare the predicted temperature, viscosity and convection flow patterns.

The influence of degree-1 mantle heterogeneity on the past dynamo of Mars

HAGAY AMIT[1], ULRICH R. CHRISTENSEN [2] & BENOIT LANGLAIS[1]

[1] CNRS UMR 6112, Université de Nantes, Laboratoire de Planétologie et de Géodynamique, 2 Rue de la Houssinière, Nantes F-44000, France
(Hagay.Amit@univ-nantes.fr, Benoit.Langlais@univ-nantes.fr)
[2] Max-Planck-Institut für Sonnensystemforschung, 37191 Katlenburg-Lindau, Germany
(christensen@linmpi.mpg.de)

The hemispheric dichotomy in the crustal magnetic field of Mars may indicate that the planet's past dynamo was influenced by a degree-1 heterogeneity on the outer boundary of its liquid metallic convecting core. Here we use numerical dynamos driven by purely volumetric internal heating with imposed degree-1 heat flux heterogeneities to study mantle control on the past dynamo of Mars. We quantify both south-north and east-west magnetic field dichotomies from time-average properties that are calculated according to two different end member crust formation scenarios. Our results indicate that a moderate heat flux anomaly may have been sufficient for obtaining the observed dichotomy. Because of the excitation of a strong equatorial upwelling in the dynamo, the efficiency of a mantle heterogeneity centered at the geographical pole in producing a south-north dichotomy is much higher than that of an heterogeneity centered at the equator in producing an east-west dichotomy. These results argue against a significant True Polar Wander event with major planet re-orientation after the cessation of the dynamo.

Anelastic Dynamo Models with Radially Varying Conductivity, an Application to the Gas Giants

Lúcia Duarte

May 30, 2012

Abstract

Observations of the two gas giants show that both planets have dipolar magnetic fields: Jupiter's is very similar to Earth's magnetic field and Saturn's is very axisymmetric. Our main goal is the constructed realistic numerical models that explain these features.

While the small density jump across terrestrial iron cores allows to use the Boussinesq approximation, the picture is different for the gas giants. Here, the density decreases by a factor of around 150 from the deep interior to the surface (1 bar level). Most of this density jump, however, is accommodated in the outer molecular envelopes. But it may still be significant in the metallic dynamo region. We use an anelastic numerical dynamo model (which differs from a fully compressible model by neglecting sound waves) to explore the effects of density stratification on magnetic field generation, increasing the density from 0 to 21. Using an Ekman number of $E=10^{-4}$ and Prandtl number 1, we find that dipolar dynamos only exist for density stratifications below 6. This suggests that magnetic field generation is confined to the deeper parts of the gas giants.

All our simulations were done with an outer stress free boundary condition, which promotes the zonal flows known from observations of the gas giants. When the density jump is increased beyond 6, we loose the typical dipolar α^2 dynamo, and the Ω-effect starts to play an important role.

We also used a radially varying conductivity profile to explore the effect of coupling between the inner conducting layer (metallic Hydrogen) and the outer non-conducting layer (molecular Hydrogen). The dipolarity reaches high values, but only during rather brief periods of the highly time dependent solution.

Interior models of Mercury with equatorial ellipticity

Mathieu Dumberry[1]

[1] Department of Physics, University of Alberta, Edmonton, Alberta, Canada
(dumberry@ualberta.ca)

The combination of planetary rotation observations and gravity field measurements by the MESSENGER spacecraft can be used to constrain the internal structure of Mercury. A recently published model suggests a mean mantle density of $\rho_m = 3650 \pm 225$ kg m^{-3}, substantially larger than that expected of a silicate mantle (3300 kg m^{-3}) and possibly hinting at the presence of an FeS-rich layer at the base of the mantle. Here, we develop simple models of Mercury's interior and show that a large ρ_m is only required if the core-mantle boundary (CMB) of the planet is assumed axially-symmetric. An equatorial ellipticity of CMB of the order of 2×10^{-5} makes it possible to satisfy gravity and rotation constraints with a mean mantle density typical of silicate material. Possible origin of such topography include past mantle convection, aspherical planetary shrinking, remnant tidal deformation, or a combination thereof.

The feedback dynamo on Mercury

Natalia Gómez-Pérez[1], Daniel Heyner[2]

[1] Departamento de Física, Universidad de los Andes, Colombia (email:ngomez@uniandes.edu.co)
[2]Institute for Geophysics and extraterrestrial Physics, Braunschweig University of Technology, Germany

Mercury, the planet closest to the sun, is the only terrestrial planet other than Earth which exhibits a self sustained magnetic field. The MESSENGER spacecraft has been studying this planet from orbit for over a year and they have found a stable off-centered dipole with a dipole moment of 195 ± 10 nTR_M^3. The measured dipole moment in Mercury is too weak for a magnetostrophic dynamo operating in the Hermean core, this is why the magnetic field generation mechanism has ben a subject of study in the past years. We have studied the effect that the magnetosphere may have in the internal dynamo, also called "Feedback Dynamo". In this paper, we use numerical simulations of the magnetosphere to estimate the magnitude of the induced field at the top of the core. With this, we introduce this induced field to the top of the Hermean convecting core in a self-sustained dynamo simulation. Here we present results for sets of simulations under various parameters regimes and study in detail the feedback effect as function of initial conditions and convection strength.

Cessation of early Martian dynamos due to subcriticality

KUMIKO HORI[1] & JOHANNES WICHT [2]

[1] Earthquake Research Institute, University of Tokyo, Tokyo, Japan
(khori@eri.u-tokyo.ac.jp)
[2] Max-Planck Institute for Solar System Research, Katlenburg-Lindau, Germany

Mars has no active dynamo action at present, but likely had one in the early stage of its history. Clarifying why and how ceased is a challenging question. Several different scenarios have been proposed so far, here we explore the possibility that the dynamo stopped operating due to its subcritical nature. The presence of a strong magnetic field modifies the convective structure, mainly due to a balance between Lorentz and Coriolis forces. This modification can guarantee dynamo action at smaller Rayleigh numbers, where a weak seed field may simply decay, i.e. it can lead to a subcritical situation. Former studies suggested that the subcritical regime is rather narrow, indicating that it may therefore not play an important role for the cessation.

Here we show that a more appropriate model for the early Martian dynamo yields a much wide subcritical regime than previously reported. Even today Mars may not have developed a solid inner core so that the early dynamo was purely driven by secular cooling. The thermal temperature gradient in the conductive state is steepest at the core-mantle boundary (CMB), and hence the convection is strongly affected by the respective thermal boundary condition. Constant heat flux rather than constant temperature conditions should be used here. These more realistic conditions lead to magnetoconvection which favors much larger convective length scales than for a weak or non-existing magnetic field. This strongly modified convection allows to lower the Rayleigh number significantly below the point where a weak seed field would start to grow. This increased extend of the subcritical regime makes it more likely that this effect may have played a role in the shutdown of the early Martian dynamo.

Compressible Models of Jupiter's Dynamo

CHRIS JONES[1]

[1]Department of Applied Mathematics, University of Leeds, Leeds, UK
(cajones@maths.leeds.ac.uk)

Boussinesq convection-driven models for planetary dynamos, in which compressibility is ignored, are now well established. The numerically accessible regions of parameter space have now largely been explored for incompressible models. Compressible models based on the anelastic approximation, more suitable for the dynamos in giant planets, are now coming onstream. In contrast to the Boussinesq case, systematic coverage of the parameter space has not yet been undertaken. An international benchmarking exercise has been conducted to verify these new codes, with very encouraging results. Excellent numerical agreement for a series of test cases was achieved, despite the complexity of these codes. The compressible models are already showing some differences from the Boussinesq case: transverse dipoles, hemispherical dynamos and travelling dynamo wave solutions can be found, and these more complex patterns appear to be generated more readily.

The large variation in pressure in giant planets results in a relatively high electrical conductivity in the metallic hydrogen region, which in Jupiter is located mainly in the lower 80% by radius of the planet. Above this region, the electrical conductivity falls off rapidly. This variation in electrical conductivity has important dynamical consequences, because magnetic field tends to block strong zonal flows from building up in the deep interior, but large zonal flows can persist in the outer equatorial regions.

The anelastic approximation is based on convection about an equilibrium reference state model. This reference model is based on an isentrope in hydrostatic equilibrium, which depends on the equation of state. A model based on the SCVH equation of state, appropriate for high pressure hydrogen/helium mixtures is used here. These more physically realistic models can be compared with simpler polytropic reference state models.

We present some fully three-dimensional, rapidly rotating, dynamically consistent simulations of Jupiter's dynamo, both with and without internal heating and with a variety of boundary conditions. The anelastic equations are used in a form suitable for non-perfect gases. As in Boussinesq models, we find that at sufficiently high magnetic Reynolds number, magnetic fields are readily generated by the convective flow. In some models, Jupiter-like fields can be found, but in other models, a very different final state results, with strong asymmetry developing between the northern and southern hemispheres. Whereas in Boussinesq models, dipolar dynamos are often found provided the Rossby number based on the length scale of convection is sufficiently small, in compressible models dipolar fields are less common.

Tides driven flows: an alternative explanation for the generation of zonal winds on Jupiter and for the early Moon magnetic field

MICHAEL LE BARS[1], ALBAN SAURET[1], DAVID CÉBRON[1], PATRICE LE GAL[1], OZGUR KARATEKIN[2], MARK WIECZOREK[3]

[1]IRPHE, CNRS & Aix-Marseille University, Marseille, France (lebars@irphe.univ-mrs.fr)
[2]Royal Observatory of Belgium, Brussels, Belgium
[3]Institut de Physique du Globe de Paris, Univ Paris Diderot, France

A huge amount of energy is stored in the spin and orbital motions of any planet, and under certain circumstances, dynamic or static tides are capable of conveying a portion of this energy to drive three-dimensional flows in planetary liquid layers. Two such mechanisms are illustrated here in correlation with two planetary applications.

In the first experiment, we describe a new phenomenon of zonal wind generation in a rotating spherical shell by tidal forcing [1, 2]. We present the first experimental evidence that the nonlinear self-interaction of a tidally forced inertial wave can drive an intense axisymmetric flow, seen at the surface of the spherical shell as an intense shear band. This zonal flow becomes unstable at low Ekman number following a shear instability and generates space-filling turbulence. Systematic measurements are carried out by an embarked system of particle image velocimetry (PIV), allowing the determination of general scaling laws. These results illustrate a generic mechanism of geostrophic flow generation by any external harmonic forcing. At the surface of Jupiter's atmosphere, tides from the various Galilean moons would thus generate zonal winds, in complement to the already suggested models based on convection.

In the second experiment, we illustrate how the so-called elliptical instability, coming from the parametric resonance of tides with two inertial waves, may be responsible for the early Moon magnetic field [3]. Indeed, several lunar magnetic anomalies are associated with Nectarian-aged impact basins, and these signatures are the result of an impact melt sheet that was magnetized in the presence of a stable magnetic field over several thousands of years. The impact events that formed each of these basins were energetic enough to have unlocked the Moon from synchronous rotation, and the subsequent dissipation at the core-mantle boundary, combined with large-scale fluid flows in the core excited by tidal instabilities, could have powered a lunar dynamo at the time their impact melt sheets were cooling through the Curie temperature. Predicted surface magnetic field strengths are on the order of several μT, consistent with paleomagnetic measurements.

These two examples illustrate that rotational dynamics has to be considered in addition to convection as possible driving mechanisms at the planetary scale.

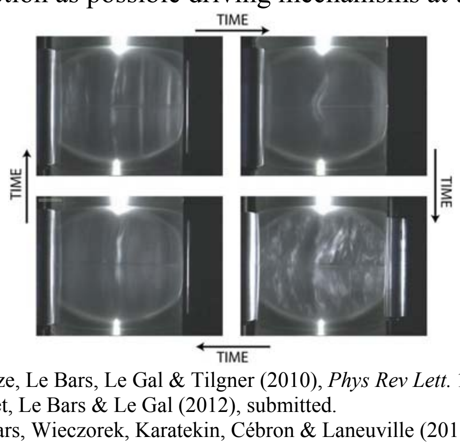

Figure 1: illustration of the chaotic behavior of the flow excited by tidal instability, with cycles of growth, space-filling turbulence and relaminarization. Such a flow may be responsible for transient magnetic fields on the Moon following its desynchronization by large impacts.

[1] Morize, Le Bars, Le Gal & Tilgner (2010), *Phys Rev Lett.* **104**(21), 214501
[2] Sauret, Le Bars & Le Gal (2012), submitted.
[3] Le Bars, Wieczorek, Karatekin, Cébron & Laneuville (2011), *Nature* **479**, 215–218.

Further Constraints and Uncertainties on the Deep Seismic Structure of the Moon

Pei-Ying Patty Lin[1,2], Renee Weber[3], Edward J. Garnero[1], Nicholas Schmerr[4]

[1]School of Earth and Space Exploration, Arizona State University, Tempe, AZ, USA
[2]Lamont-Doherty Earth Observatory, Palisade, New York, USA
[3]NASA Marshall Space Flight Center, Huntsville, AL, USA
[4]NASA Goddard Space Flight Center, Greenbelt, MD, USA

The Apollo Passive Seismic Experiment (APSE) consisted of four 3-component seismometers deployed between 1969 and 1972, that continuously recorded lunar ground motion until late 1977. The APSE data provide a unique opportunity for investigating the interior of a planet other than Earth, generating the most direct constraints on the elastic structure, and hence the thermal and compositional evolution of the Moon. Owing to the lack of detection of far side moonquakes, past seismic models of the lunar interior were unable to constrain the lowermost 500 km of the interior. Recently, users of array methodologies aimed at detecting deep lunar seismic reflections found evidence for a lunar core, thereby providing an elastic model of the deepest lunar interior consistent with geodetic parameters (Weber et al., 2011 and Garcia et al., 2011). Here we study the uncertainties in these models associated with the double array stacking of deep moonquakes for imaging deep reflectors in the Moon. We investigate the dependency of the array stacking results on a suite of parameters, including amplitude normalization assumptions, polarization filters, assumed velocity structure, and seismic phases that potentially interfere with our desired target phases. These efforts are facilitated by the generation of synthetic seismograms at high frequencies (~ 1Hz), allowing us to directly study the trade-offs between different parameters. Results from separate versus combined station stacking help to establish the robustness of stacks. Synthetic seismograms for every path geometry of the APSE data were processed identically to that done with data. Experiments were aimed at examining various processing assumptions, such as adding random noise to synthetics, comparing imaged reflection depths between stations, and investigating the dependency of imaged reflect depths on different lunar mantle seismic velocity models. The double array stacking method on synthetics seismograms demonstrate the capability of detecting faint reflections. Results from separate versus combined station stacking help to establish the robustness of stacks. The principal stacked energy peaks put forth in recent work (e.g., Weber et al., 2011) persist, but their amplitudes (which map into reflector impedance contrasts) and timing (which map into reflector depths) depend on factors that are not well constrained, most notably, the velocity structure of the overlying lunar interior. Thus, while evidence for the lunar core remains strong, the depths of imaged reflectors have associated uncertainties that will require new seismic observations to markedly improve constraints. These results strongly advocate for further investigations on the Moon to better resolve the interior (e.g., the Selene mission), since the Moon apparently has a rich history of construction and evolution that is inextricably tied to that of Earth.

References:
[1] Garcia, R. F., J. Gagnepain-Beyneix, S. Chevrot, and P. Lognonné (2011), Physics of the Earth and Planetary Interiors, 188, 96-113. [2] Weber, R. C., P.-Y. Lin, E. J. Garnero, Q. Williams, and P. Lognonné (2011), Science, 331(6015), 309-12.

Can a sinking metallic diapir generate a dynamo?

JULIEN MONTEUX [1], NATHANAEL SCHAEFFER [2], HAGAY AMIT [1] & PHILIPPE CARDIN [2]

[1] CNRS UMR 6112, Université de Nantes, Laboratoire de Planétologie et de Géodynamique, 2 Rue de la Houssinière, Nantes F-44000, France.
(julien.monteux@univ-nantes.fr, hagay.amit@univ-nantes.fr)
[2] Université de Grenoble 1, CNRS, F-38041 Grenoble, France.
(nathanael.schaeffer@ujf-grenoble.fr, Philippe.Cardin@ujf-grenoble.fr)

Metallic diapirs may have strongly contributed to core formations during the first million years of planetary evolutions. The length-scales of these diapirs can range from several centimetres to several hundred kilometres. The aim of this study is to determine whether the dynamics enhanced by the diapir sinking can drive a dynamo and to characterize the required conditions on the size of the diapir R, the mantle viscosity η_s and the planetary latitude at which the diapir sinks (see Fig.1 for candidate diapirs). We impose a classical Hadamard flow solution for the motion at the interface between a sinking diapir and a viscous mantle on dynamical simulations that account for rotational and inertial effects in order to model the flow within the diapir. The flows are confined to a velocity layer with a thickness that decreases with increasing rotation rate. This decrease depends on the initial latitude of the diapir. This 3D flow is then used as input for kinematic dynamo simulations to determine the critical magnetic Reynolds number for dynamo onset. Our results demonstrate that the flow pattern occurring inside a diapir sinking through a partially molten mantle within a rotating planet can generate a magnetic field. This dynamo generation is more favourable for a large diapir sinking from the equator than from the planet's rotational pole.

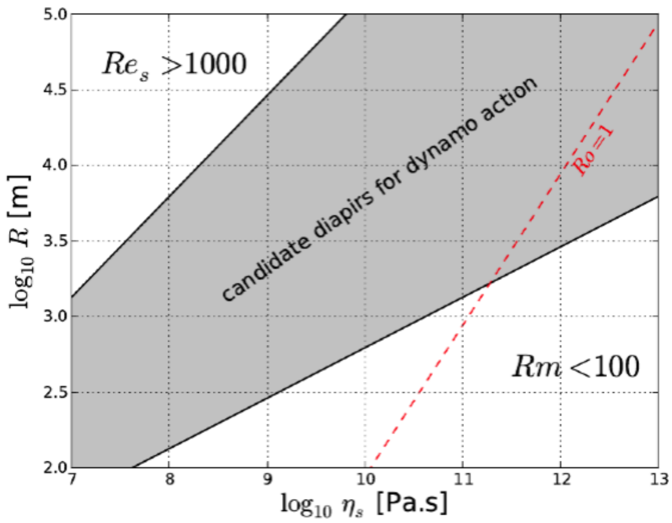

Figure 1: Candidate diapirs for possible dynamo action (shaded region) must have $Re_s \lesssim 1000$ (Re_s is the mantle Reynolds number) to be stable and $Rm \gtrsim 100$ (Rm is the diapir magnetic Reynolds number) for magnetic induction to be possible. The $Ro = 1$ (Ro is Rossby number) contour shows that for large mantle viscosity η_s, the rotation of the planet will dominate the liquid metal flow dynamics inside the diapir.

Lithospheric magnetic field reconstruction using vector Slepian functions

ALAIN PLATTNER[1], FREDERIK J. SIMONS [2]

[1] Department of Geosciences, Princeton University, Princeton, NJ, USA,(plattner@princeton.edu)
[2] Department of Geosciences, Princeton University, Princeton, NJ, USA, (fjsimons@alum.mit.edu)

Spherical harmonics and vector spherical harmonics are the bases of choice for most global geophysical problems, including the inversion for the magnetic field from satellite data obtained for example by CHAMP and SWARM, but also planetary missions such as MESSENGER. The advantage of spherical harmonics is their orthogonality over the entire sphere and their perfect bandlimitation. Their disadvantage is that they are global functions. This leads particularly to problems when either dealing with only local data, or if the satellite data are to be combined with data from ground-based or airborne surveys. An additional disadvantage of global basis functions is that in any geophysical setting, the analysis of lithospheric magnetic structure and its spectral power density will need to honor geological boundaries such as ocean-continent boundaries or individual geological terrains. Therefore, global functions are not ideal. A suitable basis would be spatially localized, bandlimited and orthogonal over the entire sphere and over a chosen target region. Such a basis can be generated by solving an optimization problem within the setting of bandlimited (vector) functions. A basis of so-called Slepian functions has been previously designed and successfully applied to scalar data on the sphere. In order to make optimal use of the vectorial data collected by modern satellite missions, we construct vector Slepian functions. In this work, we present the results of the theory and numerical experiments applicable to real data analysis.

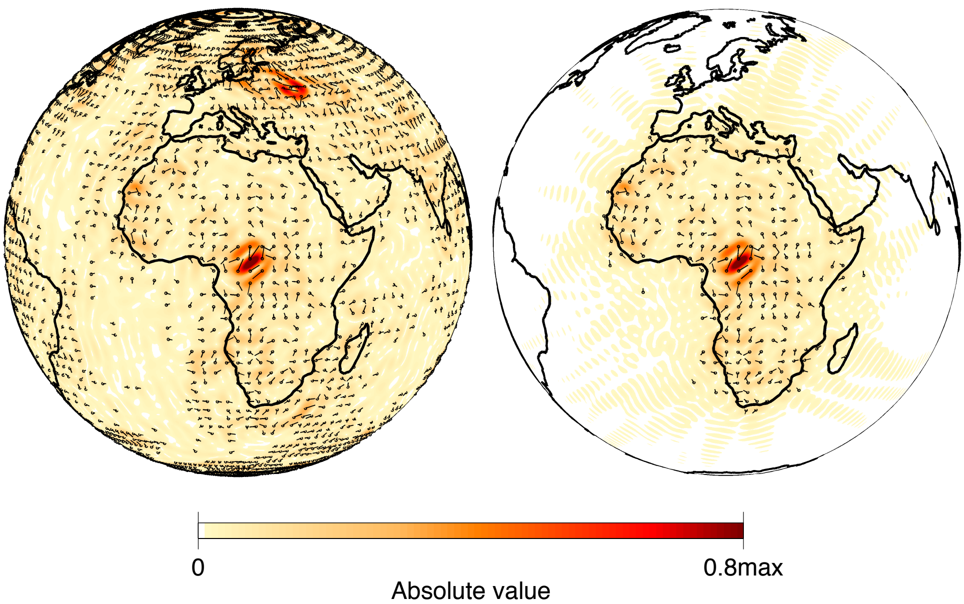

Figure 1: A tangential geophysical vector field (left panel) and its local reconstruction (right panel) using vectorial Slepian functions designed to maximize their spatial concentration in Africa. The reconstruction is calculated using the 10% best-concentrated tangential vector Slepian functions. The rms error of the reconstruction over Africa is 0.4%.

The magnetic field and secular variation of Jupiter

VICTORIA RIDLEY[1] AND RICHARD HOLME[1]

[1]School of Environmental Sciences, Dept. Geology and Geophysics, University of Liverpool, Liverpool, United Kingdom (var@liv.ac.uk)

Planetary dynamos, resulting from fluid flow in electrically conductive parts of their interior, are thought to be highly time dependent. Currently, our understanding of temporal variation of these fields is limited because we only have observations for one example, the Earth. To overcome this, data acquired by 6 NASA space missions between 1973-2003 are used to investigate possible time variation (secular variation) of Jupiter's magnetic field.

Previous attempts to model jovimagnetic secular variation have been inconclusive or ineffective for a number of reasons, including limited data usage, inadequate consideration of the external current disk field and the modelling approach taken. We attempt to resolve these issues by using all data available within 12 Jovian radii, establishing and removing the current disk field for each individual orbit and taking a regularised minimum norm approach to modelling the internal planetary field. This approach allows construction of numerically stable models with constrained small-scale (high spherical harmonic degree) structure that directly fit the observations.

Two models of Jupiter's magnetic field are presented: the first time-averaged over the whole dataset, whilst the second allows for linear time variation of the field. Comparison of these allow inferences to be made about jovimagnetic secular variation with our favoured models indicating a ~0.042%yr^{-1} decrease in the dipole magnetic moment over the investigated time period; this value is comparable with Earth (~0.06%yr^{-1}). Under-damped solutions display a northern polar configuration indicative of a magnetic field anomaly, previously identified only through the analysis of satellite auroral footprint location. Furthermore, simple models of Jovian "core flow", while highly speculative, also show patterns resembling those of the Earth.

These models are calculated with reference to the Jovian System III 1965.0 reference frame, itself defined by the magnetic field. Thus, some of the secular variation could result from inaccuracies in this determination; however, such an effect cannot explain all the observed secular variation. The constraint on changes in planetary rotation rate allow a bound to be placed on angular momentum transfer between the atmosphere and deep interior, as seen for variations in Earth's observed length-of-day. Using changes in zonal atmospheric wind structure, if the winds were to extend to depths only 2% into the planet, observed atmospheric changes between 1979-1996 would translate to a ~10° rotation of the planetary interior via angular momentum exchange, inconsistent with the magnetic observations. We thus provide strong observational evidence against models linking surface winds to deep Jovian convection, particular deep convection on cylinders.

Constraints on Mercury's interior structure from recent data on its gravity field and spin state

ATTILIO RIVOLDINI, TIM VAN HOOLST

Royal Observatory of Belgium, 3 Avenue Circulaire, B-1180 Bruxelles, Belgique (Attilio.Rivoldini@oma.be)

The recently determined global gravity field of Mercury by the MESSENGER mission [3] and the accumulated radar measurements about the spin state of Mercury [1, 3] provide important constraints on its interior structure. By combining both data sets the moment of inertia of Mercury and of its silicate shell can be determined. Both are expected to provide constraints on Mercury's core radius and on the core's light elements concentration. In this study our aim is to determine to what precision those two core parameters can be obtained by using as data Mercury's mass, its global moment of inertia, and the moment of inertia of its outer silicate shell. The other parameters of our interior model are the density and thickness of Mercury's crust and the density of its mantle. In agreement with the observation that the mantle of Mercury has a low iron content and with the low pressure range inside its shallow mantle we assume a mantle density that is within the $[3100, 3500]\mathrm{kg/m^3}$ range. The temperature inside the core is assumed conductive or adiabatic and for the adiabatic case it is calculated from the temperature at the core-mantle boundary which is a parameter of our model. The range for the core-mantle boundary temperature is chosen such that it is below the mantle solidus and above the eutectic temperature of the iron-light element core constituents).

Acknowledgements

This work was financially supported by the European Space Agency in collaboration with the Belgian Federal Science Policy Office.

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Development of an anelastic convection model in rotating spherical shells for stars, gas and icy giant planets.

Youhei Sasaki[1], Shin-ichi Takehiro[2], Ken-suke Nakajima[3], Yoshi-Yuki Hayashi[4]

[1] Department of Mathematics, Kyoto University, Kyoto, Japan
(uwabami@gfd-dennou.org)
[2] Research Institute for Mathematical Sciences, Kyoto University, Kyoto, Japan
(takepiro@gfd-dennou.org)
[3] Faculty of Sciences, Kyushu University, Fukuoka, Japan
(kensuke@geo.kyushu-u.ac.jp)
[4] Department of Earth and Planetary Science, Kobe University, Kobe, Japan
(shosuke@gfd-dennou.rg)

The problem of convection and MHD dynamo in rotating spherical shells has been studied vigorously as a fundamental generation mechanism of intrinsic magnetic field of celestial bodies, such as stars, gas and icy giant planets, and terrestrial planets. Recently, according to development of numerical computational abilities, fundamental aspects and characteristics of convection and MHD dynamo have been revealed and knowledge about this issue is increased under the assumption of Boussinesq approximation, which ignores compressibility of the fluid. However, characteristics of compressible convection in rotating spherical shells have not been understood yet compared with Boussinesq convection, although some studies performed so far use the anelastic approximation in order to deal with compressibility. Compressibility is an important element for discussing deep convection of stars and gas and icy planets, since thickness of their convection layers is several times larger than the scale height. Not only for these celestial bodies but also for extra-solar gas giant planets, which have been discovered with recent sophisticated technologies of astronomical observation, compressibility cannot be ignored for considering fluid motion in their interiors. Investigation of effects of compressibility on convection and MHD dynamo in rotating spherical shells would contribute to the basic knowledge of fluid motions in the interiors of these many celestial bodies and of generation mechanism of their magnetic fields.

Based on the consideration described above, we are now developing a numerical model of an anelastic conductive fluid in rotating spherical shells in order to assess effects of compressibility on convective motions and dynamo processes. On the development of the model, we extended our numerical model of Boussinesq MHD dynamo in rotating spherical shells developed so far to the anelastic system. We described mass flux with poloidal and toroidal potentials instead of velocity field in the case of Boussinesq fluid. This procedure enables us to extend our Boussinesq model constructed so far to the anelastic case in a natural way.

In the presentation, results of some numerical experiments using our newly developed model will be shown, and our future plan is also discussed.

Seismic Investigation of Icy Moons: Insights from Earth Analogs and Modeling

NICHOLAS SCHMERR[1], JEANNE SAUBER[1], KELLY BRUNT[1], HERBERT FREY[1], TERRY HURFORD[1], THORSTEN MARKUS[1], TOM NEUMANN[1], ALYSSA RHODEN[1]

[1]NASA Goddard Space Flight Center, Greenbelt, MD 20771 USA nicholas.c.schmerr@nasa.gov

The outer satellites of the Solar System are a diverse set of objects that span a large spectrum of sizes, compositions, and evolutionary histories. In particular, the surface crusts of the icy outer satellites, such as Europa and Enceladus, are predominantly water ice with evidence for tidally driven large-scale surface deformation and subsurface oceans. In addition to providing a potential habitat for life, the oceanic layer enables extensive surface tectonics that result in brittle failure within the ice crusts of these moons. The complex fissures and cracks seen by orbital flybys of the moons are evidence of this process and potentially indicate a high level of seismic activity. Future seismic missions to take advantage of ice quakes and image icy moon interiors need to be built around predictions for the expected background noise levels, seismicity, wavefields, and elastic properties of the interior. A preliminary seismic velocity profile for the icy satellites can be calculated using moment of inertia constraints, planetary mass and density, estimates of moon composition, and experimentally determined relationships of elastic properties for relevant materials at pressure and depth. While the uncertainties in these types of models are high, it allows us to calculate a first-order seismic response to such structures using 1-D and 3-D high frequency wave propagation codes that enable investigation the seismic wavefield of icy satellites up to 1 Hz at both global and regional scales. Here, we show the presence of a global subsurface ocean layer 10-100 km thick has strong implications for the seismic response of icy bodies and we explore how future seismic instruments could provide detailed elastic information and reduced uncertainties on satellite internal structure. For example, receiver functions and surface wave orbits calculated for a single seismic instrument could provide information on crustal thickness and the presence and/or depth of an ocean layer. Likewise, evaluation of arrival times of multiply reflected waves observed at a single seismic station would record properties of the mantle and core of an icy moon. We demonstrate these examples of single station results using analogous seismic experiments on Earth, for example where seismometers have been placed upon the Ross Ice Shelf of Antarctica. We use both local ice quakes and teleseismic sources to formulate our analog experiments. Ultimately this work reveals that seismometer deployments will be essential for understanding the internal dynamics and surface evolution of the icy moons, and that seismic instruments need to be a key component of future missions to the satellites of the outer planets.

Transport coefficients free hydromagnetic scaling in fast rotating planets

SERGEY V. STARCHENKO[1]

[1]IZMIRAN, Troitsk, Moscow region, 142190 Russia (sstarchenko@mail.ru)

In the limit of negligible molecular diffusivity, viscosity and magnetic diffusivity effects I derive scaling laws for convection and magnetism from the first principles for fast rotating planets. Magnetic energy should dominate over kinetic one in the Earth, Jupiter, Saturn and ancient dynamo active Mars. This results in the typical magnetic field B proportional to the third root of the buoyancy flux F driving the convection, while B is independent on conductivity σ and angular rotation rate Ω. The same scaling law was previously obtained via compilation of many numerical planetary dynamo simulations [1]. Besides, I obtained scaling laws for typical hydrodynamic scale h, velocity V, Archimedean acceleration A, electromagnetic scale d and sinus of the angle between magnetic and velocity vector s. In Uranus, Neptune and Ganymede a local magnetic Reynolds number $r_m = \mu\sigma Vd$ is of order one or small. Magnetic energy of order kinetic one gives $B=(\mu\varrho)^{1/2}V$ explaining magnetic field values and structures there.

1. ***Scaling laws for convection*** are determined by heat-mass-transfer [2] giving $AV=F$. (1)
Radial component of curl of momentum equation contain no radial buoyancy force $\sim A$. Due to non-penetrating conditions on velocity I also remove the Coriolis force from this component integrating it along the axis of rotation from one boundary of the dynamo region to another. That relate magnetic to kinetic (inertia) energy ratio as $(B/V)^2/(\mu\varrho)=(d/h)^2$. (2)
Using (2) and other components of the same curl give $\Omega V/H=(V/h)^2=A/h$ (3-4)
in conditions of fast rotation. H is thickness of the spherical shell where the dynamo is acting. Solving equations (1, 3, 4) I obtain Rhines [3] scaling $V^5=F^2H/\Omega$, $h^5=FH^3/\Omega^3$, $A^5=F^3\Omega/H$. (5-7)

2. ***Electromagnetic scaling*** are 1st determined by Faraday's law with typical electric field E on large dipolar scale and Ohm's law with $r_m >> 1$ giving $BV/H=E/d$ and $E=sBV$. (8, 9)
Neglecting by magnetic diffusivity terms and using $d>>h$ in the induction equation I estimate the inverse time of magnetic field change as $sV/h=Vd/Hh$. Supposing the work of Archimedean force is of the order of magnetic energy time-change I finally have $(Vd/Hh)B^2/\mu=\varrho AV$. (10)
The equations (1-4, 10) give the first principles' scaling law known previously only from compilation of many numerical simulations [1]: $B=(\mu\varrho)^{1/2}(FH)^{1/3}$. (11)
For moderate or small local magnetic Reynolds number r_m magnetic energy could be of order kinetic one and in according with (2) $B=(\mu\varrho)^{1/2}V$. (12)

3. ***Typical planetary dynamo values*** are given in the following two tables for different r_m.

Value, unit	Ganymede	Uranus	Neptune
F, 10^{-14} m^2/s^3	6	3000	5000
Ω, 10^{-5}/s	10	10	11
ϱ, Mg/m^3	8	2.5	3
H, Mm	0.5	4	5
B, µT	15	500	700
$h=d$, km	1	20	25
V, mm/s	0.2	8	12
$r_m=\mu\sigma Vd$	0.2	1	1.5

Value, unit	ancient Mars	Earth	Jupiter	Saturn
F, 10^{-13} m^2/s^3	4	2	200	100
Ω, 10^{-5}/s	7.3	7.3	17.7	16.4
ϱ, Mg/m^3	10	11	1.8	1.8
H, Mm	1.1	2.3	41	16
B, mT	1	2	5	3
h, km	4	6	45	25
d, km	30	90	500	250
V, mm/s	1.2	1	9	6
$s=d/H$	0.03	0.04	0.01	0.02
$r_m=\mu\sigma Vd$	300	700	350	120

This work was supported by 22-d program of the presidium of Russian Academy of Sciences.

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Dynamical signature of a subsurface ocean: a normal mode expansion for the librations of icy moons

ANTONY TRINH[1,2], ATTILIO RIVOLDINI[2], TIM VAN HOOLST[2] & VÉRONIQUE DEHANT[2]

[1] Earth and Life Institute, Georges Lemaître Centre for Earth and Climate Research, Université Catholique de Louvain, Louvain-la-Neuve, Belgium (antony.trinh@uclouvain.be)
[2] Royal Observatory of Belgium, Brussels, Belgium

A number of icy moons are thought to harbour a liquid ocean below their surface. For Jupiter's moons Europa, Ganymede, and Callisto, this is supported by the study of surface geological features, and by the detection of an induced component in magnetic field measurements made from the Galileo spacecraft. Further evidence for the putative presence of a subsurface ocean and constraints on the thickness of the overlying shell could also be obtained by libration (i.e. variation of the moon's rotation rate) measurements (e.g. [1] and [3]) such as planned in the coming years, from the Earth or as part of future space missions.

As a result of tidal dissipation and stress relaxation, many moons now orbit their parent body along a nearly circular orbit, locked in a state of synchronous rotation, and take the shape of a triaxial ellipsoid. This triaxial shape favours the action of gravitational torques by their parent body and other neighbouring celestial bodies; therefore, it plays a significant role in the occurrence of librations and must be taken into account in rotation models.

However, all present models of the librations of synchronously rotating moons either neglect the tidal deformation intrinsically coupled to any rotation perturbation, or represent this tidal deformation using a parameter (the Love number k_2) computed for simplified, spherical, non-rotating models, thus neglecting triaxiality and rotation.

For a full and self-consistent consideration of triaxiality, we extend Smith and Wahr's rotation model, originally designed for a biaxial, rotating Earth ([2] and [4]), to triaxial, synchronously rotating moons. We model librations as global infinitesimal degree-1 order-0 material (Lagrangian) displacements from a state of steady rotation, and solve the equations of continuum mechanics in a triaxial domain. We use a programming language with symbolic capabilities to generate, truncate and solve the equivalent infinite system of scalar ordinary differential equations and boundary conditions.

Acknowledgments: Antony thanks Yves Rogister for helpful discussions and advice.

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The Effect of Lower Mantle Metallisation on the Dynamo Generated Magnetic Fields of Super Earths

Ryan Vilim[1], Sabine Stanley[2], Linda Elkins-Tanton[3]

[1] Department of Physics, University of Toronto, Toronto, Canada
(rvilim@physics.utoronto.ca)

[2] Department of Physics, University of Toronto, Toronto, Canada
(stanley@physics.utoronto.ca)

[3] Department of Terrestrial Magnetism, Carnegie Institute, Washington, United States of America
(ltelkins@dtm.ciw.edu)

Recent work has shown that a host of materials commonly thought to be present in terrestrial planet mantles (e.g. $CaSiO_3$[1], Al_2SO_3[2], FeO[3]) will conduct electricity at the conditions present in the lower mantles of large, terrestrial exoplanets. A solid, electrically conducting lower mantle layer should have a significant effect on any dynamo present in the planet, as magnetic field lines should be simultaneously anchored in the convecting fluid core, and the solid mantle. This should create a new source of shear for the dynamo to generate magnetic fields.

We use a numerical dynamo model to simulate magnetic field generation in the cores of terrestrial exoplanets with an electrically conducting mantle layer. We study the effect that the conductivity of the layer and the inner core size have on the observable field.

In all cases, a conducting lower mantle increases the core field strength significantly, due to the increased shear of magnetic fields in the core. We also find that the addition of an electrically conducting mantle layer makes the magnetic field at the top of the fluid region stronger, but less dipolar and more time variable. This counterintuitively decreases the observed field strength, as the electrically conducting mantle preferentially attenuates small scale, quickly varying components of the magnetic field.

We therefore find that while the addition of an electrically conducting mantle increases the strength of a dynamo generated field, it should be more difficult to detect the magnetic fields of extra-solar terrestrial planets because the observable field is weakened.

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S2: Inner Core - Structure, Dynamics & Composition

Invited Talk

Evolution and Dynamics of Earth's Inner Core

BRUCE BUFFETT

Department of Earth and Planetary Science, University of California, Berkeley, CA 94720 USA
(buffett@berkeley.edu)

Seismological studies reveal a surprising degree of complexity in Earth's inner core. Early indications of seismic anisotropy with a simple cylindrical structure have given way to a much more complicated picture with strong radial and hemispherical variations, including the possibility of a distinct innermost inner core. This complexity defies our expectations but it also offers a unique opportunity to interpret the geological history of the deep interior if we can unravel the origins of the observed seismic structure.

An interpretation of inner-core structure begins with an understanding of the thermal and chemical state of the inner core. Growth of the inner core by gradual solidification of the surrounding liquid inevitably produces radial gradients in both temperature and composition. Unfortunately, the stability of the resulting density stratification is open to question. Rapid growth during the early history of the inner core favors an unstable density stratification, whereas a stable stratification would be expected with recently revised values for the thermal conductivity of iron at high pressure and temperature.

Superimposed on the gradual evolution of the inner core are a large number of mechanisms that could potentially produce or contribute to the observed seismic structure. In many cases, the viability of these mechanisms is contingent on the density stratification of the inner core. In this talk I review many of the recently proposed mechanisms and assess the consistency of each mechanism with the growing collection of seismic observations. Shortcomings help to identify areas for future progress.

Invited Talk

Asymmetric Dynamics of the inner core

Thierry Alboussière[1], Renaud Deguen[2], Mickaël Melzani[3] & Philippe Cardin[3]

[1] Laboratoire de Géologie de Lyon, ENS-Lyon, université Lyon 1, France (thierry.alboussiere@ens-lyon.fr)
[2] Department of Earth and Planetary Sciences, Johns Hopkins University, Baltimore, USA (rdeguen@gmail.com)
[3] ISTerre, Université de Grenoble 1, CNRS, Grenoble, France (mickael.melzani@ens-lyon.fr, philippe.cardin@ujf-grenoble.fr)

More and more data become available on the inner core, yet a consensus has not been reached on its dynamics. Among the most recently discovered features, we have focused on hemispherical asymmetry and on the 'slow' bottom layer of the outer core, both revealed by seismology. The measurement of P-wave velocity near the boundary of the inner core displays a two-levels distribution that very precisely matches an eastern and a western hemisphere [1]. We hold that this is a strong indication in favour of a translation of the inner core along a direction perpendicular to the rotation axis and we have provided an 'intrinsic' buoyancy-driven model for it [2]. An alternative model is based on the 'external' influence of the mantle's heat flux at the CMB on the long-term dynamics of the outer core, which in turns affects the crystallization rate on the ICB, and even possibly causing melting to occur in some places [3,4]. Incidently, with a sufficient ratio of melting to crystallization on the ICB, both models might explain the existence of a stably stratified bottom layer in the outer core [2].

What has not yet been investigated is the strong feedback of the crystallization rate on the buoyancy flux driving convection in the outer core, and this may mainly affect the 'external' model. There is actually evidence for degree-one features in the dynamics of the outer core. Regarding the 'intrinsic' convective model, there are recent indications that the thermal conductivity might be about three times larger than the currently accepted value, which might invalidate thermal buoyancy convection in the inner core: we shall discuss whether compositional buoyancy could be the driving force for convection.

To make progress, there is a need to consider the coupled dynamics of the inner and outer cores. So far, the emphasis has been put on either object and the other one has been treated as a simplistic boundary condition. The main difficulty is that they do not live on the same timescales, the hope is that this can be sorted out with a time filter between the inner and outer cores.

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Invited Talk

Thermal and electrical conductivity of the Earth's outer core

MONICA POZZO[1], CHRIS DAVIES[2], DAVID GUBBINS[2] & DARIO ALFE[1]

[1] Department of Earth Sciences, and Thomas Young Centre at UCL, UCL, London, UK
(d.alrfe@ucl.ac.uk)
[2] School of Earth and Environment, Institute of Geophysics and Tectonics, University of Leeds, Leeds, UK

We calculated the electrical and thermal conductivity of liquid iron and iron-silicon-oxygen mixtures at the pressure-temperature conditions of the Earth's outer core. The mixtures were selected on the basis of the likely composition of the core. The calculations are based on quantum mechanics, using the implementation known as density functional theory. We find that the thermal conductivity of the core ranges between 100 and 140 (SI units) from the top to the bottom of the core, which is 2-3 times higher than estimates in current use. We find that the Wiedeman-Franz law is satisfied well, and therefore also electrical conductivities are correspondingly 2-3 times higher than currently used values. The geophysical implications (which I will not discuss in depth) of such high conductivities are significant, including a 15-16 TW heat flux at the core mantle boundary, a stratification at the top of the core and a significant reduction of the power available to drive the geodynamo (see poster by Chris Davies).

A Comparison of Annealed Sn-Zn and Al-Zn Directionally Solidified Alloys, and Implications for the Earth's Inner Core

Michael I. Bergman[1], Yahya al-Khatatbeh[1], Daniel J. Lewis[2], Zach Mason[1]

[1]Physics Department, Bard College at Simon's Rock
[2]Materials Research Center, Rensselaer Polytechnic Institute

There is increasing evidence that the Earth's inner core is asymmetric, with the western hemisphere exhibiting slower direction-averaged P wave velocity, less overall attenuation, and greater elastic anisotropy. One possibility to explain these hemispherical variations is long term mantle control over outer convection, which affects inner core solidification and deformation, which in turn affects its microstructure and texture. It was recently suggested however, that the hemispherical variations might result from a positive feedback mechanism whereby enhanced solidification in the western hemisphere, beyond that simply due to inner core growth, leads to a net eastward translation of inner core material, with melting occurring in the east. Accompanying this eastward movement of iron might be grain growth and loss of texture, which can explain the seismic observations.

A previous study examined experimentally a previously unobserved sequence of grain growth and loss of texture during the annealing of a directionally solidified Sn-Zn alloy. Our hypothesis is that the growth of newly nucleated grains results because the original grains that resulted from directional solidification have a high energy associated with intragranular interphase boundaries, and because the alloy has a low solubility of the two phases so that a more traditional sequence of coarsening is not possible. This supplies a physical mechanism for the loss of texture that is suggested seismically. To test the solubility hypothesis we are annealing directionally solidified Al-Zn alloys, where there is some solid solubility of the two phases. We are examining whether traditional coarsening with no change in texture occurs, versus nucleation and grain growth accompanied by a loss of texture. Differing behavior informs us that the microstructure and texture of the inner core might be exquisitely sensitive to the exact nature of the inner core phase diagram.

F-layer formation in dynamo simulations forced by inner core convection

RENAUD DEGUEN[1], PETER OLSON [2], THIERRY ALBOUSSIERE[3] & PHILIPPE CARDIN[4]

[1] Department of Earth and Planetary Sciences, Johns Hopkins University, Baltimore, USA.
(rdeguen@gmail.com)
[2] Department of Earth and Planetary Sciences, Johns Hopkins University, Baltimore, USA.
(polson@jhu.edu)
[3] LGL, Laboratoire de Géologie de Lyon, CNRS, Université Lyon 1, ENS-Lyon, Villeurbanne, France.
(thierry.alboussiere@ens-lyon.fr)
[4] ISTerre, Université de Grenoble 1, CNRS, Grenoble, France.
(Philippe.Cardin@ujf-grenoble.fr)

The seismological observation of the so-called F-layer - a stably stratified $\sim$ 200 km thick layer at the base of the outer core - is difficult to reconcile with the classical picture of outer core convection, where buoyant liquid is released at the inner core boundary (ICB) by the progressive crystallization of the inner core. We have recently proposed that this layer could have been generated by simultaneous melting and crystallization at the inner core boundary [1]. Melting inner core material produces a dense iron-rich liquid which would spread at the surface of the inner core, while crystallization produces a buoyant light element rich liquid which may carry along part of the dense melt as it rises. The stratified layer would result from a dynamic equilibrium between production of iron rich melt and entrainment and mixing associated with the release of buoyant liquid.

A plausible way to melt inner core material is to generate dynamically a topography that will bring locally the ICB at a potential temperature lower than that of the adjacent liquid core. The melting rate is then limited by the ability of outer core convection to provide the latent heat absorbed by melting, and only a significant ICB topography can lead to a non-negligible melting rate. The most efficient mechanism for producing a sizable ICB topography and widespread melting appears to be inner core thermal convection. In the limit of a large inner core viscosity, the only unstable mode is a translation of the inner core with associated melting in one hemisphere and crystallization in the other [1,2]. With a smaller viscosity, the convection regime is typical of high Rayleigh number internally heated convection, with narrow plumes falling down from a thermal boundary layer below the ICB. In this regime, freezing is localized above plumes roots and melting occurs above upwellings.

Here we investigate numerical dynamo models forced by ICB boundary conditions from inner core convection models. We explore the effect of both an hemispherical forcing, corresponding to the inner core convective translation regime, and smaller scale heterogeneities corresponding to the plume convection regime. We find that in both cases it is indeed possible to produce a globally stratified layer at the base of the outer core if the magnitude of the forcing is strong enough. With an hemispherical forcing, the resulting magnetic field can be strongly asymmetric, depending on the relative importance of the CMB and ICB buoyancy fluxes.

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Benard convection in the presence of horizontal magnetic field and rotation: Model 3 revisited

IBRAHIM A. ELTAYEB

Department of Mathematics and Statistics, College of Science, Sultan Qaboos University, P.O. Box 36, Muscat 123, Sultanate of Oman. Email: ieltayeb@squ.edu.om

The stability of a horizontal layer of thickness, d, heated from below and rotating uniformly, with angular velocity $\mathbf{\Omega}$, about a horizontal axis is studied in the presence of a uniform horizontal magnetic field, $\mathbf{B_0}$, inclined at an angle, ϕ, to the rotation vector. i.e. the so-called model 3 (Eltayeb, 1972). The contained fluid has a kinematic viscosity, ν, thermal diffusivity, κ, and magnetic diffusivity, η. The stability is governed by five dimensionless numbers: the Modified Rayleigh number R ($=\alpha\beta g d^2 / 2|\mathbf{\Omega}|\eta$, where α is the coefficient of thermal expansion and β the temperature gradient), measuring the buoyancy force relative to the Coriolis force, the ratio of the diffusivities, q ($=\kappa / \eta$), the so-called Elsasser number, Λ ($=|\mathbf{B}|_0 / 2|\mathbf{\Omega}|\mu\rho_0\eta$), which measures the Lorenz force relative to the Coriolis force, the Ekman number, E ($=\nu / 2|\mathbf{\Omega}|d^2$), which measures the viscous force relative to the Coriolis force and the ratio of conductivities, r (= σ_b / σ_f, where σ_b and σ_f are the electrical conductivities of the boundary and fluid, respectively). The stability is identified for the full range of the set $\{\Lambda, q\}$ always assuming that E is much smaller than unity but necessarily non-zero. The correct solutions are obtained in the form of mainstream and boundary layer solutions when the bounding planes are either both free and both rigid. Both steady and time dependent types of convection are investigated. The preferred mode of convection is identified for each type of convection and the overall preferred mode is is discussed in the parameter space (Λ, q, r). It is shown that the system supports a rich variety of modes and the transition of the unstable mode from one type of mode to another can be clarified by the presence viscosity. The influence of the electrical conductivity of the boundary is also included in the analysis.

Hemispheric variation of the depth dependent attenuation structures of the top half of the inner core observed by the global seismic array data

RYOHEI IRITANI[1], NOZOMU TAKEUCHI[2] & HITOSHI KAWAKATSU[3]

[1]Earthquake Research Institute, University of Tokyo, Tokyo, JAPAN
(ryohei9@eri.u-tokyo.ac.jp)
[2] Earthquake Research Institute, University of Tokyo, Tokyo, JAPAN
(takeuchi@eri.u-tokyo.ac.jp)
[3] Earthquake Research Institute, University of Tokyo, Tokyo, JAPAN
(hitosi@eri.u-tokyo.ac.jp)

Previous studies suggested the existence of the hemispheric heterogeneities in the top 100 km of the inner core (ex. Wen and Niu, 2002). However, the depth dependent profiles of the attenuation have not been well constrained because of the poor resolution due to difficulties in analysing contaminated core phase data. Iritani et al. [2010, GRL] employed a waveform inversion method based on simulated annealing (SA) that enables to analyse complicated waveforms with phase overlapping and applied it to NECESSArray which is a large temporary broadband seismic array installed in Northeastern China and Japanese Hi-net data. The obtained models show similar features that we have definite high attenuation zone around 200 km depth from ICB.

In this study, we collect high-quality core phase data from large number of broadband arrays to obtain the depth dependent profiles of the top half of the inner core in various regions. The resultant data set consists of about 8,500 waveform traces from PASSCAL arrays deployed in a number of places in the world, permanent European stations and USArray. Sampling regions are beneath northeastern Pacific, American and African continent for the western hemisphere of the inner core, and eastern and central Asia for the eastern hemisphere. We apply the same method as Iritani et al. [2010] to these data. In general, the obtained attenuation models for the western hemisphere show the gradually increase from ICB and have a peak around 200 km depth and those for the eastern hemisphere have a high attenuation zone at the top 150 km layer. However, almost all models show common features below 250 km depth and attenuation gradually decreases with depth. We also obtain the averaged structure models for each hemisphere, and similar features are observed. It appears that hemispheric heterogeneities of the inner core are confined in the top 150 – 250 km of the inner core.

Body wave tomography of Earth's inner core

JESSICA IRVING[1] & ARWEN DEUSS[2]

[1] Bullard Laboratories, Department of Earth Sciences, University of Cambridge, UK (jcei2@cam.ac.uk)
[2] Bullard Laboratories, Department of Earth Sciences, University of Cambridge, UK (afd28@cam.ac.uk)

The inner core of the Earth contains heterogeneity in P-wave velocity, with variation in both the isotropic velocity and anisotropy. The dominant signature of inner core structure is the 'hemispherical' pattern in the inner core; the eastern hemisphere has much weaker anisotropy than the western hemisphere. The fast axis of anisotropy coincides with earth's rotational axis. This large scale structure has been observed in both body wave studies and analysis of normal mode splitting functions. In addition to the hemispherical pattern, there is some variation of anisotropy with depth in the inner core; the uppermost western hemisphere is isotropic.

In order to better understand the heterogeneity present, we carry out tomographic imaging of the inner core under the northern Pacific Ocean and North America. We have gathered a high quality data set of PKPbc-PKPdf differential travel times corresponding to waves travelling through this region of the core. PKPdf is a compressional wave which travels through the inner core and can therefore reveal information about the velocity structure it encounters. By using PKPbc, which travels through the outer core but not the inner core, as a reference phase we are able to negate the effects of crustal structure and earthquake mis-location and mis-timing. We correct the measured differential travel times for ellipticity and known mantle structure. Our data come from earthquakes both in the Tonga-Samoa-Kermadec region and along the Kamchatka-Kuril Islands-Japan subduction zone, recorded at stations 145-156° from the events, over a ten year period. The crossing ray-paths afforded by these two different seismic regions enable us to carry out a tomographic inversion for the isotropic and anisotropic velocity structure of the inner core. We investigate the structure in both the eastern and western hemispheres, with a particular focus on the boundary between the two hemispheres. We invert the differential travel-time measurements for depth variation as well as lateral variation in properties of the inner core. Studies of regional variation in the seismic properties of the inner core, especially when combined with informations from studies of the inner core as a whole, will shed new light on the physical processes at work in Earth's core and will improve constraints that seismology can provide for studies of thermal evolution of the core and models of the geodynamo.

Can the F-layer be explained by a slurry model?

Marine Lasbleis[1], Stephane Labrosse [2], John Hernlund [3]

[1] Laboratoire de géologie de Lyon, Ecole Normale Supérieure de Lyon, CNRS, France
(marine.lasbleis@ens-lyon.fr)
[2] Laboratoire de géologie de Lyon, Ecole Normale Supérieure de Lyon, CNRS, France
[3] UC Berkeley, California, USA

For the last decades, seismic studies of the Earth core have improved tremendously our knowledge of its present structure. The solid inner core presents heterogeneity at all scales, including both regional and hemispherical variations in degree and possibly orientation of elastic anisotropy, small-scale scattering, and potential indications of internal layering. Recent observations also reveal interesting structures inside the liquid outer core, that may be interpreted as stratified layers. Because the inner core is growing from crystallization of the liquid iron from the outer part, thermal and structural evolution of the two parts are closely related.

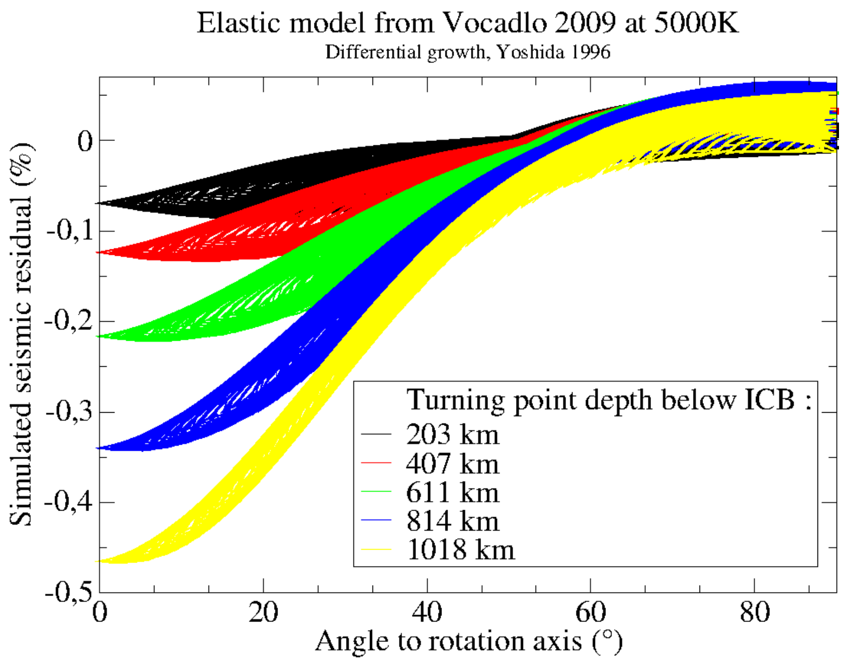
The F-layer, just above the inner core boundary (ICB), reveals gradients in seismic velocity different from the overlying isentropic outer core. This layer has been interpreted as a stably compositionally stratified region, depleted in light elements. The exact place where freezing occurs and the processes inside the F-layer determine the structure of the crystallizing inner core and may induce layering structure of the inner core without any need of movements after freezing. To explore this possibility, we propose a model of slurry inside the F-layer. Considering nucleation, settling and reactions of grains falling through a stratified layer, we compute the stability of a stratified layer undergoing a freezing snow. Modelling this reveals a dynamical feedback that could drive the system toward a basic state such as the entire stratified region is maintained at the liquidus. We find that diffusion is the dominant transport phenomenum inside the layer, between the outer core and the freezing inner core, for both temperature and composition. However, variations in heat flow with time, imposed by mantle convection, are likely to disrupt this basic state. The existence of such a stratified layer gives us better constraints on the present-day heat flow above the ICB.

Seismic anisotropy of the inner core deduced from geodynamical and mineralogical models

AINHOA LINCOT[1], PHILIPPE CARDIN[1] & SÉBASTIEN MERKEL[2]

[1] Institut des Sciences de la Terre (ISTerre), Université de Grenoble/CNRS, Grenoble, France (philippe.cardin@ujf-grenoble.fr)
[2] UMET, Université de Lille1/CNRS, Lille, France.

We generate different geodynamical models of formation of the inner core which take into account differential growth and stratification. According to the relative importance of these different processes, the present day inner core exhibits different signatures of the time evolution of its internal dynamics. Then, we use a visco plastic standart model to compute the lattice prefered orientation generated by the stresses associated to the geodynamical deformation process. Considering the presumed stable crystallographic phases of iron at inner core conditions, we define a chosen set of mineralogical elastic models both published and artificially generated. We compute the variation (amplitude and direction) of the P-wave velocity in the inner core. Then, we represent these results as maps/graph of travelling time anomalies (such as the figure below) which can be easily compared to real seismological data. These comparisons lead us to propose a preferred model of the growth evolution of the inner core. Also, the comparative study of the artificial elastic models allows a better understanding of the impact of the variation of specific crystallographic parameters on the resulting seismic signal and feedback on the different published Ab-Initio elastic models of iron.



High-pressure phase transitions and equations of state in NiSi: a combined *ab initio* and experimental study

OLIVER T. LORD[1], LIDUNKA VOČADLO[1], IAN G. WOOD[1], DAVID P. DOBSON[1], SIMON M. CLARK[2,3] AND MICHAEL J. WALTER[4]

[1] Department of Earth Sciences, University College London, Gower Street, London WC1E 6BT, England
[2] Advanced Light Source, Lawrence Berkeley National Laboratory, MS6R2100, 1 Cyclotron 67 Road, Berkeley, CA 94720-8226, USA
[3] Present Address: Department of Earth and Planetary Sciences, Macquarie University, NSW 2109, Australia
[4] School of Earth Sciences, University of Bristol, Wills 68 Memorial Building, Queen's Road, Bristol BS8 1RJ, England

First-principles calculations [1] have been combined with synchrotron-based X-ray powder diffraction experiments [2] in the laser-heated diamond anvil cell (LHDAC) to determine the high-pressure structures of NiSi, and their equations of state, up to inner core pressures. The static *ab initio* simulations sucessfully predict the thermodynamic stability of the known ambient pressure MnP (B31) structure (space group *Pnma*). With increasing pressure, the simulations predict the stabilization of the following sequence of previously undescribed polymorphs: 1) the tetragonal γCuTi (B11) structure (space group: *P4/nmm*) at ~23 GPa, 2) an orthorhombic structure (*Pbma*) at ~61 GPa, 3) the orthorhombic FeB (B27) structure (*Pnma*) at ~168 GPa, and finally, 4) the CsCl (B2) structure (*Pm3m)* at ~247 GPa.

Subsequent synchrotron XRD analysis of quenched, laser-heated NiSi samples at room temperature and pressures up to 124 GPa in the LHDAC revealed two high *P-T* phase transitions, from the known ambient pressure MnP (B31) structure: first to the ε-FeSi (B20) structure (space group $P2_13$) at 12.5±4.5 GPa and 1550±150 K and then to the CsCl (B2) structure at 46±3 GPa and 1900±150 K as predicted by the simulations. This strongly suggests that at inner core conditions (and indeed throughout most of the Earth), both NiSi and FeSi [3] are isostructural, leading to a solid solution and a single (Fe,Ni)Si phase. The ε-FeSi (B20) structure was not stable at any pressure in the static *ab initio* simulations. However, given its low enthalpy difference relative to the stable structures (as low as 8 meV atom^{-1} at 60 GPa) and the fact that this structure is the stable form of FeSi at ambient conditions, its appearance at the high temperatures (up to 2700 K) reached in the LHDAC experiments is not surprising. Experimental 3rd order Birch-Murnaghan equations of state for all three phases produce *P-V* curves which match closely with those derived from the *ab initio* equations of state. Three trace phases, possibly formed during temperature quench, represent at least one, and possibly all three of the remaining non-ambient phases predicted to be stable in the *ab initio* simulations) although one of these may represent another new polymorph (space group *Pmmn*) recently detected in multi-anvil press quench experiments [4] and subsequently found to be more stable than the tetragonal γCuTi (B11) structure in ab initio simulations [5]. A fourth trace phase represents a modification of the FeB (B27) also detected in the simulations though not predicted to be stable. However, the close correspondence between simulation and experiment in terms of both the stability of the different NiSi polymorphs and their *P-V* relations lend weight to the accuracy of both approaches and highlight the power of combining them. Further experimental work is currently underway to determine the details of the surprisingly rich NiSi phase diagram.

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Combining seismic constraints with thermal models of inner core evolution

KAREN LYTHGOE[1], ARWEN DEUSS[2], JOHN RUDGE[3] & JEROME NEUFELD[4]

[1] Bullard Laboratories, Department of Earth Sciences, University of Cambridge, Cambridge, UK
(khl43@cam.ac.uk)
[2] Bullard Laboratories, Department of Earth Sciences, University of Cambridge, Cambridge, UK
(afd28@cam.ac.uk)
[3] Bullard Laboratories, Department of Earth Sciences, University of Cambridge, Cambridge, UK
(jfr23@cam.ac.uk)
[4] Institute of Theoretical Geophysics, Department of Mathematics and Theoretical Physics, University of Cambridge, Cambridge, UK
(j.neufeld@bpi.cam.ac.uk)

Seismology has provided many important insights into the structure of the Earth's inner core, including observations of anisotropy, isotropic layering and hemispherical variations: polar rays travel faster than equatorial rays, with strong anisotropy in the western hemisphere and weak anisotropy in the eastern hemisphere. However, many questions remain unanswered, particularly regarding the depth dependence of inner core properties and the origin of seismic anisotropy. The inner core grows through the solidification of the outer core at the inner core boundary, resulting in a time-depth relationship with deeper structure being older. Understanding the structure and dynamics of the inner core is needed to constrain key events in Earth's history, particularly in the context of the Earth's magnetic field.

PKIKP is a seismic phase that travels through the inner core, therefore PKIKP observations provide one of the only methods to study the deep inner core. We use absolute PKIKP travel-time observations to investigate inner core anisotropy. We further use thermal models of inner core growth to place our seismological observations in context of the growth history. In this way, a comparison of seismological observations and thermal growth models can be used to place dynamical constraints on the depth-dependence of observed structures within the Earth's inner core.

Anelasticity in the Earth's inner core studied using normal modes

ANNA M. MÄKINEN[1] & ARWEN DEUSS[2]

[1] Bullard Laboratories, Department of Earth Sciences, University of Cambridge, Cambridge, UK (amm210@cam.ac.uk)
[2] Bullard Laboratories, Department of Earth Sciences, University of Cambridge, Cambridge, UK (afd28@cam.ac.uk)

Normal modes – the free oscillations of the planet Earth as a whole – offer the mathematical seismologist a powerful tool for studying large-scale structures in the Earth. Normal mode seismology is particularly well suited to analyses of the deeper parts of our planet, where surface waves do not propagate and where body-wave studies are severely limited by source-receiver geometries. Sensitive to the 'average' Earth, normal modes have, in the past, been extensively used in studies of velocity anisotropy in the inner core, the planet's deepest region, which grows by crystallization of the highly dynamic outer core. Such studies have shed light on the cylindrical anisotropy of the inner core. Cross-coupling (resonance) between different modes of similar frequencies, on the other hand, has previously been used to elucidate the hemispherical anisotropy also present in the inner core. A detailed understanding of such features is a prerequisite for integrating evidence from geodynamics, geodynamo modelling and outer core dynamics for a more complete model of the Earth as a planet.

Anelasticity in the deep Earth has, for a number of years, presented a problem to seismologists; for the inner core in particular, distinguishing between the effects of geometric spreading, scattering and intrinsic attenuation – anelasticity – remains a challenge when body wave data and methods are utilized. Normal modes, with their wavelengths of thousands of kilometres and global nature of oscillation, are affected by neither scattering off small-scale heterogenities in the deep Earth nor by geometric spreading of wavefronts, and thus possess the ability to provide direct information on anelasticity. In this work, we have developed a new method to use the splitting of normal modes to map the lateral variations in anelasticity in the deep Earth. This study has a particular emphasis on the inner core, where the relationship between elastic and anelastic structures, as elucidated by normal mode splitting, is also investigated.

The effect of nickel on the sismic wave velocities of iron at the conditions of Earth's inner core

BENJAMÍ MARTORELL[1], JOHN BRODHOLT[2], IAN G. WOOD[2], LIDUNKA VOČADLO[2]

[1] Department of Earth Sciences, University College London, London, WC1E 6BT, UK (b.massip@ucl.ac.uk)

[2] Department of Earth Sciences, University College London, London, WC1E 6BT, UK

Understanding the physical properties of the Earth's core is a key step in the study of the evolution and dynamics of our planet. The Earth's inner core is a solid Fe-Ni alloy at high temperature (~ 6000 K) and high pressure (330<P<360 GPa). Furthermore, to account for the lower than expected density in the Earth's core, it has been suggested that light elements must also be present. While the effect of light elements on the properties of iron have been the subject of an extensive literature, the effect of nickel on the properties of iron has often been overlooked, possibly due to the expectation that the properties of Ni and Fe will be similar. However, recently, high P-T experiments and theoretical studies of Fe-Ni alloys studies have been undertaken in order to assess whether this assumption is valid. Here we present athermal periodic plane-wave density functional calculations within the generalized gradient approximation on the bcc, fcc and hcp structures of $Fe_{1-X}Ni_X$ alloys (X= 0, 0.0625, 0.125, 0.25, and 1) in order to obtain their relative stability and elastic properties at 360 GPa and 0 K. For the hcp structure, using ab initio molecular dynamics, we have also calculated the high temperature elastic properties and wave velocities, for X = 0, 0.0625, 0.125, at 360 GPa and 5500 K.

At 0 K, the hcp structure is the most stable for X = 0, 0.0625, 0.125, and 0.25, with the fcc structure becoming the most stable above X ~ 0.45; the bcc structure is unstable throughout. The compressional and shear wave velocities are structure dependent: in the case of fcc the velocities for the alloys are very similar to pure Fe, but for the hcp structure the addition of Ni markedly reduces both V_p and, especially, V_s. However, at 5500 K, this effect disappears and the wave velocities of hcp-Fe/Ni alloys remain very similar to those of pure iron throughout the range of compositions studied. At 0 K, the maximum anisotropy in V_p is found to be only very weakly dependent (slightly positive slope) on nickel content, but dependent on structure, being ~15% for fcc and ~8% for hcp. For the hcp structure at 5500 K, the maximum anisotropy in V_p is also ~8%. We conclude, therefore, that Ni does indeed behave simlarly to Fe and can safely be ignored when considering its effect on the seismic properties of hcp-Fe under core pressures and temperatures.

Implications for thermal and mechanical states of the inner core in numerical dynamo simulations with heterogeneous boundary heat flux

TAKASHI NAKAGAWA[1]

[1]Institute for Reasearch on Earth Evolution, Japan Agency for Marine-Earth Science and Technology, Yokohama, 236-0001, Japan; ntakashi@jamstec.go.jp

Recent progresses on numerical dynamo simulations can be implied for thermal state of the inner core [2][4]. Those models are simulated for numerical dynamo models with non-uniform top thermal boundary condition. Their non-uniform boundary conditions have been obtained from some linear relationship between shear anomalies of global tomography and heat flux across the core-mantle boundary (CMB). In our previous study [5], the CMB heat flux cannot be simply converted from seismic anomalies because their conversion relationship is strongly non-linear and the peak-to-peak amplitude of CMB heat flux heterogeneity would be extremely huge compared to ordinary numerical dynamo simulations with a non-uniform top boundary converted from tomographic image. In addition, they did not check the mechanical state of the inner core in terms of differentation rotation. Aubert and Dumberry [2011] [3]has systematically investigated the variation and stability of inner core rotation in numerical dynamo simualtions but not checked how the thermal heterogeneity at the top boundary affects the rotation of the inner core. Here, we investigate both thermal and mechanical states of inner core using numerical dynamo simulations with an non-uniform boundary condition calculated from numerical mantle convection simulations. For numerical dynamo models, we assume incompressible and Boussinesq fluid in a rotating spherica shell with insulating top and conductive inner boundary. In order to convert from CMB heat flux heterogeneity calculated from numerical mantle convection to imposed thermal heterogeneity for numerical dynamo simulations, we use $q_{CMB} = k_m \Delta T_m / q_0 d_m \; F_{CMB} = a F_{CMB}$ where k_m is the thermal conductivity of mantle, ΔT_m is the temperture-scale of mantle, d_m is the thickness of mantle and q_0 is the reference heat flux from the core. Here we assume two patterns calcualted from numerical mantle convection simulations (both isochemical and thermo-chemical mantle convection (after [6]) with three different values of a (=0.02, 0.04 and 0.08), which assume different reference heat fluxes from the core corresponding to 5 to 20 TW because mantle properties should be fixed here. One tomographic pattern is used with q*=0.5 based on a conversion formula provided from Amit and Choblet [2009] [1]. The CMB heat flux is given as spherical harmonic coefficients up to degree of 16 because the resolutions between mantle convection and dynamo simulations are different. Preliminary results on our simulations suggest that the thermal heterogeneity of the inner core boundary (ICB) seems to be low path or band path filter for the CMB heat flux heterogeneity. This means that the ICB heat flux is likely to have large-scale feature even small-scale boundary heat flux across the CMB has been imposed thus the inner core also tends to have large-scale heterogeneous anomalies as well as on its growth. This is somewhat similar discussion to previous studies [4]. Regarding with the rotation direction of the inner core, it is strongly dependent on the horizontal-scale and the peak-to-peak amplitude of CMB heat flux heterogeneity and viscous torque caused by fluid flow in the outer spherical shell.

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Thermal and electrical conductivity of iron at Earth's core conditions

MONICA POZZO[1], CHRISTOPHER DAVIES[2], DAVID GUBBINS[2,3] & DARIO ALFÈ[1,4]

[1] Department of Earth Sciences and Thomas Young Centre @ UCL, UCL, Gower Street, WC1E 6BT, London, U.K
m.pozzo@ucl.ac.uk
[2] School of Earth and Environment, University of Leeds, Leeds LS2 9JT, UK
c.davies@leeds.ac.uk
[3] Institute of Geophysics and Planetary Physics, Scripps Institution of Oceanography, University of California at San Diego, 9500 Gilman Drive #0225, La Jolla, CA 92093-0225
gubbins@earth.leeds.ac.uk
[4] Department of Physics and Astronomy and London Centre for Nanotechnology, UCL, Gower Street, WC1E 6BT, London, U.K
d.alfe@ucl.ac.uk

The power supplied to the geodynamo, measured by the heat-flux across the core-mantle boundary (CMB), places constraints on the evolution of Earth's deep interior. Estimates of CMB heat-flux depend on properties of iron mixtures under the extreme pressure and temperature conditions in the core, most critically on the thermal and electrical conductivities. We compute these conductivities at core conditions for liquid iron mixtures that fit the seismologically-determined core density and inner-core boundary density jump using density functional theory (see research talk by Dario Alfè in session S2). We find both conductivities to be 2-3 times higher than estimates in current use. The changes are so large that core thermal histories and power requirements must be reassessed. New estimates of adiabatic heat-flux give 15-16 TW at the CMB, higher than present estimates of CMB heat-flux based on mantle convection. A thermally stratified layer beneath the CMB is therefore inevitable unless a very high present-day CMB heat-flux can be maintained, which requires a rapid CMB cooling rate and an inner core that is only $\sim 300 - 400$ Myr old. We estimate stable layer thicknesses using the condition of neutral buoyancy for a range of plausible values for CMB heat-flux, finding thermally stable layers that can span hundreds of kilometres. These calculations also suggest that compositional buoyancy is insufficient to overcome the large stabilising thermal gradient; any convection in the upper core must be driven by penetration or instabilities arising from convection deeper inside the core, or by lateral variations in CMB heat flow.

Dissolution of the protocore and geomagnetic field generation

YURY D. PUSHKAREV[1], SERGEY V. STARCHENKO[2]

[1]Institute of Precambrian Geology and Geochronology, St.-Petersburg, Russia. (ydcanon@rambler.ru)
[2]Institute of Terrestrial Magnetism, Ionosphere and Radio Wave Propagation, Troitsk, Moscow Region, Russia (sstarchenko@mail.ru)

There are evidences of an ancient geomagnetic field existence [2, 3, etc.] up to the early Archean [8], which intensity is identical to the modern one. This information contradicts with the generally accepted ideas according to which the geodynamo, that generates the modern magnetic field of the Earth, is produced by the compositional convection caused due to crystallization of a liquid core [1, 5, 7]. The most probable time of excitation of compositional convection is estimated not earlier than 2 Ga [4, 7]. It follows that before this time the geomagnetic intensity had to have the lower value because it was generated only by inefficient thermal convection. Thus, if the compositional convection is required to generate the Archean geomagnetic field, the intensity of which is close to the modern one, this convection should have some other nature. At the same time magmatic derivatives of the mantle material sometimes contain primary noble gases and in particular the isotope ^{129}Xe. It demonstrates that somewhere in the Earth there is a material which become geochemically closed with regard to noble gases before ^{129}I complete decay, i.e. <150 million years after the beginning of accretion.

The conception [6] which can explain all above mentioned is offered. It suggests that the solid core of the Earth didn't crystallize from the liquid one, but represents the small relict of the protocore on which heterogenic accretion has begun. The protocore consists of a mixture of heavy metal iron-nickel alloy and light chondrite silicate component which contains primary noble gases. Soon after the end of accretion or near to its end, the geosphere of the liquid core was formed in an external part of planet. It started to plunge, expanding due to melting of new portions of iron-nickel alloy. This expansion is happening rather fast during the period of initial formation of the liquid core geosphere due to its intensive overheating. Then the expansion rate is decelerated. The first reason of this is the decreasing of the temperature difference between liquid geosphere and solid protocore. It leads to the slower conductive transport of the heat necessary to melt the protocore. Namely the rate of this conductive heat transport determines the time needed for the protocore dissolution in the liquid core geosphere. If we use thermal conductivity of the modern liquid core for estimation of this time we will obtain a few billion years as it is required for our conception. During protocore dissolution the silicate chondritic component of protocore is liberated (fig.1). It floats up through metallic melt of liquid core and generates composite convection, which mainly supports geodynamo.

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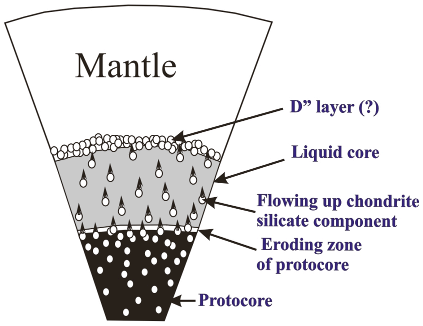

Fig. 1. Liquid core-protocore interaction as a reason of geomagnetc field generation

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Reevaluating gravitational coupling in the core-mantle system

DAVE R. STEGMAN[1], CHRIS J. DAVIES [2]

[1] Scripps Institution of Oceanography, Institute of Geophysics and Planetary Physics, University of California, San Diego, La Jolla, USA
(dstegman@ucsd.edu)
[2] School of Earth and Environment, Institute of Geophysics and Tectonics, University of Leeds, Leeds, UK
(c.davies@leeds.ac.uk)

Angular momentum exchange between the mantle and core has long been associated with observed variations in the length of the day (LOD). Decadal variations in LOD have previously been inferred to represent periods of torsional oscillations in the fluid outer core (Braginsky, 1970), rigid rotations of concentric cylindrical surfaces that are coupled by the magnetic field that permeates them. A critical aspect to this explanation is the strength of the component of the magnetic field that provides the restoring force for the motions: stronger field decreases the oscillation period. On shorter timescales, a six-year variation in LOD has been attributed to gravitational coupling due to mass anomalies in the mantle, which deflect equipotential surfaces in the core thus leading to oscillations associated with angular momentum exchange (Buffett, 1996; Mound and Buffett, 2006). Crucial to this mechanism is a sufficiently large viscosity of the inner core, such that deflections of its equilibrium shape relax on timescales longer than the period of oscillation, and the amplitude of the coupling constant, which determines the period of oscillation. The majority of studies since the work of Buffett (1996) use standard values for these parameters that are consistent with gravitational coupling being the cause of the six-year LOD signal. However, recent work has found that the magnetic field strength in the core is much larger than previously thought, with the implication that torsional oscillations can be fast enough to explain the six-year signal in LOD (Gillett et al, 2010). Therefore, we are motivated to reanalyse the gravitational coupling problem in a more general manner without the onus of demonstrating causality for the six-year LOD signal. We use a method similar to that of Buffett (1996) to calculate three-dimensional density and gravitational potential anomalies throughout the mantle from recent models of seismic tomography. We calculate the response of a hydrostatic core to these anomalies and present revised estimates for the gravitational coupling constant, showing its dependence on the assumed tomographic model. Finally, we calculate the frequency spectrum for the eigenmodes of inner core oscillations and estimate the minimum viscosity of the inner core associated with each eigenmode.

Frequency dependent amplitude ratio of PKiKP/PcP observed at the Hinet array: Possible detection of a thin liquid layer above the inner core boundary

SATORU TANAKA[1] and HRVOJE TKALČIĆ[2]

[1] IFREE, JAMSTEC, 2-15 Natsushima-cho, Yokosuka 237-0061, Japan (stan@jamstec.go.jp)

[2] RSES, The Australian National University, Canberra ACT 0200, Australia

The inner core boundary (ICB) is a vital region for understanding the Earth's core dynamics. Seismological studies of its physical condition are important in elucidating the growth mechanism of the inner core and the source of geodynamo. The amplitude ratio of PKiKP/PcP has been used for the inference of the density jump at the ICB as well as the shear velocity at the top of the inner core. Previous studies, which have usually analyzed amplitudes of PKiKP waves with predominant frequency of 1 Hz, were hampered by their large scatter which precluded constraining relevant parameters of the ICB structures. Recently, Poupinet and Kennett (2004) reported the existence of high frequency PKiKP (up to 5 Hz) with steep incident angles at the ICB observed across arrays and temporal broadband networks on the Australian continent. Here we observe and collect a significant volume of such high frequency PKiKP waves recorded by a dense network in Japan — Hinet, to examine its frequency characteristics and relevance for understanding the Earth's core dynamics in the quasi-eastern hemisphere.

We found clear PcP and PKiKP phases on high-pass filtered seismograms of 9 events with magnitude greater than 6.5 around Japan, of which hypocenters are located at Volcano Is., Mariana Is., Andreanof Is., Kuril Is., Sea of Okhotsk, Philippine, Banda Sea, Sumatra Is. The location of these events and the Hinet array covers epicentral distance range from 15 to 45°. The spectra of PcP and PKiKP waves show several peaks around 1 and 2 Hz, resulting in the variations in the spectral ratio of PKiKP/PcP. For some events, clear spectral peaks at frequencies greater than 3 Hz emerge. We find a general tendency that the spectral ratio of PKiKP/PcP around 2 Hz is almost constant (~0.2) whereas that around 1 Hz differs for different events (or as a function of epicentral distance). Further analysis including the effects of source radiation, attenuation in the mantle and variations with epicentral distance reveals that the peak spectral ratios present around 1 Hz gradually decrease from ~0.2 at 15° to ~0.04 at 45°, which is similar to PKiKP/PcP amplitude ratio predicted by the refection of a plane wave from the ICB. The spectral ratio around 2 Hz shows a smaller amplitude decay from ~0.2 at 15° to ~0.1 at 45°. This observation and preliminary trials by using a finite-difference simulation qualitatively suggests the existence of a very thin liquid layer with thickness of 1 km or slightly less just above the ICB. This might be in agreement with recently proposed core dynamics in which the eastern hemisphere of the ICB is characterized by melting (Monnereuau et al., 2010; Alboussiere et al., 2010).

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The composition of the cores of terrestrial planets – understanding the iron-nickel-silicon system

ELIZABETH WANN[1], LIDUNKA VOČADLO, IAN G. WOOD & DAVID P. DOBSON

Department of Earth Sciences, University College London, London, UK
[1] elizabeth.wann.11@ucl.ac.uk

The composition of the cores of terrestrial planets is not well understood, but it is believed that they consist primarily of an iron-nickel alloy with a small fraction of light elements[1]. In the case of the Earth, the possible candidates for the light elements are constrained by cosmochemical arguments[2]. However, although the exact nature of the light element is still in dispute, it is widely believed that Si is a significant light element in the core[3]. As such, research into the iron-nickel-silicon ternary system is invaluable for our understanding of the composition of the Earth's core and of planetary cores in general.

Both experimental and computational methods have been used to understand the iron-nickel-silicon ternary system. We have intially focused on the FeSi and NiSi binary systems as an understanding of these is beneficial in understanding the ternary. We have carried out *ab initio* calculations on a variety of different structures, including structures that have previously been considered for NiSi[4] and we find that, as expected, the CsCl structure is the stable structure at high pressures for both end members. Currently we are carrying out further computer simulations to investigate the effect of temperature on the ε-FeSi to CsCl transition pressure.

The complementary methods of experiment and computational work have already yielded important results, and we hope to build upon these results to develop a greater understanding of the iron-nickel-silicon system.

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The attenuation structure of Earth's uppermost inner core, and its relationship to seismic velocity

LAUREN WASZEK, ARWEN DEUSS

University of Cambridge, Bullard Laboratories, Department of Earth Sciences, Cambridge, CB3 0EZ (lw313@cam.ac.uk)

The attenuation properties of the inner core are directly linked to energy loss mechanisms which occur as a result of the crystalline structure, and thus when investigated in combination with the velocity structure, we can gain much insight into the compositional properties of the inner core. An east-west hemispherical structure in the seismic attenuation of Earth's upper inner core has been found, displaying stronger attenuation in the east than the west. Furthermore, attenuation anisotropy has also been observed. These structures appear to correspond to features in the velocity structure, and in particular, that regions of high (low) velocity correspond to strong (weak) attenuation. However, the detailed attenuation structure is relatively unconstrained compared to the well-documented velocity; the difficulties in measuring attenuation are due to large quantities of scatter in the data. As a result, the relationship between the attenuation and velocity properties remains unclear.

Earth's inner core grows through solidification of material from the fluid outer core, freezing in seismic properties into the structure as the inner core grows. This results in an age-depth relation for the inner core, whereby deeper structure is older, meaning that we are able to study the history of the growth of the inner core through examining variations in seismic structure with depth. As the most recently formed part of the inner core, the upper layers provide us with information regarding growth processes and post-solidification mechanisms. We explore the detailed hemispherical attenuation structure in the uppermost inner core by using a large global dataset of amplitude ratios of PKIKP and PKiKP. We use this dataset to derive models of the seismic attenuation structure in the upper 100 km of the inner core, detailing the isotropic and anisotropic Q_α values separately for each hemisphere, ultimately resulting in a layered hemispherical model.

In order to investigate the link between attenuation and velocity, we combine our new attenuation model with a seismic velocity model which we previously calculated using the differential travel time residuals of PKIKP and PKiKP [1]. Understanding the relationship between these two seismic structures is another step towards determining the origins of the hemispherical differences and anisotropy, and the associated growth and post-solidification mechanisms which create the fabric of the inner core.

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S3: Outer Core - Observations of Structure & Composition

Invited Talk

Observational Constraints on the Dynamics of the Outer Core

Chris Finlay[1]

[1] National Space Institute, Techincal University of Denmark, Copenhagen, Denmark.
(cfinlay@space.dtu.dk)

This review talk will focus on recent advances in the use of magnetic observations to probe the dynamics of the Earth's outer core. A brief introduction will be given to sources of the Earth's magnetic field, and how these may be observed on various time scales. Use of the magnetic induction equation to infer core motions from magnetic observations will briefly be described. Examples of recent studies using magnetic observations to provide insights into the core and the geodynamo will be presented. These will include reconstructions of the core surface field during the past 10,000 years, results from new ensemble inversion methods applied to the observatory era, and what has been learnt concerning rapid changes in the core from the past decade of continuous, high resolution, satellite observations. Future prospects, outstanding observational challenges, and the opportunities presented by ESA's upcoming Swarm satellite constellation will also be discussed.

Invited Talk

Modelling Earth's magnetic field variation

INGO WARDINSKI[1]

[1] Helmholtz Centre Potsdam, GFZ German Research Centre for Geosciences, Potsdam, Germany (ingo@gfz-potsdam.de)

Observations of the Earths magnetic field taken at the Earth's surface and at satellite altitude have been combined to construct models of the geomagnetic field and its variation. Most recently we have developed a method for constructing core field models that satisfy the frozen-flux constraint [2]. Constraining the field evolution to be entirely due to advection of the magnetic field at the core surface maintained the spatial complexity of the field morphology imposed by satellite field model backward in time [3]. Here, one question (at least) arises; can such formalism of kinematic secular variation reconstruction be used to indicate future Earths magnetic field variation?

Our approach to forecast geomagnetic field changes consists of two parts. In the first part we seek to identify typical time scales of the magnetic field variation by studying magnetic field models which cover decades to millennia. In the second part we model the temporal variability of the field variation and the core surface flow by stochastic models. Thereby, the coefficients of the spherical harmonic expansion describing the secular variation and the core surface flow $(\dot{g}_\ell^m(n), \dot{h}_\ell^m(n), t_\ell^m(n), p_\ell^m(n))$ are considered as discrete time series. The simplest stochastic model for a finite discrete series is a first-order autoregressive 'AR(1)' process

$$r_n = \rho r_{n-1} + \eta_n$$

where r is a time series of N successive observations with discrete time increments, ρ the lag-one autocorrelation coefficient, and η_n a Gaussian white noise sequence with variance σ^2. In general, an autoregressive 'AR(p)' process of order p

$$r_n = \rho_1 r_{n-1} + \rho_2 r_{n-2} + ...\rho_p r_{n-p} + \eta_n$$

is a linear model that relates a dependent variable r_n to a set of p independent variables ρ_p. Many time series, and secular variation in particular, show a non-stationary behaviour and do not vary around a fixed mean. However, the broad behaviour may consist of some homogeneity, which might only be captured by a generalized model that calls for the d'th difference of the process to be stationary. Such model is referred to autoregressive integrated moving average process (ARIMA) [1].

By computing stochastic models, we obtain two sets of field-forecasts, the first set is obtained from stochastic models of the Gauss coefficients $(\dot{g}_\ell^m(n), \dot{h}_\ell^m(n))$. Here, first results suggest that secular variation on time scales shorter than 5 years behaves rather randomly and cannot be described sufficiently well by stochastic models. Whereas the second set is derived from the forward modelling the secular variation using the diffusion-less induction equation

$$\dot{\mathbf{B}}_r = -\nabla_h \cdot \left(\tilde{\mathbf{v}}\mathbf{B}_r^0\right)$$

where $\tilde{\mathbf{v}}$ represent the forecast of the flow variation $(t_\ell^m(n), p_\ell^m(n))$, and $\mathbf{B}_r^0$ the radial magnetic field at a given epoch. Yet, this approach has not provide consistent results.

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Invited Talk

Evidence for and consequences of outer core stratification

GEORGE HELFFRICH[1] AND SATOSHI KANESHIMA[2]

[1]Dept. of Earth Sciences, University of Bristol, Bristol, United Kingdom. George.Helffrich@bristol.ac.uk
[2]Department of Earth and Planetary Sciences, Kyushu University,Fukuoka, Japan.

Seismic waves that are multiply reflected from the underside of the core-mantle boundary (CMB) at grazing incidence provide a detailed probe of the velocity structure at the top of the outer core. There is a long history of study of these arrivals due to the constraints they potentially place on processes acting at the CMB: core-mantle reaction, localized melting, lateral variation of heat flux are a few of the them. The deployment of dense regional seismometer networks represents an opportunity to broaden the observational bases of a new generation of CMB studies. We report here on one such study that indicates that the top few hundred km of the outer core has significantly lower wavespeeds than the reference model PREM, in agreement with previous studies of the outermost core. Detection and measurement of higher-order multiple reflections in the data allow narrower uncertainty bounds to be placed on the wavespeed profile than were previously possible. Birch's self-compression test, applied to the profile, indicates that the region significantly deviates from homogeneous self-compression, indicating compositionally different material at the top of the outermost core.

Stratification has consequences for the dynamical behavior, energetics, and chemical evolution of the core. The region is probably not stagnant, but radial mixing in it must be suppressed in order to maintain its compositional identity. Horizontal flows are still possible and would carry radial magnetic flux, contributing to geomagnetic secular variation. Radial mixing is probably quelled due to a subadiabatic temperature gradient in the region. This is possible given the combined uncertainty of the thermophysical properties of core materials and the heat flux out of the core.

The time-dependence of intense archeomagnetic flux patches

HAGAY AMIT[1], MONIKA KORTE[2], JULIEN AUBERT[3], CATHERINE CONSTABLE[4] & GAUTHIER HULOT[5]

[1] CNRS UMR 6112, Université de Nantes, Laboratoire de Planétologie et de Géodynamique, 2 Rue de la Houssinière, Nantes F-44000, France
(Hagay.Amit@univ-nantes.fr, Benoit.Langlais@univ-nantes.fr)
[2] HelmholtzZentrum Potsdam, Deutsches GeoForschungsZentrum, Potsdam, Germany
(monika@gfz-potsdam.de)
[3] Equipe de Dynamique des Fluides Géologiques, Institut de Physique du Globe de Paris, Sorbonne Paris Cité, Université Paris Diderot, INSU, CNRS, UMR 7154, Paris, France
(aubert@ipgp.fr)
[4] Institute for Geophysics and Planetary Physics, Scripps Institution of Oceanography, University of California, San Diego, La Jolla, California, USA
(cconstable@ucsd.edu)
[5] Equipe de Gomagnétisme, Institut de Physique du Globe de Paris, Sorbonne Paris Cité, Université Paris Diderot, INSU, CNRS, UMR 7154, Paris, France
(gh@ipgp.fr)

The long-term temporal behavior of intense geomagnetic flux patches at the core-mantle boundary and the relation with lower mantle lateral heterogeneity are under debate. We apply an algorithm to detect centers of intense flux patches and track their time evolution in a recent archeomagnetic field model in order to study the kinematics of such intense magnetic flux patches on millennial timescale. We find that most intense flux patches appear near the edge of the tangent cylinder. Quasi-stationary periods with small oscillations of patches occur more than drifts. Detailed comparison of the archeomagnetic patches' behavior with that seen in numerical dynamos with tomographic heat flux boundary conditions suggests that core-mantle thermal coupling could be the cause of a statistical preference for some longitudes on the long term, which does not exclude significant time spent away from the preferred longitudes. This could explain the roughly coincident locations of high-latitude patches in the historical geomagnetic field with that of the timeaverage paleomagnetic field together with the much weaker patches intensity in the latter. Alternating eastward and westward drifts are also observed. The drifts are more westward than eastward, especially in the southern hemisphere, indicating that the time-average zonal core flow may also be driven by coremantle thermal coupling. An average patch lifetime of 300 years is found, which we hypothesize may indicate the vortex lifetime in the outer core.

An analysis of recent subdecadal variations of core flow and LOD

SEIKI ASARI[1] & INGO WARDINSKI[2]

[1] Helmholtz Centre Potsdam, GFZ German Research Centre for Geosciences, Potsdam, Germany (asari@gfz-potsdam.de)
[2] Helmholtz Centre Potsdam, GFZ German Research Centre for Geosciences, Potsdam, Germany (ingo@gfz-potsdam.de)

C^3FM2 geomagnetic field model (1957.0-2008.4; order 6 B-spline, knot interval 1.39 year) is used to study rapid variations of the geostrophic flow (axially and equatorially symmetric azimuthal flow) in the Earths fluid core. We examine the joint C^3FM2 flow model (purely toroidal flow model coestimated with C^3FM2 field model under the frozen-flux hypothesis) as well as time-dependent flow models built by the conventional inversion with different constraints, including tangential geostrophy, tangential magnetostrophy (TM), helical flow and relaxed quasi-geostrophy. The time variability of the geostrophic flows from these models is analyzed in spectral and temporal domains. For the spectral analysis, the multi-taper method is applied to obtain the spectral power densities of the observed length-of-day (LOD) variation and its coherences with the core angular momentum (CAM) carried by the geostrophic flows. In the temporal analysis, rapid variations are extracted from the geostrophic flows by filtering out longer variations and trends, in order to reveal the temporal and spatial distributions of the subdecadal fluctuations.

The findings of the analyses are: 1) Power of LOD six-year periodicity is less significant than those of slower oscillations with periods near eight and ten years. The coherence with CAM is significantly high at these longer periods. 2) The amplitude of rapid geostrophic flow oscillations is relatively small for the joint C^3FM2 flow model and those estimated with weaker constraints such as TM. 3) Six-year oscillation propagating outward from the inner core tangent cylinder is not clearly seen in the C^3FM2 geostrophic flow models estimated with any flow constraints, which contrasts with the same analysis based on gufm1 geomagnetic field model.

How to Handle Geomagnetic Jerks

Will Brown[1], Jon Mound[1] & Phil Livermore[1]

[1] Institute of Geophysics and Tectonics, School of Earth and Environment, University of Leeds, Leeds, UK (ee07wjb@leeds.ac.uk)

The secular variation of the Earth's core generated magnetic field, describes the variation of the field at timescales on the order of months to decades. The secular variation is often characterised as a series of linear trends, separated by abrupt turning points known as geomagnetic jerks. These jerks are apparent as step changes in the secular acceleration. Much is unknown about jerks; their significance, origins, recorded occurrences, spatial and temporal extent and indeed the precise definition which describes the phenomenon are still debated. These uncertainties have lead to a variety of works addressing the identification and analysis of jerks and several attempts have been made to extract further information from these phenomenon. Investigations have been made into, for example; core surface flows, mantle electrical conductivity and links to other observed properties such as length of day variations. Such studies have utilised observatory, satellite and modelled magnetic field data, predominantly at annual or monthly sampling rates. A key to jerk based studies lies in the accurate identification in time and space of jerks from which other information can be derived, a task confounded by the sparse sampling of the data and the prevalence of external field noise. No definitive method has yet been demonstrated which addresses the key issues of noise handling, accurate jerk identification and error analysis. Nevertheless, recent work has advanced the understanding in each of these areas. This poster presents the development of a combined method addressing noise reduction techniques, identification methods and attempts at quantifying errors.

It has been shown that the effects of external signals, predominantly the equatorial ring current, can be reduced by removing signal which is correlated with indices of solar activity or the residual to a magnetic field model in the direction of ring current effects[1]. This acts to improve the time resolution of features such as jerks. While traditionally jerks were identified by linear regression of selected sections of data containing a single jerk event, it is suggested that more reliable results can be achieved through methods which consider an entire timeseries at a given location. A stationary linear regression technique[2] is adapted to utilise a sliding window in time, generating a probability distribution of likely jerk occurrence times and associated error bars for the entire record of monthly means at a given magnetic observatory. This allows the significance of jerk events to be viewed relatively in each record and for error bars in time occurrences to be judged.

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Asymmetry in Paleomagnetic Field Structure and Variability

CATHERINE G. CONSTABLE [1], MONIKA KORTE [2]

[1] Institute of Geophysics and Planetary Physics, Scripps Institution of Oceanography, UC San Diego, La Jolla, CA 92093-0225, USA (cconstable@ucsd.edu)
[2] Helmholtz-Zentrum Potsdam, Deutsches GeoForschungsZentrum - GFZ, Stiftung des ff. Rechts Land Brandenburg, Telegrafenberg, D-14473 Potsdam, Germany (monika@gfz-potsdam.de)

Direct observations of the geomagnetic field extending back to 1590 AD show significant geographic differences in the secular variation, with greater average variability in the southern hemisphere than the north (for both VGP direction and field strength), and generally low secular variation in the Pacific region. Strong variability has most recently been particularly focused around the South Atlantic Magnetic Anomaly prompting questions about its longevity and relation to long term dipole strength.

Geomagnetic field evolution since 8000 BC has been reconstructed in the CALS10k.1b time varying field model, mainly based on information about magnetic field strength and directions obtained from sediment records, but including archeological artifacts and lavas wherever possible. The model was initially tailored for study of the evolution of magnetic field at the core-mantle boundary, but also provides a low-resolution description of large-scale geomagnetic field change at and above Earth's surface. We use CALS10k.1b to study geographic variability in secular variation, and compare our results with the 400 year record provided by the GUFM1 model for 1590-1990 AD. Both GUFM1 and CALS10k.1b clearly exhibit greater average variability in the southern hemisphere than in the north. However, the longitudinal variability is quite different over the longer 10ky interval. In CALS10k.1b there is significantly enhanced directional variability in the western equatorial Pacific and the Southern Ocean. It is apparent that the data do not require a persistent field anomaly in the South Atlantic, but do support enhanced variability in that general region.The stability of these secular variation structures is currently being evaluated. Once any complex or recurring field structure has been characterized the longer term goal is to link secular variation in time-varying paleomagnetic field models to statistical models for global paleosecular variation.

Investigating asymmetry in normal and reversed states of the time-averaged geomagnetic field

JAY COTTERILL AND RICHARD HOLME

School of Environmental Sciences, University of Liverpool, L69 3GP, UK. Email: holme@liv.ac.uk

The dynamo equations are symmetric in the magnetic field: if the sign of the magnetic field is reversed, then the equations are unchanged. Nevertheless, there is some evidence on many different time scales that the geomagnetic field has not been completely reversible between the normal and reversed states. Such a feature would not require a breaking in symmetry of the dynamo equations, but only suggest that the period of recording of the field is insufficient for perfect averaging to a symmetric state. This effect might manifest itself in non-equal times spent in the normal and reversed state on a reversal sequence, non-antiparallel pole positions for reversals (see poster by Potts and Holme), and in nonsymmetric structure between normal and reversed states of the time averaged field. This last was suggested by models of Johnson and Constable (1997), who found asymmetry between their models of the time-averaged field for the past 5 million years. However, the two data sets are different in character, with different locations, uncertainties, and a domination of the normal field model by recent data. Here, with extended data sets particularly from the TAFI project, we reconsider these models by constrained modelling. We determine models from the normal, reversed and combined field, both from the data alone, and also subject to various a priori models . For example, we fit the reversed data set, but using a prior model of the normal field model – to what extent do the data require departure from this field structure? Other priors include the time-averaged historical and archaeomagnetic fields. Preliminary evidence suggests that there is a difference between the two field states, although this is of course dependent on the appropriate data fit assumed. If this is verified, it would indicate a memory in the field during the reversal – that the field is not completely destroyed and recreated by the reversal process, but that some part of it remains.

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Toward constraining the long-term reversing behavior of the geodynamo : A new "Maya" superchron ~1 billion years ago from the magnetostratigraphy of the Kartochka Formation (southwestern Siberia)

YVES GALLET[1], VLADIMIR PAVLOV [1,2], GALVEN HALVERSON [3] & GAUTHIER HULOT[1]

[1] Institut de Physique du Globe de Paris, Sorbonne Paris Cité, Université Paris Diderot, CNRS, Paris, France (gallet@ipgp.fr, gh@ipgp.fr)

[2] Institute of Physics of the Earth, Russian Academy of Science, Moscow, Russia (pavlov-home@rambler.ru)

[3] Dept. of Earth and Planetary Sciences /GEOTOP, McGill University, Quebec, Canada (galen.halverson@mcgill.ca)

We present new magnetostratigraphic data obtained from the late Mesoproterozoic (~1 Ga) Kartochka Formation in the East Angara terrane of the Yenisey Ridge region (southwestern Siberian platform). A ~200 m-thick section encompassing the carbonate Kartochka Formation was densely sampled and another more limited outcrop several kilometers away was sampled in order to conduct a paleomagnetic fold test between the two sites. Paleomagnetic analyses revealed the existence of two magnetization components. A low unblocking temperature component, which likely has a viscous origin, was first isolated below 200°C. A characteristic component, carried either by magnetite or by a mixture of magnetite and hematite, was then isolated in the medium to high temperature range (up to 585°C or 680°C). The hematite-bearing component has a shallower inclination than the magnetite component showing that magnetite was less sensitive to flattening. A positive paleomagnetic fold test was obtained between the two studied sections indicating that the characteristic magnetization was likely acquired during or very soon after sediment deposition. This primary origin was further verified by comparison between the paleomagnetic poles derived for the Kartochka Formation and other late Mesoproterozoic Siberian sections. All data from the Kartochka Formation contain a single magnetic polarity assumed to be normal. This long normal polarity interval is consistent with the polarity zonation previously determined from magnetostratigraphic and paleomagnetic data from the Siberian Uchur Maya region. The new data fortify evidence of a normal polarity superchron spanning the ~1000 Ma old Mesoproterozoic-Neoproterozoic boundary, which we propose to call the Maya superchron. These data confirm the occurrence of sharp transitions between a frequently reversing regime and a non-reversing regime of the geodynamo. This behavior, also observed in other regions, may represent a consistent property of the Proterozoic geomagnetic field. Together with changes in the amount of time spent in the superchron regime, they may testify to a different field behavior during the late Precambrian than during the Phanerozoic. This difference could reflect a stronger influence of the heterogeneous heat flux patterns at the core-mantle boundary during the Precambrian, possibly as a consequence of the inner core not yet being nucleated at this time

Direct observation of the 5.8 year oscillation in length-of-day variation

RICHARD HOLME[1] AND OLIVIER DE VIRON[2]

[1]School of Environmental Sciences, University of Liverpool, L69 3GP, UK. Email: holme@liv.ac.uk
[2]Institute de Physique du Globe, 75252 Paris Cedex 05, France. Email: deviron@ipgp.jussieu.fr

A significant signal with period of approximately 6 years is known to be present in time series of length of day variations (del Rio et al, 2000), identified as being of likely core origin due to its lack of expression in calculated atmospheric angular momentum. It has been explained in terms of several core phenomena, including torsional waves, or from inner core oscillation due to inner-core – mantle gravitational coupling. However, further interpretation has been hampered by lack of clarity in the spectral identification, with significant power at periods above and below 6 years.

Here we present an analysis of the length of day time series in the time domain. A simple detrending of the data with smoothing splines, knot spacing 5 years, displays a clear oscillatory signal, of amplitude approximately 0.12 msec in length of day variation, period 5.8 years. There is no evidence of variation in this period, thus ruling out suspicions of a link to, for example, solar activity (a lengthened period might have been expected in the recent extend solar cycle). The 5.8-year signal is of varying amplitude, but such variations are difficult to interpret, because the detrending process is not unique. In particular, low amplitude of the 5.8 year signal corresponds to times at which the background signal has the opposite trend, suggesting that the two signals are not separated. Instead, we remove a steady 5.8 year signal from the data series; a much smoother signal results, which can be very well fit by a smoothing spline, suggesting that the non-atmopsheric signal can broadly be explained in terms of a decadally varying background signal and this oscillation alone.

Nevertheless, we focus in on departures from the simple picture, in particular seeking pints at which there may be small breaks in slope of the LOD curve, perhaps corresponding to geomagnetic jerks (Holme and de Viron, 2005). While such slope discontinuities are necessary to fully satisfy the requirement of a core-flow generated jerk, we also note that the times of maximum amplitude in the 5.8 oscillation correspond to many well known jerks, from separate peaks at 1969 and 1972 up until the most recently determined jerk of 2007 (Chulliat et al 2010). We discuss the implications of these results for both geomagnetic jerks, and the interpretation and understanding of core motions, in particular torsional waves.

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Geomagnetic field reconstruction during the mid-Holocene using burned anthropogenic archaeologic artifacts from central Europe

KATHRIN LISA KAPPER[1], FABIO DONADINI[1] & ANN HIRT[1]

[1] Institute of Geophysics, ETH Zurich, Zurich, CH
(lisa.kapper@erdw.ethz.ch)

To reconstruct the evolution of the mid–Holocene geomagnetic field indirect measurements from young lava flows, lacustrine sediments, and burned archaeological artifacts can be used. Recently, [1] showed that burned Neolithic stabling sediments can provide reliable directional data. Archaeological artifacts provide also absolute paleointensities (PIs). Because of these advantages we focus on burned oriented anthropogenic sediments and deposits, and unoriented lithic artifacts and ceramics to determine direction and intensity of the geomagnetic field vector, respectively. We examine stratigraphic sequences of burned anthropogenic sediments from (1) the Riparo Gaban shelter (RGB, 4900–4500 cal. B.C.), located in Northern Italy, (2) the Arconciel shelter (ARC, 6500–5500 cal. B.C.) close to Fribourg, Switzerland, and (3) lithic artifacts and ceramics from Lugo di Grezzana (LG, 5300–4800 cal. B.C.), also located in Northern Italy. We take advantage of the well-defined stratigraphy of the cross sections and the available radiocarbon ages to construct age models that accurately constrain the burning periods of these features. Furthermore, we compare our results to the CALS10K.1b global model [2] and to the Balkan paleosecular variation curve [4] that spans back to 10ka and 8ka, respectively.

We performed fundamental rock magnetic analyses to assess the suitability of the samples for directional and PI measurements. Both thermomagnetic curves and hysteresis loops indicate magnetite as the main carrier of magnetization. In some cases maghemite and hematite are also detected. In general, new magnetic phases are formed during heating to high temperatures. Anisotropy of magnetic susceptibility (AMS) was measured at RGB and ARC to assess the preferred alignment of the magnetic grains. We observe a compaction fabric, a low anisotropy degree and an oblate AMS ellipsoid for most of the specimens.

The characteristic remanent magnetization was isolated using alternating field and thermal demagnetization. We obtained acceptable directions for nine out of 25 units from RGB, which were better burned, and seven out of eight units from ARC. Our data show an easterly trend in declination from 6000 to 5500 B.C. and from 5000 to 4400 B.C., but a rapid shift to the west around 5500 to 5300 B.C.; inclinations appear to be more scattered. These results show a more pronounced variation than what is expected from the CALS10K.1b global model. For PI measurements 20 samples were selected and the IZZI protocol [3] was used. Six specimens from LG yielded reliable PI estimates, which agree very well with the CALS10K.1b model value.

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Probability uniformization and application to statistical paleomagnetic field models and directional data

ANDREY KHOKHLOV[1,2] & GAUTHIER HULOT[2]

[1] IEPT Russian Academy of Sciences, 84/32, Profsoyuznaya 117997 Moscow, Russia.

[2] Institut de Physique du Globe de Paris, Sorbonne Paris Cité, Université Paris Diderot, CNRS, Paris, France (khokhlov@ipgp.fr, gh@ipgp.fr)

We introduce the concept of 2D probability uniformization, which allows the conversion of any 2D probability distribution into an equivalent uniform distribution in the unit square [0,1]x[0,1]. This concept is equivalent to some universal coordinate change and can be applied to any 2D statistical distribution to ease common statistical tests of data sets that have to be tested against different expressions of a common background statistics. This situation is encountered when testing so-called Giant Gaussian Process (GGP) models of the Earth's magnetic field against paleomagnetic directional data collected from different geographical sites, the predicted statistics being site-dependent. To introduce the concept, we first consider 2D Gaussian distributions in the plane $\mathbb{R}^2$, before turning to Angular Gaussian and more general 2D distributions on the unit sphere S^2. We detail the approach when applied to the 2D distributions expected for paleomagnetic directional data, if these are to be consistent with a GGP model while affected by some Fisherian error. We finally provide some example applications to real paleomagnetic data. In particular, we show how the significance of subtle inhomogeneities in the distribution of the data, such as the so-called right-handed effect in paleomagnetism, can be quantified. This effect, whether of geomagnetic origin or not, affects the Bruhnes data in such a way that they cannot easily be reconciled with GGP models originally built with the help of this data. 2D probability uniformization is a powerful tool we argue could be used to build and test better GGP models of the mean paleomagnetic field and paleosecular variation. It can be generalized to higher dimensions and could also be used for many other applications in paleomagnetism, Earth sciences and other fields of science.

Data Assimilation in a Quasi-Geostrophic Model of the Earth Core

FRANÇOIS LABBÉ[1], DOMINIQUE JAULT [2] & NICOLAS GILLET[3]

[1] ISTerre, CNRS, Université Joseph Fourier, BP 53, 38041 Grenoble Cedex 9, France (francois.labbe@obs.ujf-grenoble.fr)
[2] ISTerre, CNRS, Université Joseph Fourier, BP 53, 38041 Grenoble Cedex 9, France (dominique.jault@obs.ujf-grenoble.fr)
[3] ISTerre, CNRS, Université Joseph Fourier, BP 53, 38041 Grenoble Cedex 9, France (nicolas.gillet@obs.ujf-grenoble.fr)

Data assimilation is now becoming an important tool in the comprehension of the Earth's magnetic field secular variation. There are also theoretical, numerical and geophysical arguments in favor of quasi-geostrophic flows (i.e. invariant in the direction parallel to the rotation axis) at rapid time-scales. Following Canet et al (2009)[1], we reduce the study of the outer core dynamics to that, in the equatorial plane, of 2D motions coupled to vertical means of quadratic products of the magnetic field, derived from the Lorenz force. Our goal is to establish a first map of those quadratic quantities from satellite observations. Since the magnetic energy is orders of magnitudes larger than the kinetic enery at large length-scales, rapid changes of magnetic force can be represented as a perturbation above a stationary background, which is then directly related to the flow acceleration. We invert the background magnetic force from maps of the flow and its time derivative. Those 'data' are obtained from a previous inversion of the radial induction equation at the core-mantle boundary, using satellite geomagnetic field models.

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Towards magnetic sounding of the Earth's core by an adjoint method

Kuan Li[1], Andrew Jackson[1] and Philip W. Livermore[2]

[1] Institut fur Geophysik, ETH Zurich, Switzerland
[2] School of Earth and Environment, Institute of Geophysics and Tectonics, University of Leeds, Leeds, UK

Earth's magnetic field is generated and sustained by the so called geodynamo system in the core. Measurements of the geomagnetic field taken at the surface, downwards continued through the electrically insulating mantle to the core-mantle boundary (CMB), provide important constraints on the time evolution of the velocity, magnetic field and temperature anomaly in the fluid outer core. The aim of any study in data assimilation applied to the Earth's core is to produce a time-dependent model consistent with these observations [1]. Snapshots of these "tuned" models provide a window through which the inner workings of the Earth's core, usually hidden from view, can be probed.

We apply a variational data assimilation framework to an inertia-free magnetohydrodynamic system (MHD) [2]. Such a model is close to magnetostrophic balance [4], to which we have added viscosity to the dominant forces of Coriolis, pressure, Lorentz and buoyancy, believed to be a good approximation of the Earth's dynamo. As a starting point, we have chosen to neglect the buoyancy force, this being another unknown and, at this stage, an unnecessary complication. At the heart of the models is a time-dependent magnetic field which is interacting with the core flow (itself slaved to the magnetic field).

Based on the methodology developed in Li et al. (2011)[3], we show further developments in which we apply the adjoint technique to our version of the Navier-Stokes equation in continuous form. In order to test the method, we use perfect synthetic data without any observation error, performing closed-loop tests to demonstrate the ability of our model for retrieving the 3D structure of the velocity and the magnetic fields at the same time.

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Spikes in palaeointensity around 900 BC and 900 AD - decadal variations in the dipole moment?

ANDREAS NILSSON[1], RICHARD HOLME[2], MIMI HILL[3] & RAIMUND MUSCHELER[4]

[1]School of Environmental Sciences, Geology and Geophysics, University of Liverpool, Liverpool, UK (andreas.nilsson@liv.ac.uk)
[2]School of Environmental Sciences, Geology and Geophysics, University of Liverpool, Liverpool, UK (holme@liv.ac.uk)
[3]School of Environmental Sciences, Geology and Geophysics, University of Liverpool, Liverpool, UK (m.hill@liv.ac.uk)
[4]Department of Geology, Quaternary Sciences, Lund University, Lund, Sweden (raimund.muscheler@geol.lu.se)

A number of recently published palaeointensity studies are showing compelling evidence for ‘spikes’ in the geomagnetic field intensity around 900 BC and 900 AD, with reported Virtual axial dipole moments (VADMs) reaching as high as 25 x 10^{22} Am^2. Reconstructions of the field morphology during such periods of unusual field activity are important as they can help improve our understanding of the geodynamo. However, the short/decadal time scales of these features make them particularly difficult to study using conventional geomagnetic field modelling approaches. This is due to (i) a scarcity of palaeomagnetic data, (ii) relatively large dating errors and (iii) an inherent smoothing often associated with remanence acquisition. Here we present an alternative approach to the problem using a simplified dipole tilt model based on a selection of sedimentary palaeomagnetic data and dipole moment estimates derived from cosmogenic radionuclide data from both ice cores and tree rings. We find that directional geomagnetic field data from 4/5 sediment records converge towards an unusually dipolar field configuration coinciding with the occurrence of the palaeointensity spikes. In addition, dipole moment estimates of unfiltered ^{10}Be data (complicated by high frequency variations often associated with solar modulation and/or ‘weather noise’ in the ^{10}Be deposition) show Holocene peak values at the same time as the early palaeointensity spikes. A less prominent high in the estimated dipole moment is also observed around 900 AD. These results, although inconclusive at this point, suggest that the high geomagnetic field strength during this period may have been global – related to a ramp up of the dipole field. This raises some interesting questions about the processes that govern the geodynamo and, if the hypothesis holds true, puts new constraints on the variability of the dipole moment.

Are all reversals symmetric? Non-antiparallel reversals from the late Precambrian

GRAHAM POTTS[1] AND RICHARD HOLME[2]

[1]School of Environmental Sciences, University of Liverpool, L69 3GP, UK. Email: gpotts@liv.ac.uk
[2]School of Environmental Sciences, University of Liverpool, L69 3GP, UK. Email: holme@liv.ac.uk

The symmetry of the dynamo equations, and the experience and assumption of the palaeomagnetic community, is that when averaged over time, normal and reversed palaeomagnetic pole directions should be antiparallel. Nevertheless, a number of studies over many years have produced results where the poles are not so positioned. For many workers, this failure of the reversal test results in the automatic rejection of the data. However, some recent numerical simulations have produced results where the symmetry of the normal to reversed state is broken. This physically counterintuitive result probably results because of insufficient computational averaging time, but this only raises the question as to how long a palaeomagnetic record is necessary for symmetry to be established - does the dynamo retain a memory of its previous state after reversal?

We present results sampled from the Torridon Group which forms part of the late Precambrian Torridonian Supergroup of Northwest Scotland. The zones of alternating polarity do not record a series of anti-parallel reversals; instead, the two directions lie at or about 140 degrees apart. This pattern of magnetisation was identified in the earliest palaeomagnetic studies of these rocks and it has been, in general, confirmed by later work. In the absence of reliable demagnetisation equipment the early workers, quite reasonably, suggested that the lack of anti-parallel directions may be due to the presence of an additional component of magnetisation and this explanation has been adopted in several later studies. However, with modern methods, and in particular very fine temperature control, demagnetisation of these "Torridonian" directions has revealed behaviours that may be interpreted as single component magnetisations (directions that are stationary whilst the intensity of the remanence decreases), with well-controlled temperature steps of less than 10 degrees. Any additional component would have to be hidden or latent, but with the careful demagnetisation procedures, sampling strategies and analytical programmes which have been designed and implemented, any such latent component would have to have absurd characteristics. We therefore suggest that the Torridonian rocks do indeed record non-parallel reversals.

While it is likely that many rocks in which non parallel reversals are observed do indeed reflect an overprint, nonetheless, we suggest that in general, data with non-parallel reversals should not automatically be rejected, particularly originating from older rocks which might record a dynamo state differing from that observed today.

Long term core flow inversions: consequences for the thermal structure of the Earth's core

LUIS SILVA[1], CHRIS DAVIES [2] & JON MOUND[3]

[1] School of Earth and Environment, Institute of Geophysics and Tectonics, University of Leeds, Leeds, UK (L.A.C.Silva@leeds.ac.uk)
[2] School of Earth and Environment, Institute of Geophysics and Tectonics, University of Leeds, Leeds, UK (C.Davies@leeds.ac.uk)
[3] School of Earth and Environment, Institute of Geophysics and Tectonics, University of Leeds, Leeds, UK (J.Mound@leeds.ac.uk)

Flows at the top of Earth's outer core can be estimated from knowledge of the geomagnetic field and its evolution with time. These flows are now routinely generated over the last 180 years and have significantly enhanced understanding of the dynamo process generating Earth's magnetic field. In this paper we use such flows to estimate the pattern of temperature anomalies in the interior of the outer core. We show that core surface flows computed for epochs prior to 1840, using the gufm1 magnetic field model, depend only weakly on the assumed evolution of the axial dipole, thus allowing for the computation of core surface flows for the entire 405 yr period covered by this model. The time average of these flows shows the signature of the tangent cylinder, indicating strong rotational effects. We, therefore, assume the flow to be invariant in the direction of the rotation axis and invoke the quasi-geostrophic approximation to compute the flow inside the core. We further assume the radial velocity to be well correlated with temperature, as is to be expected in a thermally convective system, and compute the pattern of temperature anomalies inside the outer core. At the top of the inner core, we obtained a clear hemispheric pattern with higher temperatures on the eastern hemisphere and lower temperatures on the western hemisphere. If this pattern persists on long time scales, then the present study exposes a possible geomagnetic signature of the processes generating the observed hemispheric variation in seismic P-wave velocity and further supports recent suggestions of a causal relationship between flows and inner core structure.

S4: Outer Core - Modelling & Dynamics

Invited Talk

Stochastic Core Flow Reconstruction Over the Observatory Era

Nicolas Gillet[1], Dominique Jault[1,2] & Chris Finlay[3]

[1]ISTerre, CNRS, Université Grenoble 1, France, ngillet@ujf-grenoble.fr
[2]Institut für Geophysik, ETH Zürich, Switzerland, dominique.jault@erdw.ethz.ch
[3]DTU Space, Copenhagen, Denmark, cfinlay@space.dtu.dk

We consider the problem of core dynamics reconstruction, for which we differentiate between stochastic and deterministic forces that sustain the flow evolution. The former is associated with the impossibility of completely representing the forces as the magnetic field is not resolved at small length-scales. An illustration of the latter is the propagation of torsional Alfven waves at interannual periods. However, this only concerns a tiny part of the observed geomagnetic secular variation (GSV), for which a dynamical understanding still has to be developed.

This quest requires to build a consistent model for the GSV uncertainties, in order to best extract the information contained in magnetic records. If progresses have been made along those lines over the past decade, GSV error statistics still need to be improved. Here we propose a stochastic approach by which all the prior statistical information about the GSV is formally accounted for, through a dense covariance matrix for both measurement and modeling error.

We give an example in the simplest case where the prior on the flow trajectory is a random walk (zero deterministic component), by inverting for flow increments backward in time, starting from the best constrained satellite era. The consistency between the flow and GSV priors is discussed. We propose an extension of this work where both deterministic and stochastic forces are considered, within the framework of data assimilation.

Invited Talk

Imaging flow throughout the Earth's core

JULIEN AUBERT[1]

[1] Dynamique des Fluides Géologiques, Institut de Physique du Globe de Paris, Université Paris- Diderot, PRES Sorbonne Paris Cité, INSU/CNRS UMR 7154, 1 rue Jussieu, 75238 Paris cedex 5, France, aubert@ipgp.fr

Temporal variations of the Earth's magnetic field provide a powerful probe to track the motion of electrically conducting material in its liquid core. However, knowledge of the geomagnetic field does not extend below the core-mantle boundary and additional prior information is needed to image flow throughout the core, a highly desirable goal to elucidate the inner workings of the geodynamo and predict its future evolution.

In this talk, I will show how this information can be expressed through the statistical compliance to an Earth-like, three-dimensional and self-consistent numerical simulation of the geodynamo. The tradeoff between fit to the data and complexity of the solution is then uniquely determined and clearly connected to first-principle physics, thus alleviating the common difficulties encountered by most core flow inversions. Applied to the period 1970-2010, this approach reveals a large-scale, persistent circulation which reconciles columnar flow and thermal winds, and generally complies with the prior statistics at the exception of a small number of physically significant deviations. The most energetic of these, an hemispherical spiralling flow anchored to the inner-core and accounting for the magnetic westward drift in the Atlantic, is thus attributed to heterogeneous boundary control rather than to a fortuitous arrangement of buoyancy and magnetic forces. I will discuss the possible causes for such an hemispherical, whole core circulations.

The compatibility of these new whole core flow images with previous quasi-geostrophic downward continuations generally establishes the robustness of their key features and opens the way to refined, dynamically consistent predictions of future core evolution.

Invited Talk

Coupling between geomagnetic reversal frequency and mantle convection in the Phanerozoic: results from numerical dynamos

PETER OLSON[1]

[1]Department of Earth and Planetary Sciences, Johns Hopkins University, Baltimore MD 21218 U.S.A. (olson@jhu.edu)

Numerical dynamos that include time variable heterogeneous heat flow at the core-mantle boundary and core evolution are used to investigate the coupling between geomagnetic reversal frequency and mantle convection history through the Phanerozoic. Polarity reversal sequences are calculated using numerical dynamos driven by two models of lower mantle history: a reconstruction of mantle convection and plate motions by Zhang and Zhong [1] with time variable heterogeneous core-mantle boundary (CMB) heat flow that predicts an irregular evolution of the core, and a second model based on hotspot locations with a fixed CMB heat flow heterogeneity similar to the present-day seismic structure of the lower mantle that predicts a regular evolution of the core. For each mantle history, present-day values of the dynamo control parameters are tuned to match Geomagnetic Polarity Time Scale (GPTS) reversal statistics for 0-5 Ma, and the time variations of the dynamo control parameters are constrained by core thermal evolution, including time variations of CMB heat flow, inner core size and inner core boundary compositional buoyancy flux, and rotation rate. Comparison between 5 Myr. long dynamo reversal sequences and the GPTS shows that the time variable lower mantle history with irregular core evolution is in better agreement with the GPTS, producing a slow reversal cycle with long-lived constant polarity around 275 Ma and 475 Ma, frequent reversals around 180 Ma and 330 Ma, and an inclined dipole field during the time of Pangaea. In contrast, the fixed lower mantle history fails to produce slow reversal cycles. Neither of the two histories provides an explanation of the Cretaceous superchron in terms of large-scale mantle convection.

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Mantle-driven geodynamo features - Effects of compositional and narrow D” anomalies

HAGAY AMIT[1] & GAËL CHOBLET[1]

[1] CNRS UMR 6112, Université de Nantes, Laboratoire de Planétologie et de Géodynamique, 2 Rue de la Houssinière, Nantes F-44000, France
(Hagay.Amit@univ-nantes.fr, Gael.Choblet@univ-nantes.fr)

Lower mantle heterogeneity could cause deviations from axial symmetry in geodynamo properties. Global tomography models are commonly used to infer the pattern of core-mantle boundary heat flux via a linear relation that corresponds to a purely thermal interpretation of lower mantle seismic anomalies, ignoring both non-thermal origins and non-resolved small scales. Here we study the possible impact on the geodynamo of narrow thermal anomalies in the base of the mantle, originating from either compositional heterogeneity or sharp margins of large-scale features. A heat flux boundary condition composed of a large-scale pattern and narrow ridges separating the large-scale positive and negative features is imposed on numerical dynamos. We find that hot ridges located to the west of a positive large-scale core-mantle boundary heat flux anomaly produce a time-average narrow elongated upwelling, a flow barrier at the top of the core and intensified low-latitudes magnetic flux patches. When the ridge is located to the east of a positive core-mantle boundary heat flux anomaly, the associated upwelling is weaker and the homogeneous dynamo westward drift leaks, precluding persistent intense low-latitudes magnetic flux patches. These signatures of the core-mantle boundary heat flux ridge are evident in the north-south component of the thermal wind balance. Based on the pattern of lower mantle seismic tomography, we hypothesize that hot narrow thermal ridges below central Asia and the Indian Ocean and below the American Pacific coast produce time-average fluid upwelling and a barrier for azimuthal flow at the top of the core. East of these ridges, below east Asia and Oceania and below the Americas, time-average intense geomagnetic flux patches are expected.

Possible links between long-term geomagnetic variations and whole-mantle convection processes

A.J. BIGGIN[1], B. STEINBERGER[2,3], J. AUBERT[4], N. SUTTIE[1], R. HOLME[1], T.H. TORSVIK[3,5,6], D.G. VAN DER MEER[7,8], D.J.J. VAN HINSBERGEN[3]

[1] Geomagnetism Lab., Geology and Geophysics, School of Environmental Sciences, University of Liverpool. L69 7ZE, UK
[2] Helmholtz Centre Potsdam, GFZ German Research Centre for Geosciences, 14473 Potsdam, Germany
[3] Physics of Geological Processes, University of Oslo, Sem Saelands vei 24, 0316 Oslo, Norway
[4] Institut de Physique du Globe de Paris, UMR7154, INSU, CNRS – Université Paris-Diderot, PRES Sorbonne Paris Cité, 1 rue Jussieu, 75238 Paris cedex 5, France
[5] Center for Geodynamics, Geological Survey of Norway (NGU), Leiv Eirikssons vei 39, 7491 Trondheim, Norway
[6] School of Geosciences, University of the Witwatersrand, WITS 2050 Johannesburg, South Africa
[7] Institute of Earth Sciences, Utrecht University, Budapestlaan 4, 3584 CD Utrecht, The Netherlands
[8] Nexen Petroleum UK Ltd., Charter Place, UB8 1JG, Uxbridge, United Kingdom

The Earth's magnetic field is generated by convection in the liquid outer core that is modulated by the pattern of heat flowing out into the base of the overlying mantle. Variations in geomagnetic behaviour are observed on all timescales but those occurring over tens to hundreds of millions of years may be related to changes in this heat flow caused by mantle convection processes. These processes could also manifest themselves at the Earth's surface through the medium of sinking lithospheric slabs and rising mantle plumes allowing correlations to be made between palaeomagnetic behaviour and surface processes. Geodynamo simulations suggest that transitions in geomagnetic behaviour from rapidly reversing to superchron such as occurred between the mid-Jurassic and the mid-Cretaceous may have been triggered by a decrease in core-mantle boundary heat flow globally or in the equatorial region. Our synthesis indicates that this could have been related to a decrease in mantle plume head production in the core-mantle boundary region, or to a major episode of true polar wander occurring at that time, or to both. Further testing against quantitative modelling results and new observations made for earlier times will be required to establish the robustness of such intriguing links.

The Influence of Fluid Properties on the Morphology of Core Turbulence and the Geomagnetic Field

MICHAEL A. CALKINS[1], JONATHAN M. AURNOU[2], JEFF D. ELDREDGE[3] & KEITH JULIEN[1]

[1] Department of Applied Mathematics, University of Colorado, Boulder, USA
[2] Department of Earth and Space Sciences, University of California, Los Angeles, USA
[3] Department of Mechanical and Aerospace Engineering, University of California, Los Angeles, USA

Here we investigate the effects of fluid properties on the morphology and dynamics of convection in the Earth's outer core. We compare the results of two quasi-geostrophic convection simulations at comparable convective velocities for fluids in which the ratio between the kinematic viscosity and thermal diffusivity (the Prandtl number, Pr) is 0.1 and 10. The $Pr = 0.1$ case is representative of thermal convection in a liquid metal, whereas the $Pr = 10$ case is more representative of chemical convection. Both cases have zonal flows with similar strength, suggesting that Reynolds stresses in high Prandtl number convection can be large when the buoyancy forcing is strong. We find the influence of the Prandtl number to be significant: low Prandtl number fluids have a propensity for large-scale coherent vortex formation and slowly varying dynamics. Conversely, the high Prandtl case is dominated by significantly smaller length scales and more rapidly varying dynamics. However, by using a simple kinematic magnetic induction model we show that the structure of the magnetic field is not a direct indication of the underlying convective morphology when the magnetic diffusivity is large. Thus, our simulation results imply i) that the convective turbulence differs between thermally- and chemically-dominated convection, but ii) that it may be difficult to determine the dominant forcing from geomagnetic field observations alone.

Quasi-geostrophic numerical modeling of Earth's core rapid dynamics

Elisabeth Canet[1*], Chris Finlay [2], Alexandre Fournier [3], Andy Jackson[1] & Dominique Jault[1,4]

[1] Institute of Geophysics, ETH, Zurich, Switzerland
[*] ecanet@erdw.ethz.ch
[2] DTU Space, Copenhagen, Denmark
[3] IPG, Paris, France
[4] ISTerre, Grenoble, France

We present a numerical model tailored to the study of Earth's core rapid dynamics, associated with the secular variation timescales of the order of hundreds of years. At these timescales, rotation forces are strong compared to other forces in the Navier-Stokes equation, as described by the smallness of the Lehnert number which measures the ratio of the inertial wave period to the Alfvén wave period. We describe the corresponding physical processes with the quasigeostrophic assumption in which the equatorial flow is invariant in the direction of rotation whereas an axial flow, varying linearly with the coordinate parallel to the rotation axis, enables the flow to satisfy the no-slip boundary conditions in a spherical shell.

When linearized, the physics included in the model consists of Rossby waves modified by the magnetic field. At moderate Lehnert number, the linearized version of the model enables us to reproduce some known and sometimes analytical (not in a spherical shell) results of these Rossby and Magneto-Coriolis waves, when the background magnetic field corresponds to a uniform current density parallel to the axis of rotation. Magneto-Coriolis waves consist of a fast wave, nearly at the Rossby (non-magnetic) frequency, and a slow (magnetic) wave which period is decreasing with the strength and the complexity of the background magnetic field, both waves being highly dispersive. With the Lehnert number estimated for Earth's core however, the period of the slow wave is much larger than typical secular variation timescales, due to the simplicity of the background field.

In the general numerical model, the nonlinearities due to the Lorentz force disable this simple description even starting with a simple large scale initial condition, but at the same time avoid the problem of the Magneto-Coriolis wave being too slow. We will present some features of both this non-linear code and its linearized version.

Time scales of geomagnetic secular acceleration in satellite field models and geodynamo models

ULRICH CHRISTENSEN[1], INGO WARDINSKI [2] & VINCENT LESUR[2]

[1] Max Planck Institute for Solar System Research, Katlenburg-Lindau, Germany (christensen@mps.mpg.de)
[2] Geoforschungszentrum Potsdam, Germany (ingo@gfz-potsdam.de, lesur@gfz-potsdam.de)

Magnetic satellite data from the last decade allow to reliably model geomagnetic secular acceleration, the second time derivative of the field. We confirm a recent finding that the time scale of secular acceleration, τ_{SA}, is of order ten years and fairly independent of spherical harmonic degree n. This contrasts with the characteristic time scale of geomagnetic secular variation τ_{SV}, which is a decreasing function of n and is ≥ 100 yr for $n \leq 5$. Conceivably the secular acceleration time scale might be related to short-term processes in the core, distinct from convective overturn whose time scale is reflected by τ_{SV}. Previously it had been shown that dynamo simulations reproduce the shape of the secular variation spectrum and for Earth-like values of the magnetic Reynolds number Rm the absolute values of τ_{SV}. The question arises if dynamo simulations can capture the observed time scales of geomagnetic secular acceleration. We determined $\tau_{SA}(n)$ for a set of dynamo models, covering a range of values of the relevant control parameters. The selection of models was based on the morphological similarity of their magnetic fields to the geomagnetic field and not on criteria related to the time dependence of the field. We find that τ_{SA} depends only weakly on n up to degree 10, but for larger n it asymptotically approaches a $1/n$-dependence. The acceleration time scale at low n varies with magnetic Reynolds number as $Rm^{-1.3}$, but may also depend on magnetic field strength. For an Earth-like $Rm \approx 1000$, τ_{SA} is of order 10 yr for $n \simeq 2-10$, as found in the field models from satellite data. A simple scaling analysis based on the frozen flux assumption for magnetic variations can explain the spectral shape of $\tau_{SA}(n)$ in numerical models. The characteristic time scale of acceleration of the near surface flow is of the same order as τ_{SA}, suggesting that the observed 10 yr time scale of geomagnetic secular acceleration reflects the characteristic time of core flow acceleration. To explain the geomagnetic secular variation and secular acceleration time scales, the rms velocity near the core surface must be 18 km yr^{-1} and the rms flow acceleration approximately 2 km yr^{-2}, although a statistical analysis of the induction equation suggests that most of the latter may occur at flow scales corresponding to harmonic degrees $n > 12$. The ability of dynamo models to match simultaneously secular variation and secular acceleration time scales suggests that dynamic processes in the core at the decadal time scale are not fundamentally different from those at the centennial time scale.

An Overview of Torsional Oscillations

GRACE COX[1], PHIL LIVERMORE[1] & JON MOUND[1]

[1] School of Earth and Environment, University of Leeds, Leeds, UK
(eegac@leeds.ac.uk)

The geomagnetic field is continually generated and maintained against decay by convective motions in the fluid outer core through a process known as the geodynamo. Despite much scientific interest, a full understanding of the dynamics and evolution of the outer core remains elusive, partly because the Earth's deep interior cannot be observed directly. However, much may be deduced from observations of the geomagnetic field, which exhibits spatial and temporal variations over a wide variety of timescales ranging from just a few years to millions of years. This work will focus upon the rapid (1-100yr) dynamics of the outer core, in particular, a type of Alfvén wave called torsional oscillations. Alfvén waves are a set of transverse waves that propagate in an electrically conducting fluid in the presence of an ambient magnetic field. They propagate along magnetic field lines in a manner analogous to transverse waves travelling along guitar strings and their frequency is linearly dependent on the intensity of the magnetic field. Torsional oscillations are rigid azimuthal accelerations of coaxial cylinders that oscillate on decadal timescales and may be observed in two ways; as secular variation and as changes in length of day. The latter observations arise because torsional waves transfer angular momentum from the core to the mantle. Conservation of angular momentum requires that temporal variations in core angular momentum are balanced by corresponding changes in the rotation rate of the mantle, hence changing the length of day.

Studies of waves in the Earth's interior are important because inverse methods allow us to make inferences about structure and physical properties that would otherwise remain inaccessible. Just as seismic observations are routinely used to deduce the rheology and structure of the deep Earth, torsional oscillations may allow us to make inferences about core dynamics, core-mantle coupling mechanisms and physical properties such as viscosity and internal magnetic field intensity. Two independent methods have been developed to examine wave evolution in both Cartesian and cylindrical geometries. The first method is a normal mode approach in which an initial profile is projected onto a set of basis functions and evolved through time. The second method uses a time-stepping finite difference code to study the behaviour of the solutions to the appropriate wave equations. In this work, the canonical torsional wave equation was simplified by considering a completely fluid cylindrical core with constant radial magnetic field in order to allow the comparison of numerical results and known analytic solutions. Further studies will focus upon considering more realistic core geometries and profiles for the internal radial magnetic field, with the ultimate aim of using geodynamo models to investigate the excitation mechanism for torsional oscillations and the manner in which they propagate through the interior of the Earth.

On the influence of a translating inner core in models of outer core convection

CHRISTOPHER DAVIES[1], LUIS SILVA[1] & JON MOUND[1]

[1] School of Earth and Environment, University of Leeds, Leeds LS2 9JT, UK
c.davies@leeds.ac.uk

It has recently been proposed that the hemispheric seismic structure of the inner core can be explained by a self-sustained rigid-body translation of the inner core material, resulting in melting of the solid at the leading face and a compensating crystallisation at the trailing face. This process induces a hemispherical variation in the release of light elements and latent heat at the inner-core boundary, the two main sources of thermochemical buoyancy thought to drive convection in the outer core. However, the effect of a translating inner core on outer core convection is presently unknown. In this paper we model convection in the outer core using a nonmagnetic Boussinesq fluid in a rotating spherical shell driven by purely thermal buoyancy, incorporating the effect of a translating inner core by a time-independent spherical harmonic degree and order 1 (Y_1^1) pattern of heat-flux imposed at the inner boundary. The analysis considers Rayleigh numbers up to 10 times the critical value for onset of nonmagnetic convection, a parameter regime where the effects of the inhomogeneous boundary condition are expected to be most pronounced, and focuses on varying q^*, the amplitude of the imposed boundary anomalies. The presence of inner boundary anomalies significantly affects the behaviour of the model system. Increasing q^* leads to flow patterns dominated by azimuthal jets that span large regions of the shell where radial motion is significantly inhibited. Vigorous convection becomes increasingly confined to isolated regions as q^* increases; these regions do not drift and always occur in the hemisphere subjected to a higher than average boundary heat-flux. Effects of the inner boundary anomalies are visible at the outer boundary in all models considered. At low q^* the expression of inner boundary effects at the core surface is a difference in the flow amplitude between the two hemispheres. As q^* increases the spiralling azimuthal jets driven from the inner boundary are clearly visible at the outer boundary. Finally, our results suggest that, when the system is heated from below, a Y_1^1 heat-flux pattern imposed on the inner boundary has a greater overall influence on the spatio-temporal behaviour of the flow than the same pattern imposed at the outer boundary.

Influence of Boundary conditions on Planetary Dynamos

GIRIJA DHARMARAJ[1] AND SABINE STANLEY[2]

[1]University of Toronto, 60 St. George street, Toronto, ON, Canada, M5S1A7, dgirija@physics.utoronto.ca
[2]University of Toronto, 60 St. George street, Toronto, ON, Canada, M5S1A7, stanley@physics.utoronto.ca

Numerical dynamo models have been successful in generating some of the basic properties of the geomagnetic field such as the field's dipole dominance, approximate strength and reversal statistics. Here we investigate the influence of different thermal and velocity boundary conditions on the magnetic field generation mechanism. We find that dynamo models with fixed heat flux thermal boundary conditions have different generation mechanisms than models with fixed temperature boundary conditions independent of the velocity boundary conditions. At strongly supercritical Rayleigh numbers (~ 50 times critical), even though the total magnetic energy of the models are similar in magnitude, the fixed temperature models produce frequently reversing weak-field dynamos and the fixed heat flux models produce non-reversing strong-field dynamos. Hence, an intense planetary magnetic field does not imply that the dynamo operates in the strong field regime as is usually presumed. We show that the Lorentz force is balanced by the Coriolis force in the fixed heat flux models resulting in magnetostrophically balanced dynamos whereas the Lorentz force is balanced by the Reynolds force (and not the Coriolis force) in the fixed temperature models resulting in a non-magnetostrophically balanced dynamo.

We also examine and compare the Nusselt number of dynamo models with and without magnetic field to study the power budget of planetary cores. We discuss why the characteristics of the fixed heat flux and stress-free models are more similar to the geodynamo and compare preliminary scaling laws for these models with those in the literature.

Finite Volume simulations of dynamos in ellipsoidal planets

J. Ernst-Hullermann[1], H. Harder and U. Hansen

Institute of Geophysics, University of Münster, Germany ([1] j.ernst-hullermann@uni-muenster.de)

It is widely accepted, that the planetary magnetic fields are powered by a magnetohydrodynamic dynamo-process. So far theoretical studies and numerical simulations have mostly assumed that the flow generating the dynamo-process is driven by buoyancy forces. But also precession can drive a dynamo, as first suggested by Bullard in 1949. A precession-driven laminar flow is mainly toroidal and cannot maintain a dynamo. However, experimental and numerical studies show that these basic flows are unstable and several kind of wave-like instabilities are generated. Therefore precession can also be regarded as a viable driving-mechanism of a core flow generating the planetary magnetic fields.

We have used a spherical, finite-volume code, already used for the simulation of convection-driven dynamos and mantle convection, to solve the equations of a precession-driven dynamo in a spherical shell. We investigated a full MHD-dynamo in a spherical shell, similar to that of Tilgner [1]. This flow can maintain a magnetic field but the magnetic field structure is not very similar to that of the Earth. For example the radial magnetic field at the outer boundary is not dipole dominated.

Furthermore the non-sphericity of the planetary bodies trigger some crucial instabilities. However, up to now there is only one available full MHD study of precessing spheroids [2]. These preliminary results for a full spheroid showed that topographic coupling offers more favourable conditions than viscous coupling for the generation of a sizeable dipole component of the magnetic field. We shall discuss how the ellipticity of the planets can be included in numerical simulations by the use of a non-orthogonal grid. We will present some first results of MHD calculations with parameters similar to known dynamo solutions but with no-slip instead of stress-free boundary conditions to clarify the influence of boundary layers on the dynamo process.

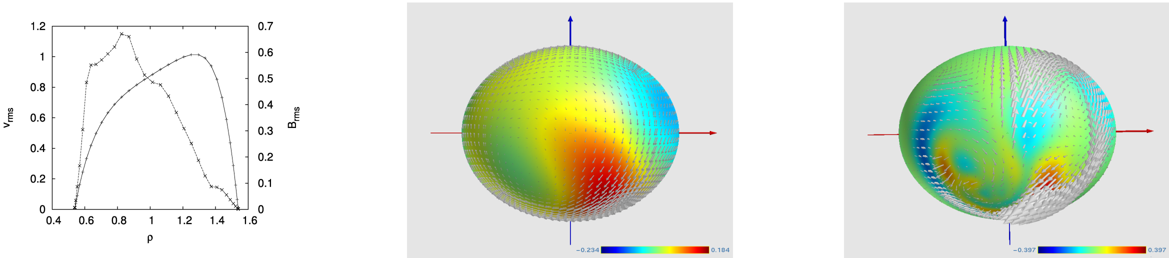

Figure 1: Snapshot of a kinematic spheroidal dynamo with parameters Ekman-number $E = 3.75 \cdot 10^{-3}$, precession rate $\Omega = 0.25$, precession angle $\alpha = 90°$, oblateness $e = 0.2$ and magnetic Prandtl-number $Pm = 24$. Left: Lateral averaged velocity (solid line) and magnetic field strength (dashed line). Snapshot of velocity (mid) and magnetic field (right) in precession frame on the spheroid, where the magnetic field is strongest ($\rho = 0.824941$). Color coded is the normal component of the velocity and magnetic field respectively.

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Nested synthetic databases of observations for geomagnetic data assimilation practice: millennial to centennial time scales

ALEXANDRE FOURNIER[1], JULIEN AUBERT [1], ERWAN THÉBAULT[1] & NATHANAËL SCHAEFFER[2]

[1] Institut de Physique du Globe, Paris, France
(fournier@ipgp.fr, aubert@ipgp.fr, ethebault@ipgp.fr)
[2] Institut des Sciences de la Terre, Grenoble, France
(nathanael.schaeffer@obs.ujf-grenoble.fr)

Data assimilation aims at producing an optimal estimate of the state of the dynamical system one is interested in by combining two sources of information : physical laws (in the form of a numerical model) and observations. A mandatory step during the development of a data assimilation framework involves a validation phase using synthetic data. In this well-controlled environment, the true dynamical trajectory of the system is known (it results from the integration of the numerical model), and it is used to generate synthetic observations. Those are subsequently used to assess the efficacy, and to highlight possible shortcomings, of the chosen methodology. Data assimilation has recently come to the fore in geomagnetism (e.g. Fournier et al., 2010), a surge motivated by our increased ability to observe the geomagnetic field (thanks to dedicated satellite missions), and by the concurrent progress in the numerical description of core dynamics. Open questions are related to the type of physical models one should resort to, and to the choice of a suitable algorithm, able to integrate the highly heterogeneous geomagnetic record at our disposal, and to deal with the non-linearities of the problem at hand (e.g. Aubert & Fournier, 2011; Fournier et al., 2011).

At the 2012 SEDI meeting in Leeds, we will report on the construction of a database of synthetic observations meant at reproducing the heterogeneity of the geomagnetic record (in terms of temporal and spatial coverage). This database relies on two dynamical trajectories:

1. a long-term dynamical trajectory (spanning the equivalent of the past few millenia) computed from a three-dimensional, convection-driven, dynamo model, able to represent accurately the long-term variability of the geomagnetic field.
2. a short-term dynamical trajectory (spanning the equivalent of a few decades), computed from a high- resolution three-dimensional model, able to represent interannual to decadal core processes (e.g. Gillet et al., 2011), and whose basic state is determined from the long-term trajectory. This short-term trajectory is described in detail in the companion contribution by Schaeffer et al.

This contribution will specifically describe trajectory (1), and the associated catalog of synthetic observations.

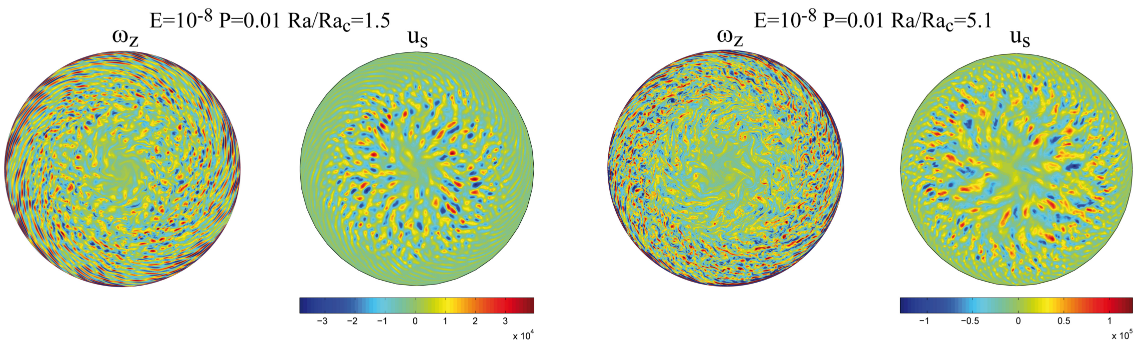
We have integrated a high resolution numerical dynamo simulation and selected a portion of the dynamical trajectory spanning 10,000 years, during which the CMB field displays an excellent morphological semblance with the geomagnetic field (see Fig.1 below). The magnetic Reynolds, Lundquist, Lehnert and Alfvén numbers are of the order of 600, 600, 0.015 and 1, respectively. The flow exhibits a fair amount of z-invariance, but there is little evidence of fast waves propagating inside the shell.

Zonal flow formation and convection structures in spherical quasigeostrophic models at low Prandtl number

CÉLINE GUERVILLY[1,2] & PHILIPPE CARDIN[1]

[1] Institut des Sciences de la Terre (ISTerre), Université de Grenoble/CNRS, Grenoble, France
(philippe.cardin@ujf-grenoble.fr)
[2]University of California, Santa Cruz, USA

We present calculations of thermal convection in a rapidly rotating sphere, using a hybrid numerical approach where a 2D quasigeostrophic code modeling the velocity field is coupled to a 3D spherical code modelling the temperature field. No inner core is present to avoid any discontinuity, which would occur at the tangent cylinder in quasigeostrophic models, and consequently uniform heating is used to force thermal convection. This hybrid approach is particularly suitable for low Prandtl number fluids, where the 3D thermal structures are larger scale than the dynamical (quasigeostrophic) structures, and can be modelled using coarse 3D grid while the QG flow is solved in the equatorial plane only. Numerical convergence is obtained for Ekman and Prandtl numbers as low as $E = 10^{-8}$ and $P = 0.01$, i.e. one or two orders of magnitude lower than in full 3D calculations. Two dynamical regions are identified in supercritical regimes: an inner, strongly non-linear, convective region, where convection produces small-scale vortices, surrounded by an outer region, where spiraling Rossby waves propagate. Mean flows develop as multiple zonal jets. The number of jets and their amplitude vary with the vigor of the convection. At large Rayleigh numbers, the zonal velocity becomes larger than the typical convective velocity, and strongly influences the flow organization as convective vortices are destroyed by the mean radial shear. As a result, the convective heat transport is considerably reduced in radial shear regions, leading to an increase of local gradients of temperature, as observed in the map of the surface heat flux. Scaling laws for the convective and zonal flows are proposed, and tested against the numerical results. We will also present preliminary results of kinematic dynamos generated in these flows.



Stochastic modelling of the archeomagnetic field

HELLIO GABRIELLE[1†], BOULIGAND CLAIRE [1], GILLET NICOLAS[1] & JAULT DOMINIQUE[1,2]

[1] Institut des sciences de la Terre, CNRS, Université Grenoble 1, BP53, 38041 Grenoble Cedex 9, France
[2] Institut für Geophysik, Sonneggstrasse 5, ETH Zürich, CH-8092, Switzerland
[†] corresponding author (gabrielle.hellio@ujf-grenoble.fr)

Reconstructions of the geomagnetic field over the archeological timescale rely on indirect estimation of the ancient magnetic field recorded in archeological artefacts. Because these data are sparse in both time and space, and are less accurate than modern observations, all current models strongly rely on arbitrary regularization that penalize the spatial complexity and time derivatives of the Gauss coefficients, and avoid non-uniqueness issues. Such damping strategies implicitely introduce a strong prior that is not dynamically justified, and possibly filter out part of the information contained in the data. Moreover, they generate unrealistic posterior model error covariances, quantities required for the analysis of the core dynamics.

In this study we use instead a stochastic prior that relies on the shape of the geomagnetic spectrum at different time scales, which is coherent with the occurence of discontinuities in the second (resp. first) time derivative of observed magnetic series at decadal (resp. millenial) time scales. Our approach requires accurate knowledge of the different data errors sources: we plug into the inverse problem not only the measurements errors, but also the errors of representativeness arising from our ignorance of the unresolved magnetic field at small length-scales. We plan to use this stochastic strategy to produce an ensemble of field models over the past millenia from archeomagnetic data, and analyse up to which harmonic degree the model coefficients are constrained by observations.

Ancient dynamos more sensitive to core-mantle boundary heat flows

KUMIKO HORI[1], JOHANNES WICHT [2] & WIELAND DIETRICH [2]

[1] Earthquake Research Institute, University of Tokyo, Tokyo, Japan
(khori@eri.u-tokyo.ac.jp)
[2] Max-Planck Institute for Solar System Research, Katlenburg-Lindau, Germany

The early dynamos of Earth and Mars probably operated without an inner core being present. They were thus exclusively driven by secular cooling and radiogenic heating, whereas the present geodynamo is thought to be predominantly driven by buoyancy fluxes which arise from the release of latent heat and the compositional enrichment associated with inner core solidification. The impact of the inner core growth on the ancient geodynamo has been discussed extensively but is still controversial. While earlier paleomagnetic and thermal evolution models proposed a large impact, recent numerical dynamo simulations suggest that the effect on field would be rather minor. As for Mars, the Mars Global Surveyor detected a strong northern-southern dichotomy in the crustal magnetization. A scenario proposed so far is due to such an ancient dynamo, where thermal heterogeneities at the core-mantle boundary (CMB) were imposed by the lower mantle structure. A key question for this scenario is how easily influence of the boundary anomalies emerges.

Here we show that the dynamos without inner core solidification are much more sensitive to the CMB heat flows imposed by the lower mantle structure. We compare three-dimensional convection-driven MHD dynamos either driven by homogeneously distributed internal heat sources or by buoyancy sources at the inner core boundary (ICB). Several different CMB heat-flux patterns are used. In the dynamos driven by internal heating a rather small CMB heat-flux heterogeneity suffices to break symmetries and leads to boundary-induced structures and different field strength. The effect is much smaller for dynamos driven by ICB associated buoyancy sources. The result indicates that the field intensity and morphology of the ancient dynamos of Earth or Mars were more variable and more sensitive to the thermal CMB structure than the geodynamo after onset of inner core growth.

Magnetic energy transfer at the top of the Earth's core

Ludovic HUGUET[1] & Hagay AMIT [2]

[1] Laboratoire de Géologie de Lyon, CNRS, Université Lyon 1, ENS-Lyon, Géode, 2 rue Raphaël Dubois, Villeurbanne, F-69622, France.
(ludovic.huguet@ens-lyon.fr)
[2] CNRS UMR 6112, Université de Nantes, Laboratoire de Planétologie et Géodynamique, 2 rue de la Houssinière, Nantes, F-44000, France.
(hagay.amit@univ-nantes.fr)

We introduce a formalism to track magnetic energy transfer between spherical harmonic degrees due to the interaction of fluid flow and radial magnetic field at the top of the Earth's core. Large-scale synthetic single harmonic flows are characterized by a fixed difference between harmonics participating in the transfer. Large-scale toroidal flows result in more local energy transfer than small-scale poloidal flows. Axisymmetric poloidal flows are most efficient in producing energy transfer and dipole changes. The azimuthal phase relation between the field and the flow may play a major role in the energy transfer. Geomagnetic energy transfer induced by core flow models exhibit a striking transfer spectrum pattern of alternating extrema suggestive of energy cascade, but the detailed transfer spectrum matrix reveals rich behaviour with both local Kolmogorov-like transfer and non-local transfer, the latter about twice larger. The transfer spectrum reverses from even maxima and odd minima between 1840 and 1910 to odd maxima and even minima between 1955 and 1990. The transfer spectrum matrix shows geomagnetic energy cascade from low to high degrees as well as non-local transfer from the dipole directly to higher degrees, explaining the simultaneous dipole decrease and non-dipole increase during the historical period.

On the representation of the magnetic force making quasi-geostrophic motions evolve in the Earth's core interior

DOMINIQUE JAULT[1,2]

[1] Institute of Geophysics, ETH , Zürich, Switzerland [2] ISTerre, CNRS, University of Grenoble, Grenoble, France (Dominique.Jault@obs.ujf-grenoble.fr)

There is some evidence that rapid large scale motions $\mathbf{u}$ in the Earth's core interior are quasi-geostrophic. These motions are expressed as ($\mathbf{u}_\psi = \mathbf{e_z} \times \boldsymbol{\nabla}\psi(s,\phi)$) or ($\mathbf{u}_\chi = H^{-1}(\mathbf{e_z} \times \boldsymbol{\nabla}\chi(s,\phi)) + u_{\chi,z}\mathbf{e_z}$, $u_{\chi,z} = az + b$, $\mathbf{u}_\chi \cdot \mathbf{n} = 0$) where (s, ϕ, z) are polar coordinates, H is the half-height of geostrophic cylinders measured either from the equatorial plane or from the inner core surface to the core-mantle boundary, a and b are independent of the axial coordinate z, and $\mathbf{n}$ is the outward normal to the core-mantle boundary. For the large length scales we are interested in, the magnetic energy dominates the kinetic energy and the inertial terms, in the Navier Stokes equation, can be neglected. The magnetic force that enters the z-integrated motion equation can be written as a linear function of $\int B_s^2 dz$, $\int B_\phi^2 dz$ and $\int B_s B_\phi dz$ and, furthermore, diffusionless and linear evolution equations for these quantities can be derived from the magnetic induction equation. We have thus obtained a set of coupled linear equations [1], which nicely generalize the equations for axisymmetric torsional Alfvèn waves. However, the dispersion relation that can be calculated from these linear equations cannot account easily for the spectrum of the observed secular variation of the large scale magnetic field outside of the core. In addition, with this transformation of the induction equation, we have moved away from the equations governing the magnetic field transport along Lagrangian trajectories, which appear particularly well suited to data assimilation algorithms. Finally, the equations involving $\int B_s^2 dz$, $\int B_\phi^2 dz$ and $\int B_s B_\phi dz$ cannot properly account for magnetic diffusion. Other reduced descriptions of the interior magnetic field necessitate approximations. I will discuss the connections between the different possible descriptions of the magnetic field, in the framework of quasi-geostrophic dynamics, and tentatively give the pros and cons of the different choices.

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Triaxial rotation of the inner and outer spheres driven by Boussinesq thermal convection in a rotating spherical shell

Keiji KIMURA[1], Shin-ichi TAKEHIRO [2], Michio YAMADA[3]

Research Institute for Mathematical Sciences, Kyoto University, Kyoto, Japan
[1] kimura@kurims.kyoto-u.ac.jp
[2] takepiro@gfd-dennou.org
[3] yamada@kurims.kyoto-u.ac.jp

The problem of Boussinesq thermal convection in a rotating spherical shell has been investigated in reference to the global thermal convection in astronomical bodies. While there are some MHD dynamo models allowing the inner sphere rotation, studies of thermal convection performed so far have assumed that both the inner and outer spheres rotate with the same constant angular velocity (co-rotation). However, the spheres do not necessary co-rotate in the actual astronomical bodies, and it is a more natural situation that both the spheres rotate freely. Actually, recent seismological researches suggest that the inner core of the Earth rotates differentially against the mantle. Moreover, our recent study suggests that the stable traveling wave solutions in the co-rotating system at moderate rotation rates produce sufficiently large viscous torques to change the rotation rate of the inner sphere[1]. In the present study, therefore, we construct a Boussinesq thermal convection model allowing triaxial rotation of the spheres due to the viscous torques of fluid. We compare the convection flow with those in the co-rotating system[2], and discuss characteristics of rotation of the spheres.

First, we consider the case where the inner sphere rotates due to the torque while the angular velocity of the outer sphere is fixed. We seek for the finite-amplitude solutions which bifurcate supercritically at the critical point with the Newton method. The ratio of the radii of the inner and outer spheres and the Prandtl number are fixed at 0.4 and 1, respectively, while the Taylor number is varied from 52^2 to 500^2. No-slip and fixed temperature boundary conditions are given on both the spheres. The obtained solutions propagate in the azimuthal direction and have four-fold symmetry around the rotation axis. When the Taylor number is less than 100^2, the inner sphere rotates in the prograde direction with respect to the outer sphere. However, when the Taylor number is between 200^2 and 300^2, both the spheres rotate with nearly same angular velocity, and when the Taylor number is larger than 400^2, the inner sphere rotates in the retrograde direction. The marginal Rayleigh numbers of TW4s differ from those of the co-rotating system at most by one percent, and the pattern of TW4s is qualitatively the same.

Secondly, numerical time integrations are performed in the case where both the spheres freely rotate due to the viscous torque of the fluid. The radius ratio, the Prandtl number and the Taylor number are set to be 0.4, 1 and 500^2, respectively, with the Rayleigh number being $30,000$ $(= 4.7R_c)$ and $50,000$ $(= 7.8R_c)$ where R_c is the critical Rayleigh number. No-slip and fixed temperature boundary conditions are applied on both the spheres. The inertial moment of the inner sphere is set to be 0.22, assuming that the density of the inner sphere is the same as that of fluid, while the inertial moment of the outer sphere is assumed to be 100, which is similar to the value of the mantle of the Earth. When the Rayleigh number is $30,000$, the convection pattern has the equatorial symmetry and only the axial components of the angular velocity of the inner and outer spheres have significant values, although the temporal variation of convection pattern appears to be chaotic. When the Rayleigh number is $50,000$, however, an equatorially asymmetric convection pattern emerges and all the three components of the angular velocity of both the spheres have significant values.

Finally, we examine the transition Rayleigh number where the equatorially asymmetric convection pattern emerges in the range of the Taylor number between 500^2 and 5000^2. We find that the equatorially asymmetric convection patterns appear when the Rayleigh number is larger than $5R_c - 6R_c$.

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Flow scales in geodynamo models: canary in a coal mine?

Eric M. King
Department of Earth and Planetary Science, University of California, Berkeley

Geodynamo models have proliferated since the mid-90's, and are now commonly used to explain observations of geomagnetic field behavior and other phenomena related to core fluid dynamics. But how realistic are they? I look at the typical length scales of flow, ℓ, from a large suite of previously published dynamo simulations (e.g., Christensen & Aubert, 2006), in order to glean insight into the dominant forces at work. These calculations can be compared with theoretical expectations in order to assess the geophysical relevance of the models.

In both core and simulations, Coriolis forces are paramount. A truly dominant Coriolis force, however, imposes the so-called Taylor-Proudman (TP) constraint, which prohibits the convection needed for dynamo action. Therefore, the TP constraint must be broken. In the absence of magnetic fields, viscosity will break the TP constraint, but in doing so restricts convection to very small length scales, $\ell \sim E^{1/3}D$, where E is the Ekman number, and D is the shell thickness. Theory predicts that Lorentz forces due to strong magnetic fields can break the TP constraint more easily, leading to large scale flows, $\ell \sim D$. Because of the very small Ekman and magnetic Prandtl numbers in the core, it is typically assumed that core viscosity is negligble in comparison with Lorentz forces there. The general expectation, then, is that magnetic fields release the rotational constraint on core convection.

The geodynamo models, however, are found to produce flows with length scales very near $\ell \sim E^{1/3}$, regardless of magnetic field strength. This indicates that viscosity, and not the Lorentz force, breaks the TP constraint in the models. The prevalence of this visco-Coriolis balance suggests one of two possibilities: viscosity (and therefore very small length scales) may be more important in core dynamics than is usually thought; or the models are not faithfully reproducing core fluid dynamics.

Core stratification from high thermal conductivity and implications for thermal evolution

STÉPHANE LABROSSE[1], HITOSHI GOMI[2], KENJI OHTA[2], KEI HIROSE[2], RAZVAN CARACAS[1], MATHIEU VERSTRAETE[3] & JOHN HERNLUND[4]

[1] Laboratoire de géologie de Lyon, ENS de Lyon, Université Lyon-1, Lyon, France
(stephane.labrosse@ens-lyon.fr, razvan.caracas@ens-lyon.fr)
[2] Department of Earth and Planetary Sciences, Tokyo Institute of Technology, Meguro, Tokyo, Japan
(gomi.h.aa@m.titech.ac.jp, ohta@djebel.mp.es.osaka-u.ac.jp, kei@geo.titech.ac.jp)
[3] Institut de Physique, Université de Liège, Liège, Belgium
(Matthieu.Verstraete@ulg.ac.be)
[4] Department of Earth and Planetary Science, University of California, Berkeley, California, USA
(hernlund@gmail.com)

The Earth magnetic field is maintained by dynamo action via convection currents in the liquid metal outer core. Buoyancy sources for convection are of two sorts: thermal buoyancy associated with secular cooling and latent heat release at the inner core boundary and compositional buoyancy due to the release of incompatible light alloying components upon inner core crystallisation. Prior to inner core solidification, only thermal buoyancy is available to drive the geodynamo. In both situations, thermal conduction along the isentropic temperature profile represents a sink in the conversion of the core mantle boundary (CMB) heat flow into buoyancy forces and depends strongly on the poorly constrained thermal conductivity.

New measurements and ab-initio calculations of electrical resistivity of iron and $Fe_{.96}Si_{.04}$ up to 1 Mbar, along with a model accounting for saturation resistivity of core metal, show that the thermal conductivity of the uppermost core is greater than $90\mathrm{W/m/K}$. Moreover, the thermal conductivity is found to increase with depth in the core to reach a value larger than $150\mathrm{W/m/K}$ at ICB conditions. These values are much larger than those commonly used in the literature but agree with recently published results.

The increase of thermal conductivity with depth in the core makes the heat flux density along the core isentrope to have a maximum at some intermediate depth. Using the energy balance for a isentropic well mixed core integrated over any sphere of radius r allows the computation of the convective heat flow as function of r and we find that a large part of the core could present a negative (ie downward) convective heat flow, which means that the corresponding region would tend to be stably stratified. The position and extent of that region depends on the heat flow across the CMB (Q_{CMB}) and on whether the inner core is present and growing or not. For the present situation, with a growing inner core and the associated compositional buoyancy, we find that Q_{CMB} must be larger than 1.2 times the isentropic value ($Q_S \sim 10\mathrm{TW}$) to make the whole outer core convecting. For values lower than that but larger than Q_S, a shell of finite thickness at intermediate depth is stably stratified. Before the inner core crystallisation, only thermal buoyancy drives convection and Q_{CMB} must overcome Q_S for dynamo action to happen. We find that for $Q_S \leq Q_{CMB} \leq 1.77Q_S$, the central part of the core is stably stratified and the geodynamo can run only in the upper part of the core. The fact that the Earth magnetic field has existed for at least 3.2Gyr, puts constraints on the minimum CMB heat flow at different times which, included in thermal evolution models, imply a core cooling of about 1000K. This supports the existence of an initially thick magma ocean at the base of the mantle.

On axisymmetric and equatorially antisymmetric convection in rotating spheres

MAYLIS LANDEAU[1], JULIEN AUBERT[1]

[1]Dynamique des Fluides Géologiques, Institut de Physique du Globe de Paris, Université Paris-Diderot, INSU/CNRS, 1 rue Jussieu, 75238, Paris cedex 05, France

A spontaneous asymmetric flow regime, characterized by the emergence of an equatorially antisymmetric, axisymmetric (EAA) mode, was found recently in nonlinear simulations of convection in rotating full spheres, a configuration which is appropriate to study the fluid mechanics of planetary cores prior to inner core nucleation. In dynamo simulations this EAA mode induces hemispherical magnetic fields with a substantial north-south asymmetry. Possible implications for the past martian dynamo have been suggested. The aim of the present study is to characterize the structure and dynamics of this EAA mode and investigate the links with the first linearly unstable axisymmetric modes, which were studied by Roberts (1965)[1] and Bisshopp and Niiler (1965)[2] (RBN modes) as first attempts to solve the onset of convection in rapidly rotating spheres.

First of all, we show that analytical results for the onset of axisymmetric convection are compatible with numerical results, which validates both the theory and the numerical code that has never been benchmarked in a full rotating sphere. Then, we show that the EAA mode that emerges in nonlinear simulations is the nonlinear manifestation of the RBN modes. Its structure is characterized by the superposition of two scales of motion, a RBN-type mode which is formed of meridional cells of thickness $O(E^{1/3})$ carrying heat away in the direction parallel to the rotation axis, and a large-scale component that varies slowly in the equatorial plane. This large-scale component results from nonlinear interactions between the RBN-type mode and equatorially symmetric vortices.

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Westward drift, inner-core super-rotation and shear in low viscosity geodynamo models

Phil Livermore[1], Rainer Hollerbach [2,3] & Andy Jackson[3]
[1] School of Earth and Environment, University of Leeds, UK
[2] School of Mathematics, University of Leeds, UK
[3] Institut für Geophysik, ETH Zürich, 8092 Zürich, Switzerland

On this poster we reconcile two well known ideas relating to the dynamics of the deep Earth. The first is the observed westward drift of the non-dipole geomagnetic field, dating originally back to Halley in the 17th Century [3]. This basic property of the geomagnetic field, part of a complex picture of the secular variation, has persisted for at least the last 400 years or so, although archeomagnetic studies show that the main drift was predominantly eastward in the early 2nd millennium AD [1].

Independent of geomagnetic observations, mounting evidence from seismological studies point to a present-day super-rotation of the inner core [5]. One plausible idea that matches most observational theories is that the rotation rate of the inner core fluctuates in time — at the present time just we happen to observe a relative eastward motion.

Numerical models of the geodynamo typically run far from the regions of parameter space relevant to the Earth's core. However, by looking only for steady solutions that are consistent with an imposed Earth-like magnetic field, we are able to run 3D super-computer models at an unprecedentedly low viscosity. We find that at very low-viscosities of $E = 10^{-7}$ – 10^{-9} (where E is the Ekman number), the negative cylindrically-averaged axial electromagnetic torque drives a strong westward flow in the outer core whilst imparting a positive (eastward-directed) torque on the inner core, reproducing the apparent drift direction and the direction of the relative inner-core rotation of the present day. Furthermore, our models show thin shear layers on the tangent cylinder, predicted from the dominance of rotation and the associated tendency for axial alignment [4]. Such a location could be a source of torsional oscillations which have been observed to propagate away from the tangent cylinder [2].

This model linking the directions of outer-core drift and inner-core rotation suggests an intriguing possibility for the dynamics of the Earth. As we show, should the electromagnetic torque reverse in sign due to a perturbation of the internal geomagnetic field, the predominant drift direction in the outer core would be eastward, with a concomitant westward torque on the inner core. This is precisely the opposite of what is observed today, and suggests that the eastward drift of 1000 years ago may have been associated with a westward relative inner-core rotation.

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A full sphere dynamo benchmark

PHILIPPE MARTI[1], ANDREW JACKSON [2]

[1] Department of Applied Mathematics, University of Colorado, Boulder, USA
(philippe.marti@colorado.edu)
[2] Earth and Planetary Magnetism group, Institute of Geophysics, ETH Zurich, Switzerland
(ajackson@ethz.ch)

In recent years, the interest in the full sphere geometry, as opposed to a spherical shell, has increased significantly. While the geometry is simpler, the presence of the origin of the spherical coordinate system in the integration domain leads to additional numerical challenges. Several approaches have been used to overcome the issue but while there is a well defined set of benchmark cases for the spherical shell geometry, none are available for the full sphere geometry.

Using our simulation based on a spectral expansion on the spherical harmonics basis for the angular component and the Worland polynomials in radius, we searched for a suitable solution. We present a dynamo solution exhibiting a stable periodic oscillation in the magnetic and kinetic energies allowing for precise comparisons. The solution is obtained at a reasonable parameter regime with an Ekman number $E = 5 \cdot 10^{-4}$, a Prandtl number $Pr = 1$, a high magnetic Prandtl number $Pm = 7$ and a Rayleigh number roughly two times supercritical $Ra = 200$. We present a set of characteristics of the solution that will allow us to determine the accuracy of different spatial discretization schemes.

Investigation of subgrid scale (SGS) heat flux in dynamo simulations using a rotating spherical shell

HIROAKI MATSUI[1] and BRUCE A. BUFFETT[2]

[1] Department Earth and Planetary Science, University of California, Berkeley, California, USA (hmatsui@eps.berkeley.edu)
[2] Department Earth and Planetary Science, University of California, Berkeley, California, USA (bbuffett@berkeley.edu)

Flow and magnetic fields in the Earth's outer core are expected to have a vast range of length scale from the size of the outer core to the thickness of the boundary layers. Limited spatial resolution in geodynamo simulations prohibits solutions with the full range of scales. Consequently, subgrid scale (SGS) models are required to account for the effects of the unresolved fields on the large scale solution. Each nonlinear term in the geodynamo problem requires a SGS model; this includes the SGS heat flux, Reynolds stress, SGS Maxwell stress, and SGS magnetic induction. In the present study, we apply the dynamic scale-similarity model for the SGS model. The amplitudes of the SGS terms are adjusted using model coefficients, which are evaluated automatically using the fields in the numerical simulation.

We perform large-eddy simulations (LES) of a dynamo in a rotating spherical shell using the dynamic scale-similarity model. Our results show that magnetic energy generation is substantially improved when we include the Reynolds stress, SGS Maxwell stress and SGS magnetic induction in the simulations. In particular, we find a positive (upscale) flux of kinetic energy due to the modeled Reynolds stress in the region outside of the tangential cylinder, consistent with the results of a fully resolved calculation.

However, when the SGS heat flux is included in the LES, the magnetic energy is approximately 56% of that in resolved DNS. Comparable results are obtained when none of the SGS models are included, so the current model for the SGS heat flux has an adverse influence on the simulations. We investigate the role of the SGS heat flux in the present model to understand the origin of the problem.

First, we investigate the amplitude of the heat flux averaged over longitude. We find that the amplitude of the radial SGS heat flux is approximately 10% of the radial heat flux from a resolved DNS. In addition, we find that the resolved radial heat flux in LES is approximately 90% of that in the fully resolved DNS, which means that the sum of the resolved and SGS radial heat flux in the LES accurately reproduces the long-wavelength part of the resolve simulation. Even the spatial distribution of the SGS heat flux, which has a large radial component, is in good agreement with a direct estimate from the resolved simulation. All indications suggest that the SGS heat flux is reliably modeled, yet the results of the LES underestimate the magnetic energy compared with the resolved simulations.

The origin of the problem can be traced to the buoyancy flux in the LES, which underestimates the long-wavelength part of the buoyancy flux in the resolved simulation. We use energy balances to establish relationships between the various SGS models, and focus specifically on the Reynolds stress as the primary mechanism for upscale transport of energy into the resolved scales. By properly accounting for the connection between heat and buoyancy flux, we expect to achieve reliable dynamo simulations without the need to fully resolve the velocity, magnetic and temperature fields.

Influence of thermal boundary condition and anisotropic thermal diffusivity on dynamics in the Earth's core

MASAKI MATSUSHIMA[1]

[1]Department of Earth and Planetary Sciences, Tokyo Institute of Technology, Tokyo, Japan
(mmatsush@geo.titech.ac.jp)

Very small molecular viscosity of the Earth's fluid core gives rise to small-scale fluid motions, which are likely to be highly anisotropic because of the Earth's rapid rotation and a strong magnetic field in the core. Such flows can enhance a large-scale diffusive process much more effectively than molecular diffusion; that is, the eddy diffusivity is much larger than the molecular one in the core. The anisotropy also indicates that a thermal eddy diffusivity should not be a scalar but a tensor. We have been carrying out numerical simulations of magnetoconvection in a rapidly rotating system to investigate the influence of anisotropy on dynamics in the core, by prescribing elements of anisotropic thermal diffusion tensor.

It has been found that a certain degree of anisotropy has an insignificant influence on the character, like kinetic and magnetic energy, of magnetoconvection in a small region with periodic boundaries in the three-directions. However, in a region with top and bottom rigid boundary surfaces, the same degree of anisotropy can enhance kinetic and magnetic energy in magnetoconvection depending not only on prescribed anisotropic tensor diffusivity but also on location of the computational region expressed in terms of direction of gravity. That is, anisotropic tensor diffusivity, consequent on the anisotropy of small-scale flows, can alter dynamics in the core near the boundary surfaces depending on the latitude. The magnetoconvection turns out to have larger kinetic energy for larger spatial and temporal mean of absolute value of temperature gradient in the latitudinal direction, $|\partial\theta/\partial\lambda|$.

We have so far imposed a fixed temperature boundary condition, but the argument above suggests that a different thermal boundary condition may have a stronger (or weaker) influence on the dynamics in the core. Hence we investigate kinetic and magnetic energy in magnetoconvection for a fixed heat-flux boundary condition. We have found that the relationship between kinetic energy of magnetoconvection and $|\partial\theta/\partial\lambda|$ is similar to that for a fixed temperature boundary condition. However, the efficiency of magnetic field generation shows a much stronger dependence on prescribed anisotropic tensor diffusivity as well as location of the computational region. These results suggest that even a small anisotropy can change dynamics in the Earth's core.

Statistical Analysis of Stable Polarity Intervals in Geodynamo Models and its Comparison with Paleomagnetic Data

Domenico Meduri[1], Johannes Wicht[1] & Dieter Schmitt[1]

[1] Max-Planck-Institut für Sonnensystemforschung, 37191 Katlenburg-Lindau, Germany (meduri@mps.mpg.de)

Paleomagnetic observations show a sequence of sudden and occasional, apparently stochastic, global polarity reversals of the Earth's dipolar magnetic field during its history. Recent self-consistent 3D numerical dynamo simulations replicate many features of the Earth's magnetic field and several of these models show reversals of the field ([5], [1]).

The statistical study of times between successive magnetic polarity changes in both paleomagnetic data and numerical dynamo models is helpful to acquire a better knowledge of the geodynamo processes involved. In this context, we investigated different probability distribution profiles on stable polarity intervals from Earth's paleomagnetic timescales ([2] for the Cenozoic and [4] for the Cretaceous and late Jurassic) and from a numerical dynamo simulation.

Paleomagnetic studies suggest that the field intensity drops significantly during a reversal (see, e.g., [3]). Following this experimental evidence in numerical simulations, we identified reversal times of occurrence using the relative contribution of the dipole to the total field at the core-mantle boundary and stable polarity intervals as waiting times between two successive reversals. A similar criterion was also applied on dipole moment itself leading to similar results.

We fitted the identified stable polarity intervals with different probability distributions and we quantified the goodness of fit using Kolmogorov-Smirnov and Anderson-Darling measures. A gamma distribution turned out to be the most reliable fit in our numerical simulation and this is confirmed by the high probability values associated.

The careful comparison with geomagnetic reversal sequences should take into account the possibility of missing short intervals. When neglecting short polarity intervals in our numerical simulation, which gives a perfect coverage in time, a log-normal distribution becomes the best fit. This is also the distribution which best describes paleomagnetic data.

Further numerical simulations in different parameter regimes are planned to be studied to confirm gamma distributed stable polarity intervals. Furthermore, the development of mean-field dynamo models can play the key role of discriminating among different physical processes that can reproduce the observed distribution profile.

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Angular Momentum Transfer and the 5.8-year Length-of-Day Oscillation

JON MOUND[1]

[1] School of Earth and Environment, Institute of Geophysics and Tectonics, University of Leeds, Leeds, UK (J.E.Mound@leeds.ac.uk)

Observation of a 5.8-year oscillation in the length-of-day (LOD) that cannot be accounted for by variations in atmospheric or oceanic angular momentum indicates that some dynamic process within the core exchanges angular momentum with the mantle on this time scale. One explanation is that the LOD signal is due to excitation of a normal mode of oscillation involving the mantle and the solid inner core, with gravitational coupling providing the restoring force and thus transferring the angular momentum [1]. The period of the oscillation in this situation is determined by the strength of the gravitational coupling and does not depend on the strength of the magnetic field within the fluid core. Decadal changes in LOD, which have also been observed, could then be attributed to relatively slow torsional oscillations in the fluid core, implying a relatively weak (cylindrically) radial magnetic field (approximately 0.2 mT). Conversely, observation of rapidly propagating torsional waves in the outer core suggests a much stronger radial magnetic field (2 mT or more) and may provide an alternate explanation for the source of the 5.8-year LOD oscillation [2]. The rapid torsional waves imply that normal mode periods of the waves in the fluid core are of a few years or less and thus decadal LOD variations must arise for some other reason.

Gravitational coupling requires that the viscosity of the inner core is sufficiently large that the inner core does not undergo significant viscous deformation on a time scale of six years. However, recent investigations of nutation observations [3] suggest a tight constraint on inner core viscosity, of approximately $2–7\times10^{14}$ Pa s, which is at least three orders of magnitude less than required for gravitational coupling to explain the angular momentum transfer associated with the 5.8-year LOD variation. The nutation data also support a strong (spherically) radial magnetic field at the inner-core boundary.

In this work, a forward model is used to investigate the angular momentum transfer of the core-mantle system at periods of approximately six years. If gravitational coupling is excluded, it does not appear that electromagnetic torques at the CMB can transfer sufficient angular momentum to explain the observed LOD observations. Either the inner core viscosity must be larger than the nutation results suggest, the EM coupling is larger than modelled, or another physical mechanism must be involved (such as topographic coupling).

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Core flow inversion and the geodynamo.

MARIA ALEXANDRA PAIS[1] & NATHANAËL SCHAEFFER[2]

[1] CGUC, Physics Department, University of Coimbra, Coimbra, Portugal
(pais@fis.uc.pt)
[2] ISTerre, CNRS, University of Grenoble, Grenoble, France
(nathanael.schaeffer@obs.ujf-grenoble.fr)

We investigate the possibility for core flows inverted from geomagnetic measurements to produce and sustain the magnetic field of the Earth.

The variations of the magnetic field recorded at magnetic observatories as well as by magnetometers onboard dedicated satellites are partly due to the flow of liquid iron at the Earth's core surface. Geomagnetic field models allow to isolate the liquid core contribution in the observed large scale field, and this can then be inverted for core flows. The inversions rely significantly on the assumptions involving the core flow which, for the time being, have been always imposed as kinematic constraints at the core surface.

It is the case of quasi-geostrophic (QG) flows inversion. The imposed equatorial symmetry at the core surface is supported by a dynamical balance dominated by pressure and Coriolis forces. Furthermore, it has the great additional advantage of producing flows that can be continued inside the core. As flow incompressibility is assumed for the induction equation, the inverted flows are also required to obey this condition. Finally, we test incompressible QG flows for dynamo action.

Because the time-variation of the flow may be important for dynamo action, we decompose core flows into principal components. This allows to identify the main variability modes in flows computed from geomagnetic field models and provides the associated periodic time-dependence of each component. The resulting three-dimensional, time-dependent flow is then used in a code that computes the induction equation. In addition to this dynamo problem, we also study the effect of varying periods, of stronger and weaker flow regularizations, and of an unknown small-scale flow on the magnetic induction.

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Rotating Magnetoconvection with Anisotropic Turbulent Heat Transport in Spherical Geometries

COLLIN PHILLIPS[1], DAVID IVERS [2]

[1] Mathematics Learning Centre, University of Sydney, Australia (collin.phillips@sydney.edu.au)
[2] School Mathematics and Statistics, University of Sydney, Australia (david.ivers@sydney.edu.au)

A simplified picture of the turbulence in the Earth's core, developed by Braginsky and Meytlis [1], is adopted. The turbulence is highly anisotropic with preferred directions imposed by the Earth's rotation and the magnetic field. In the simplified picture the anisotropy is modelled in a thermal diffusion tensor only. The resolvable scale magnetic induction $\overline{\mathbf{B}}$, velocity $\overline{\mathbf{v}}$, temperature $\overline{\Theta}$ and modified pressure $\overline{P}$ satisfy the Boussinesq induction, heat and momentum equations,

$$\frac{\partial \overline{\mathbf{B}}}{\partial t} = \eta \nabla^2 \overline{\mathbf{B}} + \nabla \times (\overline{\mathbf{v}} \times \overline{\mathbf{B}})$$

$$\frac{\partial \overline{\Theta}}{\partial t} + \overline{\mathbf{v}} \cdot \nabla \overline{\Theta} = \nabla \cdot (\boldsymbol{\kappa} \cdot \nabla \overline{\Theta}) + \frac{\overline{Q}}{\rho c_p}$$

$$\rho \left(\frac{\partial \overline{\mathbf{v}}}{\partial t} + \overline{\boldsymbol{\varpi}} \times \overline{\mathbf{v}} + 2\boldsymbol{\Omega} \times \overline{\mathbf{v}} \right) = -\nabla \overline{P} - \rho \alpha \overline{\Theta} \mathbf{g} + \overline{\mathbf{J}} \times \overline{\mathbf{B}} + \rho \nu \nabla^2 \overline{\mathbf{v}} ,$$

with $\nabla \cdot \overline{\mathbf{v}} = 0$ and $\nabla \cdot \overline{\mathbf{B}} = 0$. The reference density ρ, the thermal expansivity α, the viscous diffusivity ν, the magnetic diffusivity η and the specific heat at constant temperature c_p are uniform.

The equations are linearised about a basic state $(\mathbf{B}_0, \mathbf{v}_0, \Theta_0)$, where $\mathbf{B}_0 = B_0 \mathbf{1}_\phi$ and $\mathbf{v}_0 = v_0 \mathbf{1}_\phi$. The turbulent diffusion tensor is then

$$\boldsymbol{\kappa} = \kappa (\mathbf{I} + \varphi B_0^2 \, \mathbf{1}_\phi \mathbf{1}_\phi + \zeta \, \mathbf{1}_z \mathbf{1}_z) \, ,$$

and to satisfy the basic state heat equation with anisotropic thermal diffusion, the basic state temperature Θ_0 is a function of ζ. To investigate the effects of the anisotropic thermal diffusion the linearised magnetoconvection problem is solved in a rotating sphere with electrically insulating exterior using vector and tensor spherical harmonics in angle and finite-differences in radius.

The effects of the anisotropy on convective instabilities are discussed for a range of different Ekman and Elsasser numbers, different symmetries including azimuthal wavenumber, and varying diffusivities in the directions of the basic state magnetic field and the rotation axis. We also consider buoyancy catalysed instabilities for higher Elsasser numbers (stronger magnetic fields). Different methods of controlling the total diffusion, which varies with the anisotropic diffusion parameters φ and ζ, are given to allow comparison of stability/instability for different values of κ, φ and ζ.

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Thermal traps in domino's dynamo model

MAXIM RESHETNYAK[1] & PAVEL HEJDA[2]

[1] Institute of the Physics of the Earth, Russian Academy of Sciences, Moscow, Russia
(m.reshetnyak@gmail.com)
[2] Institute of Geophysics, Czech Academy of Sciences, Prague, Czech Republic
(ph@ig.cas.cz)

Generation of the planetary magnetic fields is a subject of the dynamo theory, which describes successive transformation of the thermal and gravitational energy, concerned with a compositional convection, to the energy of the kinetic motions of the conductive liquid and then to the energy of the magnetic field. One of the important results of the geodynamo theory is that frequency of the reversals depends on the spatial distribution of the heat flux at the outer boundary of the liquid core. In particular, it has been shown that increase of the heat flux along the axis of rotation leads to increase of the axial symmetry of the whole system and stops reversals [1]. In a sense the thermal trap of reversals appears. On the contrary, decrease of the thermal flux at high latitudes leads to a chaotic behaviour of the magnetic dipole accompanied with a frequent reversals, what is closely connected to the break of the geostrophic balance and predominance of the radial Archemedean forces. It looks attractive to get this result using toy dynamo models, which can provide extensive statistics and obviousness of the results.

For this reason we select the domino dynamo model [2], which is an extension of Ising-Heizenberg XY-models of interacting magnetic spins. The main idea of the domino model is to consider system of interacting spins in the rotating media. The spins are located over the ring, have unit length and can vary the angle from the axis of rotation on the time. Each spin is forced by the random force, effective friction, as well as by the forces from the closest neighbour spins. Such a system can generate time series of the reversals, very similar to that ones, known from the paleomagnetic records.

Here [3] we present modification of the domino model, which takes into account heterogeneity of the heat flux at the core-mantle boundary, and repeat main results obtained in [1]. Moreover, we demonstrate how the heat flux variations can lead to the various very specific regimes, like those with a large inclination of the magnetic dipole as at Saturn and Uranus. The other possibility discussed in the talk is existence of the systems, when the magnetic dipole is located in two regions: either near the geographic pole or at the middle latitudes, as follows from some paleomagnetic data [4].

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Westward drift, torsional oscillations and jerks in a low-viscosity numerical geodynamo model

ATARU SAKURABA[1]

[1] Department of Earth and Planetary Science, School of Science, University of Tokyo, Tokyo, Japan (sakuraba@eps.s.u-tokyo.ac.jp)

Time variations of flow and magnetic field produced by a numerical geodynamo model are analysed to explain physical processes creating relatively short-term phenomena such as geomagnetic westward drift, torsional oscillations and jerks. Thermal convection in a rotating Boussinesq fluid spherical shell, which we hereafter call the core, is taken as a crude model of the Earth's dynamo. The nondimensional parameters are the same as those used by Sakuraba and Roberts (2009). For example, the Ekman number is 5×10^{-7}, the magnetic Prandtl number is 0.2 and the Rayleigh number is 3.2×10^{10}. Fourier analysis is performed for the core-surface magnetic field to illuminate the westward (or eastward) drift in the model. The drift phase velocity coincides with the zonal flow angular velocity near the core surface in an order-of-magnitude sense. Detailed investigation shows, however, that there are several types of waves traveling at different angular velocities. The magnetic field signals of azimuthal wavenumber of 1 and 2 largely move westward at a relatively slow angular velocity that does not depend on latitude very much. The high-wavenumber signals are seen in low latitudes and has a faster drift speed in the westward direction, but the speed is still slower than the peak westward flow speed at the equator. There is a tendency of latitudinal migration of magnetic field signals toward the equator in the low latitudes. The results indicate that the westward drift is dispersive and does not exactly reflect the zonal flow velocity just below the core. We also investigate the torsional oscillations in the core using Fourier analysis. The power spectrum in the frequency domain shows that the low-frequency powers whose period is longer than the turnover time (c/U, c and U being the core radius and a characteristic flow speed) are nearly flat and the high-frequency powers decrease obeying a power-law distribution with respect to frequency. The power of outgoing waves (i.e., waves traveling apart from the rotation axis) is slightly larger than that of ingoing waves in the place where the distance from the rotation axis is greater than about $0.6c$. In the inner part of the core, both outgoing and ingoing waves coexist with similar powers. The phase velocity of the high-frequency signals basically coincides with the Alfven velocity and there is no dispersion. The phase velocity of the more powerful low-frequency waves is slower. The results suggest that the excitation source of the torsional waves is located in the inner part of the core. Magnetic secular variations at test observatories located at $r = 1.83c$ show that the most remarkable high-amplitude signals have periods similar to the turnover time. These variations sometimes show a zig-zag pattern in time domain resembling the geomagnetic jerks, but the occurrence is not global. There are also shorter-period variations but the amplitude is relatively small. These short-period signals also show a zig-zag pattern in the time domain. In the analysis of the westward drift, we find that time change of the drift phase velocity (i.e., westward acceleration) is propagated mainly from the mid-latitude to the equator, which is reasonably explained by field changes caused by the torsional waves. We discuss the relation between the shorter-period jerk-like secular variations and the torsional waves, which has been suggested in earlier studies.

A modified probability distribution for superchrons, consistent with an amplification mechanism stabilising longer chrons

GRAEME SARSON[1] & DAVID RYAN[1]

[1] School of Mathematics and Statistics, Newcastle University, Newcastle upon Tyne NE1 7RU, UK (graeme.sarson@ncl.ac.uk)

We argue that the occurrence of fixed-polarity states of the reversing geomagnetic field of exceptionally long duration — i.e. the observed superchrons — can be characterised by an 'amplification' mechanism, which acts to enhance the stability of longer chrons. Such a mechanism, acting within a multiplicative process, has been proposed as a model for economic systems [Montroll & Shlesinger (1982), *Proc. Natl. Acad. Sci. USA*, **79**, 3380–3383], and results in a transition from lognormal statistics to a Pareto (power law) tail. Such a transition seems consistent with paleomagnetic reversal records, where superchrons appear as outliers to the distribution of shorter chrons.

We explore this mechanism using a low order model for the geodynamo, adapted from an earlier model [D. A. Ryan & G. R. Sarson (2011), *Phys. Earth Planet. Inter.*, **188**, 214–234] by the addition of turbulent diffusion. This model produces reversal distributions with Pareto type tails, consistent with the proposed amplification process. Within our model, this occurs as a natural part of the underlying dynamics. This work therefore supports a modified probability distribution for superchrons (distinct from the distribution of shorter chrons), and may help to guide further study on their occurrence within geodynamo dynamics.

Effects of latitudinally heterogeneous buoyancy flux conditions at the inner boundary on MHD dynamos in a rotating spherical shell

YOUHEI SASAKI[1], SHIN-ICHI TAKEHIRO[2], SEIYA NISHIZAWA[3] & YOSHI-YUKI HAYASHI[4]

[1] Department of Mathematics, Kyoto University, Kyoto, Japan
(uwabami@gfd-dennou.org)
[2] Research Institute for mathematical Sciences, Kyoto University, Kyoto, Japan
(takepiro@gfd-dennou.org)
[3] RIKEN Advanced Institute for Computational Science, Kobe, Japan
(seiya@gfd-dennou.org)
[4] Center for Planetary Science/Department of Earth and Planetary Sciences, Kobe University, Kobe, Japan
(shosuke@gfd-dennou.org)

Outer core flows, contributing to generation and maintenance of the intrinsic magnetic field of the earth, is considered to be driven by buoyancy caused by the light elements released at the inner core boundary (ICB) through selective condensation of iron and nickel along with the inner core growth. On the other hand, existence of inner core flows has come to be studied as a candidate of the origin of the anisotropy of seismic velocity in the inner core. The typical flow pattern expected in the inner core is axisymmetric and flows are directed from the equatorial region to the polar regions or vice versa. Since such a flow accompanies mass flux through the ICB, it affects the condensation process of iron and nickel, and as a result, latitudinal heterogeneity of the buoyancy (light elements) flux is expected to occur at the ICB.

In the present study, we investigate effects of latitudinally heterogeneous buoyancy flux at the ICB on dynamo process in the outer core through numerical experiments of a 3-dimensional rotating spherical MHD Boussinesq dynamo model. Three types of the buoyancy flux at the ICB is considered; 1) homogeneous distribution, 2) strong flux around the equatorial region and weak flux around the polar regions, 3) strong flux around the polar regions and weak flux around the equatorial region. The ratio of the inner and outer radii, the Prandtl number and the Ekman number are fixed to 0.35, 1, and 10^{-3}, respectively. The magnetic Prandtl number is varied from 1 to 10, and the modified Rayleigh number is from 100 to 500.

Flow fields of fully developed non-magnetic compositional convection with different ICB buoyancy flux patterns are similar except for the distributions of mean zonal flow. However, a prominent difference in development and maintenance of magnetic field becomes apparent in the MHD dynamo calculations. Solutions with simultaneously developed and sustained magnetic field (dynamo solutions) are obtained in the cases of homogeneous buoyancy flux and strong equatorial flux. On the contrary, in the case of strong polar buoyancy flux, all solutions are failed to sustain the magnetic fields in the surveyed ranges of the parameters. This difference in development of magnetic fields is considered to be affected by thedifferent pattern of mean zonal flow.

The consequence that dynamo solution cannot be established when strong flux is given around the polar region might suggest the flow direction of the earth's inner core, because such a buoyancy flux pattern may be unfavorable for development and maintenance of the strong geomagnetic field. It may not be expected that the inner core flows is directed from the polar regions to the equatorial region.

Nested synthetic databases of observations for geomagnetic data assimilation practice: interannual to decadal time scales.

NATHANAËL SCHAEFFER[1] ALEXANDRE FOURNIER[2], JULIEN AUBERT [2], ERWAN THÉBAULT[2] &

[1] Institut des Sciences de la Terre, Grenoble, France
(nathanael.schaeffer@obs.ujf-grenoble.fr)
[2] Institut de Physique du Globe, Paris, France
(fournier@ipgp.fr, aubert@ipgp.fr, ethebault@ipgp.fr)

Data assimilation aims at producing an optimal estimate of the state of the dynamical system one is interested in by combining two sources of information : physical laws (in the form of a numerical model) and observations. A mandatory step during the development of a data assimilation framework involves a validation phase using synthetic data. In this well-controlled environment, the true dynamical trajectory of the system is known (it results from the integration of the numerical model), and it is used to generate synthetic observations. Those are subsequently used to assess the efficacy, and to highlight possible shortcomings, of the chosen methodology.

At the 2012 SEDI meeting in Leeds, we will report on the construction of a database of synthetic observations meant at reproducing the heterogeneity of the geomagnetic record (in terms of temporal and spatial coverage). This database relies on two dynamical trajectories:
(1) A long-term dynamical trajectory (spanning the equivalent of the past few millenia) computed from a three-dimensional, convection-driven, dynamo model, able to represent accurately the long-term variability of the geomagnetic field. This long-term trajectory is described in detail in the companion contribution by Fournier et al.
(2) short-term dynamical trajectory (spanning the equivalent of a few decades), computed from a high- resolution three-dimensional model, able to represent interannual to decadal core processes (e.g. Gillet et al., 2011), and whose basic state is determined from the long-term trajectory.
This contribution will specifically describe trajectory (2), focusing on the short timescale features and the associated catalog of synthetic observations.

We start our simulations with a snapshot of the long-term trajectory (1), but significantly change the parameters in order to allow short timescale dynamics. In particular, we increase independently the rotation rate (to increase the Coriolis force strength), the magnetic field (to allow Alfvén-type waves). Spatial and temporal resolution are increased accordingly. Additionaly, we remove the thermal forcing term, so the simulations are started off-balance and we observe a free-decay turbulence, hopefully filled with waves. The Lundquist number is crancked up to 6000, the Lehnert is lowered down to 1.5e-4, and the Afvén number to 0.1.

This short timescale dynamics simulations span a few years, and we specifically record the magnetic field at the CMB, as well as its first and second time derivatives (also known as secular variation and secular acceleration), in order to mimmic state-of-the-art geomagnetic models covering the satellite era.

Reference:

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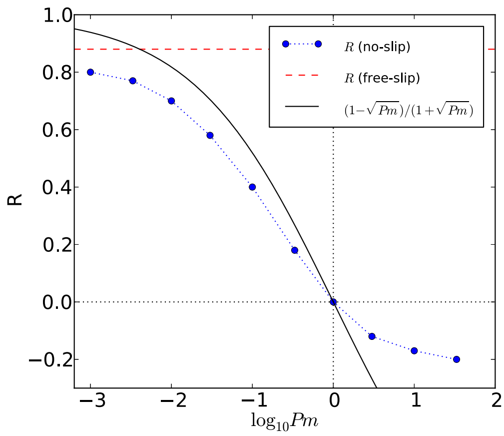
On the reflection of Alfvén waves and its implication for Earth's core modeling.

NATHANAËL SCHAEFFER[1], DOMINIQUE JAULT[1,2] & PHILIPPE CARDIN[1]

[1] ISTerre, Université de Grenoble 1, CNRS, F-38041 Grenoble, France
(nathanael.schaeffer@obs.ujf-grenoble.fr)
[2] Earth and Planetary Magnetism Group, Institut fr Geophysik, Sonnegstrasse 5, ETH Zrich, CH-8092, Switzerland

We investigate the reflection of Alfvén waves, including torsional oscillations. Alfvén waves propagate in electrically conducting fluids in the presence of a magnetic field. Their reflection properties depend on the ratio between the kinematic viscosity and the magnetic diffusivity of the fluid, also known as the magnetic Prandtl number Pm. In the special case $Pm = 1$, there is no reflection on an insulating, no-slip boundary, and the incoming wave energy is entirely dissipated in the boundary layer.

We investigate the consequences of this remarkable behaviour for the numerical modeling of torsional Alfvén waves (also known as torsional oscillations), which represent a special class of Alfvén waves, in rapidly rotating spherical shells. They consist of geostrophic motions and are thought to exist in the fluid cores of planets with internal magnetic field. In the geophysical limit $Pm \ll 1$, these waves are reflected at the core equator, but they are entirely absorbed for $Pm = 1$. Our numerical calculations show that the reflection coefficient at the equator of these waves remains below 0.2 for $Pm \geq 0.3$, which is the range of values for which geodynamo numerical models operate. As a result, geodynamo models with no-slip boundary conditions cannot exhibit torsional oscillation normal modes.



Reflection coefficient for a torsional Alfvén wave for insulating and no-slip boundary conditions, as a function of Pm. The Lundquist number is always large ($S > 5000$ for $Pm \geq 0.01$ and $S > 600$ otherwise). For reference, the black curve is the planar Afvén wave reflection coefficient $(1 - \sqrt{Pm})/(\sqrt{Pm} + 1)$, and the red line marks the reflection coefficient for a stress-free boundary with $Pm = 1$ (corresponding to a no-slip boundary with $Pm \to 0$)

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Low latitude dynamics and secular variation in rapidly-rotating convection driven dynamos

ANDREY SHEYKO[1], CHRISTOPHER FINLAY [2], PHILIPPE MARTI[3] & ANDREW JACKSON[4]

[1] Earth and Planetary Magnetism group, Institute of Geophysics, Swiss Federal Institute of Technology Zurich, Zurich, Switzerland
(andrey.sheyko@erdw.ethz.ch)
[2] National Space Institute, Technical University of Denmark, Copenhagen, Denmark
(cfinlay@space.dtu.dk)
[3] Department of Applied Mathematics, University of Colorado, Boulder, USA
(Philippe.Marti@colorado.edu)
[4] Earth and Planetary Magnetism group, Institute of Geophysics, Swiss Federal Institute of Technology Zurich, Zurich, Switzerland
(ajackson@ethz.ch)

Motions of liquid metal inside the Earth's outer core are responsible for generating the geomagnetic field in a dynamo process. Prominent features in the observed core surface field are intense equatorial flux patches drifting westwards at a rate of 17km/yr. We investigate the formation and dynamics of such flux features in numerical dynamo models, varying the convection strength. We study a set of numerical dynamo models varying the convection strength by a factor of 30 and ratio of magnetic to viscous diffusivities by a factor of 20 at fixed rapid rotation rate ($E = \nu/(2\Omega d^2) = 10^{-6}$) using a heat flux outer BC. This regime has been little explored (aside from a pioneering study by Sakuraba & Roberts) due to the significant computing resources required. Our simulations are carried out using a discretisation of degree and order 256 in spherical harmonics, and 516 finite difference points in radius and parallelized on 516 processors. We present an analysis of the time-evolution and force balance associated with low-latitude magnetic flux concentrations. We also report a comparison of our results with the proposed rotating convection and dynamo scaling laws.

Benchmark dynamos with pseudo-vacuum magnetic boundaries

ANDREY SHEYKO[1], ANDREW JACKSON[2], PHILIPPE MARTI[3], STIJN VANTIEGHEM[4] & DAVID CÉBRON[5]

[1] Earth and Planetary Magnetism group, Institute of Geophysics, ETH Zürich, Zürich, Switzerland (andrey.sheyko@erdw.ethz.ch)
[2] Earth and Planetary Magnetism group, Institute of Geophysics, ETH Zürich, Zürich, Switzerland (ajackson@ethz.ch)
[3] Department of Applied Mathematics, University of Colorado, Boulder, USA (Philippe.Marti@colorado.edu)
[4] Earth and Planetary Magnetism group, Institute of Geophysics, ETH Zürich, Zürich, Switzerland (stijn.vantieghem@erdw.ethz.ch)
[5] Earth and Planetary Magnetism group, Institute of Geophysics, ETH Zürich, Zürich, Switzerland (david.cebron@erdw.ethz.ch)

The insulating magnetic boundary conditions are difficult to implement in non-spectral numerical dynamo codes and a pseudo-vacuum condition (only radial field is non zero) alternative is often used instead. Christensen et al. (2001) precisely described an easily repeatable steady dynamo that is very useful for benchmarking codes with the insulating boundaries, but there has been no equivalent comparable benchmark case for codes using a pseudo-vacuum boundary conditions. Here we propose a new benchmark case for the convection-driven magnetohydrodynamic dynamo problem in a rotating spherical shell, with pseudo-vacuum boundary conditions. Entirely steady solutions for two different ratios of thermal and magnetic diffusivities (Roberts number $q = \kappa/\eta = 5, 8$) are presented together with accurate values for the drift rate, kinetic and magnetic energies and some local data. Change of the boundary conditions from insulating to pseudo-vacuum modifies these diagnostics significantly. Dynamos are subcritical and require a specific initial state, an example of which is given in an analytical form. Results for the new benchmark with three different types of code (Pseudo-Spectral, Finite Elements, Finite Volume) are presented.

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Hydromagnetic dynamos in rotating spherical fluid shells in dependence on the Prandtl and Ekman numbers

JÁN ŠIMKANIN[1], PAVEL HEJDA[2]

[1] Institute of Geophysics, Academy of Sciences of the Czech Republic, Prague, Czech Republic (jano@ig.cas.cz)
[2] Institute of Geophysics, Academy of Sciences of the Czech Republic, Prague, Czech Republic (ph@ig.cas.cz)

A dependence of hydromagnetic dynamos on the Prandtl and Ekman numbers is investigated. In all the investigated cases, the generated magnetic fields are dipolar and neither transition to hemispherical dynamos nor weaker magnetic fields (which are less dipole dominated) are observed, although the inertia becomes important. We show that at low Prandtl numbers the magnetic diffusion regulate an influence of inertia on the dynamo, i.e. inertial forces become influential as the magnetic Prandtl number is reduced. However, the magnetic Prandtl number has to exceed a minimum value in order to sustain dynamo. The convective flow is at low Prandtl numbers more overcritical than at the Prandtl number equal to one. Large-scale flows are columnar and we do not observe the significant breakdown of the columnar structure of the convection although the magnetic field is convected out of polar regions.

Polarity reversals in dependence on the Prandtl number: Preliminary results

JÁN ŠIMKANIN[1], PAVEL HEJDA[2], ALEXANDRA MARSENIĆ[3]

[1] Institute of Geophysics, Academy of Sciences of the Czech Republic, Prague, Czech Republic (jano@ig.cas.cz)
[2] Institute of Geophysics, Academy of Sciences of the Czech Republic, Prague, Czech Republic (ph@ig.cas.cz)
[3] Institute of Geophysics, Academy of Sciences of the Czech Republic, Prague, Czech Republic (geofalma@ig.cas.cz)

Polarity reversals of dipolar dynamos in dependence on the Prandtl number are investigated. The Prandtl numbers $P_r = 1$ and $P_r = 0.2$ are considered. The obtained results indicate that a duration of the opposite polarity is shorter at $P_r = 0.2$ than at $P_r = 1$. It is found that a frequency of polarity reversals is the same in both cases, i.e. two polarity reversals occur during 1000 time units for both values of the Prandtl number. At $P_r = 0.2$ excursions are probably inhibited - we get less excursions and not as noticeable as at $P_r = 1$. The beginnings of polarity reversals in the case of $P_r = 1$ are characterized by a significant decrease of both the kinetic and magnetic energies, the energies tend almost to zero. However, at the beginning of polarity reversals at $P_r = 0.2$, the kinetic energy increases while the magnetic energy decreases but it is not being reduced so much as at $P_r = 1$. This may be due to presence of the quadrupole component of the magnetic field, which is significantly stronger in the case of $P_r = 0.2$ than at $P_r = 1$.

Correct description of heat and mass transfer in the Earth's liquid core

SERGEY V. STARCHENKO[1]

[1]IZMIRAN, Troitsk, Moscow region, 142190 Russia (sstarchenko@mail.ru)

Geodynamo's heat transfer are usually described via not so correct [1] Boussinesq equation for temperature T that have partly been justified in [2] where similar temperature equation was derived using entropy, momentum and the other initial equations. Unfortunately the basic assumption (2.12) from [2] about comparable magnitudes of pressure and buoyancy force is not correct because the pressure is balanced by the Coriolis force greatly exceeding the buoyancy force. This leaves no way to justify using of temperature equation for dynamo modelling in the fast rotating planets. In this work I derive correct and simple enough equations of heat and mass transfer basing on specific entropy S and mass fraction of the lighter component ξ in the Earth's liquid core. The standard notations similar to [1, 2] are further used thought this paper.

1. ***Heat transfer*** is correctly [1, 2] described by $\rho TDS/Dt = \nabla \cdot (\mathrm{K}\nabla T) + Q$. (1)

The density equation of state is $\rho(P,S,\xi) = \rho_a + c^{-2}p - \rho_a(\alpha T_a s/C_P + \beta\xi)$. (2)

Hereafter small variables $p \equiv P - P_a, s \equiv S - S_a, x \equiv \xi - \xi_a, T - T_a = T_a\alpha p / C_P\rho_a + s - h\tilde{\delta} / C_P$.(3-6)

Adiabatic entropy time-change leads to normalization: $\dot{S}_a \equiv \dfrac{dS_a}{dt} = \dfrac{-Q_o}{M_c T_c} \Rightarrow \displaystyle\int_{r_i \le r \le r_o} \rho s\, d^3r = 0$. (7-8)

Substituting (3-6) in (1-2) and doing regards to the other dynamo equations with their scaling (see the other contribution of me to S1 session on this meeting) in fast rotating planets I have the entropy equation $\dfrac{Ds}{Dt} = \kappa\nabla^2 s + \dfrac{Q_a}{\rho_a T_a}$ with adiabatic heat $Q_a \equiv \nabla \cdot (\mathrm{K}\nabla T_a) + Q - \rho_a T_a \dot{S}_a$. (9-10)

The correspondent boundary conditions are for radial derivatives of super-adiabatic entropy that requires using of (8): $-T_i\rho_i\kappa\left(\dfrac{\partial s}{\partial r}\right)_{r=r_i} = q_i$, $-T_o\rho_o\kappa\left(\dfrac{\partial s}{\partial r}\right)_{r=r_o} = q_o = \dfrac{Q_o}{4\pi r_o^2} + \mathrm{K}\left(\dfrac{dT_a}{dr}\right)_{r=r_o}$. (11-12)

Here the subscript "i"/"o" means the inner/outer boundary of the liquid core in a planet.

2. ***Mass transfer*** is correctly described [2] by $\rho D\xi/Dt = \nabla \cdot (\rho k \nabla \xi)$. (13)

Substituting (3-6) in (2, 13) and doing regards to the other geodynamo equations I have diffusion equation driven by change of the reference state concentration $\dot{\xi}_a = \nabla \cdot (\rho k \nabla x)/\rho - Dx/Dt$. (14)

Accepted course of this drive is crystallization of the liquid core, while it could be dissolution of the protocore as in the contribution of Pushkarev and Starchenko to this SEDI 2012 meeting.

The simplified boundary conditions are for radial derivatives of non-uniform concentration x that requires normalization in the core volume: $\dfrac{\partial x}{\partial r}|_{r=r_o} = 0$, $\dfrac{\partial x}{\partial r}|_{r=r_i} = -\dfrac{\dot{r}_i}{k}\Delta\xi$, $\displaystyle\int_{r_i \le r \le r_o} \rho x\, d^3r = 0$. (15-17)

3. ***Archimedean buoyancy acceleration*** A drives geodynamo and is given by $A = T's + \mu'x$. (18)

A prime "'" denote the radial derivative of the reference state quantities. This acceleration (18) via momentum equation determines convection in the liquid core.

Finally equations (9) and (14) with their boundary and normalization conditions (8, 11-12, 15-17) provide us the correct description of the heat and mass transfer in the fast rotating planets. Integrating and scaling those equations with their conditions I estimate the acceleration and energy contribution to the geodynamo support from the heat (~s) and compositional (~x) effects. Normally the compositional contribution is strongly dominated over the heat contribution. Thus one could ignore the heat effects solving geodynamo problem only with (14-17) in the first approximation. In the giant planets the heat transfer could dominate, while in some terrestrial planets it could partly stabilize the liquid core working against the compositional convection.

This work was supported by the Russian RFBR project No 12-05-00523-a.

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Extracting scaling laws from numerical dynamo models

ZACHARIAS STELZER[1], ANDREW JACKSON [2]

[1] Earth and Planetary Magnetism, Institute of Geophysics, ETH Zurich, Zurich, Switzerland (zacharias.stelzer@erdw.ethz.ch)
[2] Earth and Planetary Magnetism, Institute of Geophysics, ETH Zurich, Zurich, Switzerland (andrew.jackson@erdw.ethz.ch)

Scaling laws derived from numerical dynamo models are beginning to play a part in geomagnetic data assimilation efforts. Numerical dynamo models are currently run in the wrong parameter regime compared to the Earth. Scaling laws link quantities such as magnetic field strength, heat flux and velocities to control parameters such as the Rayleigh, Ekman, Prandtl and magnetic Prandtl numbers. A large library of dynamo simulations has been amassed by Christensen, Aubert and co-workers. Favoured scaling laws that were deduced from this data set are suggested to be independent of diffusivities.

We have begun to examine the statistical basis for these laws. Using a subset of the available data, we test which control parameters appear to be required to account for the variability in the data. We have adopted a Bayesian approach to the model selection problem. This approach naturally follows 'Occam's razor', i.e. it generally favours simple theories and prefers more complex models only if required by the data. Our results agree with more classical statistical tests of parameter significance.

Features of palaeosecular variation in observations and models

NEIL SUTTIE[1], ANDY BIGGIN[1] & RICHARD HOLME[1]
[1]School of Environmental Sciences, University of Liverpool, Liverpool, UK

Long-term variations in the behaviour of the geomagnetic field may reflect changes in the deep Earth throughout the planet's history. In the absence of continuous magnetostratigraphic records, analyses of palaeosecular variation may be used to make inferences about the stability of the geodynamo. These analyses rely primarily on the relationship between inferred palaeolatitude and the angular dispersion of the virtual geomagnetic poles, but other descriptive statistics may enhance these methods and be used to assess the robustness of trends. During many periods there are few datasets of sufficient size, quality and latitudinal spread and it becomes increasingly important to insure that cogent information is not discarded during the analysis.

Some insight into the most efficient way to extract information from the palaeomagnetic record may be provided from synthetic data derived from field models. By comparing sampling distributions derived from statistical field models and geodynamo simulations with data from large igneous provinces from the past 100 million years, we develop and assess the usefulness of various descriptive statistics and consider their implication for our understanding of the geodynamo.

A detailed analysis of a dynamo mechanism in a rapidly rotating spherical shell

FUTOSHI TAKAHASHI[1], HISAYOSHI SHIMIZU[2]

[1]Department of Earth and Planetary Sciences, Tokyo Institute of Technology, 2-12-1 Ookayama, Meguro-ku, Tokyo 152-8551, Japan

[2]Earthquake Research Institute, University of Tokyo, 1-1-1 Yayoi, Bunkyo-ku, Tokyo 113-0032, Japan

The magnetic field intensification processes through dynamo action by flows of an electrically conducting fluid in a rapidly rotating spherical shell are investigated using a numerical dynamo model with an Ekman number of 10^{-5}. A strong dipolar solution with a magnetic energy 55 times larger than the kinetic energy of thermal convection is obtained. In a regime of small viscosity and inertia with the strong magnetic field, the convection structure consists of a few large-scale retrograde flows in the azimuthal direction and localized thin sheet-like plumes. We perform a detailed term-by-term analysis of the magnetic field amplification processes [1] to understand fundamental physical processes of the dynamo model. It is found that the magnetic field is amplified through stretching of magnetic lines, which occurs typically through four types of flow: the retrograde azimuthal flow near the outer boundary, the downwelling flow of the sheet plume, the prograde azimuthal flow near the rim of the tangent cylinder, and the cylindrical radially alternating flows of the plume cluster. The most remarkable effects of the generated magnetic field on the flow come from the strong azimuthal or toroidal magnetic field. Similarities of the present model in the convection and magnetic field structures to previous studies at larger and even smaller Ekman numbers suggest universality of the dynamo mechanism in rotating spherical dynamos.

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Searching for torsional oscillations in Earth-like dynamo simulations

ROBERT TEED[1], CHRIS JONES [2], & STEVE TOBIAS[3]

[1] Department of Applied Mathematics, University of Leeds, Leeds, UK (R.J.Teed@leeds.ac.uk)
[2] Department of Applied Mathematics, University of Leeds, Leeds, UK (C.A.Jones@leeds.ac.uk)
[3] Department of Applied Mathematics, University of Leeds, Leeds, UK (S.M.Tobias@leeds.ac.uk)

Torsional oscillations are a principal feature of the dynamics of the fluid outer core where the Earth's magnetic field is generated. These oscillations are Alfven waves about an equilibrium known as a Taylor state and propagate radially outwards from the tangent cylinder. Torsional oscillations are of great interest to the study of the outer core, as their structure and frequencies give information about the core geomagnetic field, providing independent tests of computer generated models. The change in core angular momentum inferred from geomagnetic observations has a measurable impact on the length of the day, and the small decadal variations in the length-of-day signal confirm the existence of torsional oscillations. However, recent data from the satellite observations suggest that there is more high frequency variation of the geomagnetic field, and hence in the core flow, than previously believed.

Recent simulations of the geodynamo have shown that the thermal boundary conditions can have a significant impact on the strength and morphology of the magnetic field generated. Fixed heat flux, as opposed to fixed temperature, boundary conditions appear to allow for more Earth-like fields with the correct amount of dipolarity and the presence of high-latitude reversed flux patches. However, geodynamo models of the core have traditionally focused on millennial or longer time-scales to understand the long term evolution of the field, for the most part ignoring the shorter time-scales. The rapid dynamics of the simulations must be considered in order to observe phenomena including torsional oscillations.

In our work we perform three-dimensional spherical dynamo simulations in the parameter regimes where Earth-like magnetic fields are produced, replicating previous results. We are interested in looking at output parameters over short time-scales. Specifically we consider the spectra of the Gauss coefficients and their time derivatives: the secular variation and secular acceleration. The ratio of the latter two quantities gives a time-scale, which may be indicative of the time-scale of torsional oscillations. We present preliminary results of this work showing both Earth-like magnetic fields and the time evolution of secular variation and secular acceleration.

Numerical study on thermo-chemical driving of convection in the Earth's core

TOBIAS TRÜMPER[1], MARTIN BREUER & ULRICH HANSEN[2]

[1] Institute of Geophysics, University of Münster, Münster, Germany (tobit@uni-muenster.de)
[2] Institute of Geophysics, University of Münster, Münster, Germany

Our numerical study focuses on convection and magnetic field generation in a rotating spherical shell with the objective to investigate the effects of combined thermal and compositional convection as proposed for the Earth's core. Since the core is cooling, a thermal gradient is established, which can drive thermal convection. Simultaneously, due to the solidification of the inner core latent heat is released at the freezing front and the concentration of the light constituents of the liquid phase increases, thus providing a source for compositional buoyancy. Typically, the molecular diffusivities of both driving components differ by some orders of magnitude. To account for this difference it is indicated to adopt a double-diffusive convection model in treating Earth's core dynamics. The ratio of thermal to chemical forcing in the Earth's core is still rather uncertain. As a joint action of both buoyancy sources is most likely, we investigate core convection in a range of varying thermal to chemical forcing ratios, while the diffusivity ratio and the Ekman number are kept fixed at 10 and 10^{-4}, respectively. The variation of the driving scenario significantly influences the spatial flow patterns, most notably differential rotation and helicity. Based on these findings we extend our study to include double-diffusive geodynamo simulations, which show that both the distribution of magnetic energy and the structure of the magnetic field vary distinctly with the applied forcing ratio.

Numerical investigation of precession-driven instabilities and dynamos in a spheroidal container

STIJN A. M. VANTIEGHEM[1], DAVID CÉBRON [1]

[1] Earth and Planetary Magnetism, Institute of Geophysics, ETH Zürich
(stijn.vantieghem@erdw.ethzz.ch)

Bullard [1] was the first to suggest that planetary precession can act as an energy source to power a dynamo; this idea was supported by a study of Kerswell [2], who found, on theoretical grounds, that the precession of the Earths rotation axis might possibly lead to a viscous power dissipation of 10^{21} Watts in the liquid core. Tilgner [3], on the other hand, has performed a numerical study in which it was demonstrated that precession might drive a dynamo in a spherically symmetric container. In a recent work, Wu and Roberts [4] have shown how topographic precession might trigger an elliptical instability and generate a magnetic field in a spheroidal container.

In this work, we revisit the work of Wu and Roberts [4] using several, independent numerical tools, which are based on a finite-volume or finite-element discretization. The first part of our work is devoted to a purely hydrodynamic instability, which is analysed in terms of an inviscid, background Poincaré flow and a perturbation velocity field. We find that an instability can take place below a certain critical Ekman number (function of the ellipticity and precession rate), which agrees well with the threshold values found in [4]. However, we can also confirm the analysis of Guermond et al. [5], who showed that the application of stress-free boundary conditions on the perturbation velocity field give rise to a saturated, non-linear state which strongly depends on the initial condition.

Furthermore, we investigate whether the hydrodynamic instability supports dynamo action. In contrast to [4], we use so-called pseudo-vacuum boundary conditions, i.e. we impose that the magnetic field is purely vertical at the boundary. Our numerical results give no evidence so far for the existence of a precession-driven dynamo.

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Librationally driven flow and dynamo in planetary cores: theory and simulation

KEKE ZHANG[1], KIT H. CHAN[2] & XINHAO LIAO[3]

[1] Department of Mathematical Sciences, University of Exeter, EX4 4QF, UK
(kzhang@ex.ac.uk)
[2] Department of Mathematics, University of Hong Kong, Pokfulam, Hong Kong
(mkhchan@hkucc.hku.hk)
[3] Shanghai Astronomical Observatory, Chinese Academy of Sciences, Shanghai 200030, China
(xhliao@shao.ac.cn)

As a consequence of their rapid rotation as well as interaction among the Sun, planets and moons, many astrophysical bodies are usually in the shape of a spheroid or a triaxial ellipsoid and rotating non-uniformly, resulting in libration or precession of those bodies. We study the dynamics of planetary fluid cores by considering a spheroidal container that rotates rapidly around its symmetry axis but undergoes slowly longitudinal or latitudinal libration. The fluid dynamical problem is investigated via both asymptotic analysis and direct numerical simulation. An asymptotic theory is developed using oblate spheroidal coordinates for a spheroidal cavity of arbitrary eccentricity without making any prior assumptions about the spatial-temporal structure of the librating flow. A new resonant phenomenon is discovered theoretically while nonlinear direct numerical simulation is performed to confirm the existence of resonance [1]. The new finding may have important implications for certain planets or moons that are thermally or chemically non-convective because the non-axisymmetric resonant flow with strong shears is likely to be capable of sustaining planetary dynamos. We shall also report some results of direct numerical simulation on how dynamo action in non-convective planetary interiors can be maintained by librationally resonant flows in triaxial ellipsoidal geometry.

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S5: Experiments & Measurements in Deep Earth Research

Invited Talk

Low frequency magnetic field fluctuations in dynamos

ANDREAS TILGNER[1]

[1] Institute of Geophysics, University of Göttingen, Göttingen, Germany
(andreas.tilgner@physik.uni-goettingen.de)

Measurements of magnetic field fluctuations in dynamo experiments revealed $1/f$-spectra at low frequencies f. Similar spectra have been reconstructed from the paleomagnetic record and have been observed in numerical simulations of the geodynamo. A $1/f$-spectrum cannot exist at all frequencies if the power integral is to stay finite. This type of spectrum generally has two characteristic frequencies: A lower cut-off, below which the spectrum turns into white noise, and a high frequency cut-off, above which the spectral power decreases faster than $1/f$.

We present a phenomenology explaining the occurrence of these spectra [1]. In this theory, the lower cut-off is related with the kinematic growth rate of the dynamo, and the upper cut-off is determined by the integral time scale of the fluid motion in the dynamo.

Spectra recorded in the Karlsruhe dynamo also contain an isolated peak at low frequency. The scaling of the frequency of this peak suggests an Alfven wave, but the origin of this peak still is an open issue.

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Invited Talk

Hemispherical and reversing dynamos

STEPHAN FAUVE[1]

[1] Laboratoire de Physique Statistique, Ecole Normale Supérieure, Paris, France
(fauve@lps.ens.fr)

We report the experimental observation of a spatially localized dynamo magnetic field, a common feature of some planetary or stellar dynamos also displayed by numerical simulations of convective dynamos. The experimental study is conducted is a von Karman swirling flow of liquid sodium driven by two coaxial courter-rotating propellers (the VKS experiment). When the two propellers are driven at frequencies that differ by 15%, the mean magnetic field's energy measured close to the slower disk is nearly 10 times larger than the one close to the faster one. This strong localization of the magnetic field when a symmetry of the forcing is broken is in good agreement with a prediction based on the interaction between a dipolar and a quadrupolar magnetic mode. We show that depending on the parameters of this model, either stationary hemispherical or reversing dynamos are expected. In addition, the model predicts the asymmetric shape of the reversal trajectory as well as the dynamics related to the localization of the magnetic energy density during a reversal. The experimental measurements are in good agreement with all these predictions.

Invited Talk

Melting phase relations at lower mantle and core conditions in the laser-heated diamond anvil cell

M. WALTER, O. LORD, L. ARMSTRONG, W. WANG, J. FROST AND A. THOMSON

School of Earth Sciences, University of Bristol, Bristol BS8 1RJ; m.j.walter@bristol ac.uk

The primary structure and composition of Earth's deep interior was established in large part through melting processes at high pressures and temperatures. Earth accretion was hot and resulted in planetary-scale melting and a deep magma ocean. Differentiation into core and mantle involved equilibrium between molten silicate and molten iron metal alloy, and magma ocean differentiation may have involved crystal settling, crystal flotation, and magma sinking [1, 2]. The origin of seismically imaged features at the base of the mantle including large low shear velocity provinces and ultra-low velocity zones may have an origin related to early mantle differentiation processes [3]. The isotopic composition of modern mantle-derived magmas reveals the possibility of long-lived incompatible element depletions that must have originated within the first 500 million years and are likely related to partial melting and differentiation [4].

Understanding global-scale magmatic processes requires a fundametal knowledge of the melting phase relations of mantle and core materials at the extreme conditions of the Earth's deep interior. Melting relations in many pertinent silicate and metal systems are relatively well understood for the upper mantle due to the accessibility of large-volume high-pressure techniques to the required pressure-temperature conditions. In contrast, much less is know about melting phase relations at conditions of the lower mantle and core where the requisite high-pressures and -temperatures require experiments using the laser-heated diamond anvil cell (LH-DAC). However, the extremely small sample-size and relatively large uncertainties, especially in temperture, have severely hampered detailed mapping of melting phase relations. Recent studies have shown the increasing utility of the LH-DAC for accurately measuring melting temperatures and deducing liquidus phase relations, especially when coupled with synchrotron radiation-based spetroscopic and imaging techniques e.g. [5, 6]. In this contribution we review the status of the LH-DAC as an instrument for investigating melting behavior of materials at extreme conditions. We will present results for new methods of micro-fabrication of samples, and uniform heating and accurate temperature measurement, that when coupled with state-of-the-art micro- and nano-analytical techniques can substantially improve our ability to construct melting phase relations at conditions of the deep lower mantle and core.

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Invited Talk

Assessment of Palaeointensity Methodologies using Historical Lava Flows

MAXWELL BROWN[1,2], JOSHUA FEINBERG[1] and JULIE BOWLES[1]

[1]Institute for Rock Magnetism, Department of Earth Sciences, University of Minnesota, Shepherd Laboratories, 100 Union Street SE, Minneapolis, MN 55455, USA
[2]Helmholtz-Zentrum Potsdam, Deutsches GeoForschungsZentrum, Telegrafenberg, 14473 Potsdam, Germany, (mcbrown@gfz-potsdam.de)

Robust determinations of the strength of the Earth's magnetic field (palaeointensity) from volcanic rocks, when combined with palaeodirections and accurate age estimates, have the potential to provide important information on the development of the geomagnetic field and related geodynamo processes on a large range of time scales: from the Holocene to Precambrian geomagnetic field.

Volcanic paleointensity data have in part been used in the development of temporally continuous spherical harmonic models of the geomagnetic field for the last 10 ka [1], allowing assessment of persistent and dynamic millennial scale geomagnetic features at the core-mantle boundary. Similarly, global models combining volcanic and sedimentary data have provided important insights into reversal and excursion processes [2]. In the Precambrian the timing and magnitude of palaeointensity changes may be related to the development of the early Earth and the inner core [3]. Accurate palaeointensity determinations can help in constraining numerical models of the paleogeodynamo, which may allow for a better understanding of the thermal evolution of the core [4] and the development of water and atmosphere on Earth [3]. An advanced understanding of these problems can only be achieved through numerous high quality data. However, a major ongoing challenge in palaeomagnetism is the development of reliable absolute palaeointensity methods.

In the last fifteen years a number of palaeointensity methods have been proposed and our understanding of existing methods has advanced greatly. However, palaeointensity results obtained from historical lavas produce significant variations about the expected field regardless of the method. The source of these variations must be investigated if we are to make robust conclusions about the palaeomagnetic field during important times in geological history. We report a detailed palaeointensity study on approximately 200 specimens from the 1951 and 1995 flow lobes of the island of Fogo, Cape Verde. We present results from LTD-DHT Shaw, Coe-Thellier, microwave, Wilson and multi-specimen parallel differential pTRM methods. All methods resulted in scattered palaeointensity estimates. We describe the specimens' rock magnetic properties in detail and attempt to link them to specific variations seen in the palaeointensity estimates. We focus on two sets of specimens that show either no/limited deuteric oxidation or a high degree of oxyexsolution with multiple generations of ilmenite lamellae growth and we show how differences in these specimens have influenced the outcome of the palaeointensity experiments.

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Penetrative convection in water cooled from below

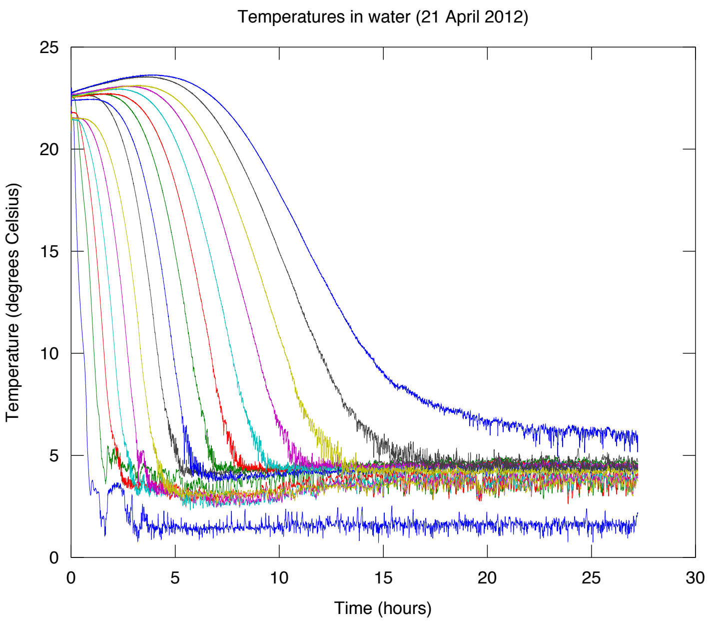
Thierry Alboussière[1], Stéphane Labrosse [1], Fabien Dubuffet [1], Fanny Thibon[1], Ludovic Huguet[1] & Renaud Deguen[2]

[1] Laboratoire de Géologie de Lyon, ENS-Lyon, université Lyon 1, France (thierry.alboussiere@ens-lyon.fr, stephane.labrosse@ens-lyon.fr, fabien.dubuffet@univ-lyon1.fr, fanny.thibon@ens-lyon.fr ludovic.huguet@ens-lyon.fr)
[2] Department of Earth and Planetary Sciences, Johns Hopkins University, Baltimore, USA (rdeguen@gmail.com)

It has already been suggested that the outer core of the Earth might not be entirely in a convective regime [1], for instance in a region close to the CMB where the heat conducted along the adiabat could be larger than the net heat transfer and where compositional buoyancy vanishes. Radial dependence of thermal conductivity could also produce neighbouring stable and unstable regions (see poster by Labrosse *et al.*). To what extent does convection spread into the stable region is then an important issue.

Liquid water and its maximum density at 4°C provides a convenient way to observe penetrative convection. We have performed experiments where a volume of water (of square cross-section 16 by 16 cm and height 20 cm) initially at room temperature (around 22°C) is then suddenly cooled around 0°C at the bottom while the sides and top walls are (imperfectly) thermally insulated. Near the bottom, where temperature is below 4°C, unstable buoyancy conditions prevail and we observe convective cells. Above 4°C, quiescent stable stratification is observed. Temperature is close to 4°C within the bulk of the convective zone, so that the flux of heat extracted from the bottom is used to change the temperature from 22°C to 4°C within the successive layers of water, while the height of the convective zone increases and eventually reaches the top of the volume.

Temperatures have been measured on a array of 15 PT100 probes protruding 5 mm into water along a vertical side wall. the extreme probes are 1 cm away from the lower and upper boundaries respectively. The evolution of all 15 temperatures can be seen on left-hand side of Fig. 1. Another type of information was obtained from a synthetic schlieren technique, whereby pictures of a random pattern placed behind the transparent water-filled box (perspex walls) are taken every 5 s with a digital camera. The cross-correlation of the different images provides a dynamical visualization of the gradients of refraction index within the volume of water. A snapshot is displayed on the right-hand side of Fig. 1.



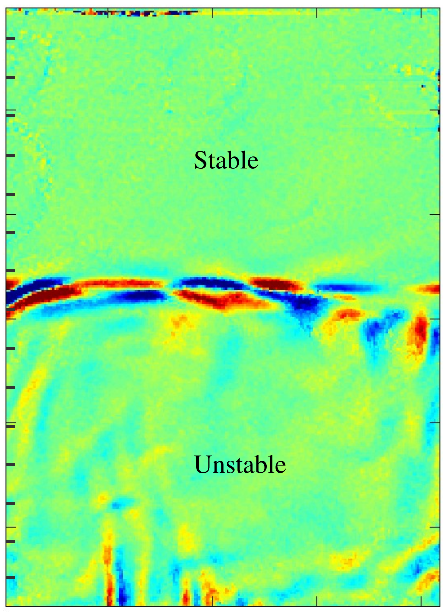


Figure 1: Temperatures on the left, time derivative of index horizontal gradient on the right

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Turbulence in the magnetostrophic regime

Simon Cabanes, Henri-Claude Nataf & Nathanaël Schaeffer

Institut des Sciences de la Terre, Université de Grenoble 1, CNRS, Observatoire de Grenoble, F-38041 Grenoble, France.
(simon.cabanes@ujf-grenoble.fr)

Numerical models of the geodynamo are very successful in recovering the main characteristics of the Earth's magnetic field. Nevertheless, the structure and dynamics of unresolved small-scale motions remains enigmatic, and it is not known whether they contribute to the large-scale magnetic field or to its destruction. Both effects have been reported in laboratory experiments of very turbulent flows submitted to weak magnetic fields. In particular, the observation of a dipolar magnetic field aligned with the axis of the axisymmetric mean flow in the Madison experiment demonstrates an α-effect capable of producing a large-scale magnetic field (Spence *et al*, 2006). On the other hand, a large β-effect, which increases magnetic diffusion and hence the dynamo threshold, has been measured in the Perm torus experiment (Frick *et al*, 2011). In both cases, symmetry reasons are invoked to exclude potential contributions of the mean flow itself.

However, little is known of such turbulent effects in flows that are constrained by both rotation and a strong magnetic field, the situation that prevails in planetary cores. We have addressed this issue, using data from the DTS experiment. The DTS has been designed to explore the magnetostrophic regime, in which the Coriolis and the Lorentz forces are comparable. It consists of a rotating spherical Couette flow in a shell filled with 50 litres of sodium and submitted to a strong dipolar magnetic field. This field is produced by a permanent magnet enclosed in the inner sphere, which is made of copper. By measuring mean velocity profiles along several rays, using ultrasound Doppler velocimetry, we have been able to map the mean flow in the shell. As shown by Brito *et al* (2011), the flow is characterized by a super-rotating Ferraro region, around the equator of the inner sphere, and a geostrophic region from the edge of the Ferraro region to the outer sphere, where the imposed magnetic field is weaker.

Our approach is to compute the magnetic field that the mean flow should produce and compare it to actual measurements. Deviations reveal cooperative effects of turbulent fluctuations to the mean magnetic field. In particular, we have analyzed the magnetic signal produced by the weak non-axisymmetric components of the applied magnetic field. When the inner sphere rotates, these components create a periodic signal, which is advected by the mean flow as it diffuses across the liquid sodium shell. We have modeled the advection by the mean flow in order to evaluate the effect of small-scale motions on the effective magnetic diffusivity. Our preliminary results indicate that small-scale turbulent motions do not strongly alter the response of the mean flow in the magnetostrophic regime.

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Asymptotic Behaviors of Convection Columns in Meter-Scale Tanks

J. CHENG[1], A. RIBEIRO[1], E. KING[2], J. AURNOU[1]

[1] SPINLAB, Earth & Space Sciences, UCLA, Los Angeles, CA, USA.
[2] Earth and Planetary Science, JC Berkeley, CA, USA.

The magnetic field of the Earth is generated in the molten outer core by a turbulent magnetohydrodynamic dynamo. The processes involved occur at extreme ranges of parameter space; the Ekman number (E) is believed to be order 10^{-15} and the supercriticality (Ra/Ra_c) is roughly order 10^5. The dominant large-scale flow structures in the core are typically taken to be axially-aligned convective columns. Theory predicts that the aspect ratio (width/height) of these columns scales as $E^{1/3}$ [1]. For core parameters, this would give columns of aspect ratio ~10^{-5}: very thin. Current numerical models are restricted to E~10^{-5} and contain columns of correspondingly low aspect ratio (typically aspect ratio ~ 1/10th). Thus, there exists a wide disparity in flow structure geometry between current models and the core. Whether the columns predicted in models extrapolate to the core is a question that must be investigated.

Laboratory experiments are invaluable for this study because they can reach greater parameter ranges with less difficulty while still resolving the small-scale structures. Our device, RoMag, simulates rotating Rayleigh-Benard convection in an axially-aligned cylinder with interchangeable tank heights (present study: 40 and 80 cm tank heights). An Ekman number of ~10^{-6} is accessible in a 40 cm tank, corresponding to a predicted column width of ~4 mm. In an 80 cm tank, we can reach E~10^{-7}. The stability of convective columns depends on the relative strengths of convection and rotation, and our experiments in tall tanks have accessed the transition between rotationally controlled, columnar convection and inertia-controlled 3D convection. We elucidate flow structures via FFTs of laser light sheet images and heat transfer measurements, allowing us to test the distinct transition scaling laws proposed by King et al 2012 [2] and Julien et al 2012 [3].

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Solidification of binary alloys under hyper-gravity

Ludovic Huguet[1], Germain Lesoeur[1], Thierry Alboussière [1], Renaud Deguen [2], Jean-Paul Masson [3] & Patrick La Rizza [3]

[1] Laboratoire de Géologie de Lyon, CNRS, Université Lyon 1, ENS-Lyon, Géode, 2 rue Raphaël Dubois, Villeurbanne, F-69622, France.
(ludovic.huguet@ens-lyon.fr)
[2] Department of Earth and Planetary Sciences, Johns Hopkins University, Baltimore
[3] ISTerre, CNRS, Université Joseph Fourier Grenoble, Maison de Gosciences, 1381 rue de la Piscine, Saint-Martin d'Hères, F-38400, France

The solidification of the Earth's inner core is probably a major source of energy for the convection of the outer core, itself being responsible for the magnetic field. In addition, the convection has an impact on the solidification processes by changing the transfer of light elements on the surface of the inner core. The Rayleigh number and the dissipation number of the Earth's core are not easily accessible in experiments, but we can approach them through hyper-gravity experiments. Loper & Roberts (1981) and Fearn *and al.* (1981) show that the solidification conditions at the inner core boundary lead to the formation of a mushy layer by analogy with metallurgy. This mush is caused by an instability of the solidification front, the Mullins-Sekerka instability. The mush itself can be subjected to further convective instability modes, driven by buoyancy. A bulk mushy-layer mode leads to the so-called chimneys. There exists another mode ahead of the mush, often called a boundary layer mode, whose main effect is to increase the solid fraction at the top of the mush. These two modes compete to extract the elements rejected during crystallization. A good analogue to the solidification of a metallic alloy is a solution of ammonium chloride. Experiments were conducted with this solution to recreate the conditions of instability of the front and directional growth. The increase of the apparent gravity by centrifugation enhances convection, mainly compositional convection in this case. In this experimental device, the gravity can reach $3500\ g$. The height of the mush is $24\ mm$ at $1\ g$ and $6\ mm$ at $1330\ g$, thus the solid fraction increases significantly with gravity due to stronger convection. The presence of chimneys in the experiments at very high gravity ($1500\ g$) suggests that the mushy-layer mode persists, however between $5\ g$ and $228\ g$, there is no chimney.

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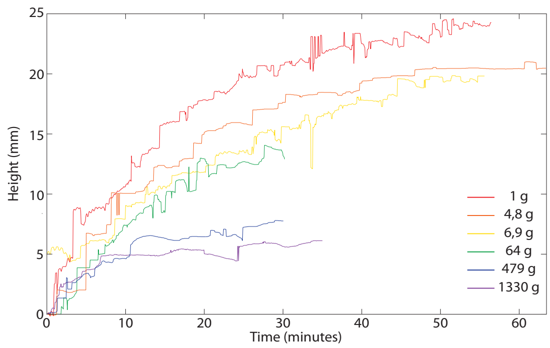

Figure 1: Height of mush as a function of time and gravity.

Experiments on metal fragmentation in a magma ocean

MAYLIS LANDEAU[1], RENAUD DEGUEN [2], PETER OLSON[2]

[1]Dynamique des Fluides Géologiques, Institut de Physique du Globe de Paris, Université Paris-Diderot, INSU/CNRS, 1 rue Jussieu, 75238, Paris cedex 05, France
[2]Department of Earth and Planetary Sciences, Johns Hopkins University, Baltimore, MD 21218, USA

Understanding the physical mechanisms that occur during metal/silicate differentiation in a low-viscosity magma ocean provides constraints on metal-silicate mixing, and thus chemical re-equilibration, during the final stages of Earth accretion. Previous studies have shown that the amount of energy released through shock heating after a large impact is sufficient to melt the projectile and a substantial part of the growing proto-Earth. The liquid core of the projectile, denser than the surrounding liquid silicates, tends to segregate at the base of the magma ocean. Partial or complete fragmentation of the projectile core is expected during this migration.

Here we present results from laboratory experiments on liquid-liquid fragmentation at density ratios comparable to the metal-silicate system (of order unity). A finite fluid volume is released at the top of a tank filled with a lighter immiscible fluid, producing destabilization and fragmentation of the released fluid. We find that, at low Weber numbers (measuring the importance of inertia versus surface tension forces), the fragmentation regime depends on a competition between a Rayleigh-Taylor instability and the formation of a vortex ring. At high enough Weber numbers ($We \geq 500$), which is the relevant regime for core formation, the flow can be described by the same turbulent entrainment concept in all the experiments. A theoretical model, which is in agreement with the experimental results in this turbulent regime, provides a simple model for metal/silicate mixing. Our flow visualizations show that the entire released fluid volume is mixed at small-scales with the ambient fluid before fragmentation starts, which occurs at about 2-4 times the initial diameter. This suggests that, for giant impacts, the projectile core may be mixed with liquid silicates, though full fragmentation may not occur before it reaches the bottom of the magma ocean.

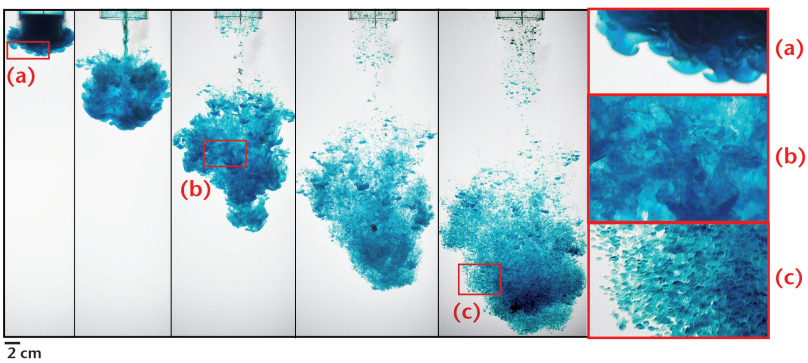

Figure 1: Series of photographs at $We \approx 2000$. Portions of the photographs (red boxes) have been magnified (on the right).

Experimental study of fluid flows in precessing cylindrical annulus

YUFENG LIN[1], JEROME NOIR [2]

[1] Institut für Geophysik, ETH Zürich, Switzerland
(yufeng.lin@erdw.ethz.ch)
[2] Institut für Geophysik, ETH Zürich, Switzerland
(jerome.noir@erdw.ethz.ch)

Precession is the slow gyroscopic motion of the planet's spin axis. It has been proposed that precession could generate and sustain planetary magnetic field from an energetic point of view. Laboratory and numerical experiments have showed that fluid flows can be unstable and even turbulent in precessing systems. Recent numerical simulations showed precession-driven flows can indeed operate a dynamo action. However, there are still some open questions in precession-driven flows, e.g. how the instability generate and develop.

In this study, we will investigate fluid flows in precessing cylindrical annulus via laboratory experiments. A cylindrical annulus filled with water is rapidly rotating around its axis at angular velocity Ω_o. The annulus is mounted on a turntable which is slowly rotating at Ω_p. The rotating axis of the tank and the turntable are perpendicular. The angular velocity of the turntable Ω_p can be varied from 1-10 rpm and the tank rotating rate Ω_o can be varied from 100-300 rpm. Cylindrical annulus with different aspect ratio and radius ratio are used. The fluid flows are diagnosed by Kalliroscope visualization and Laser Doppler Velocimetry (LDV).

First we focus on the laminar regime that is theoretically well established. We will also present preliminary observations in the weakly non-laminar regime.

Towards the robust selection of Thellier-type paleointensity data: The influence of experimental noise

GREIG A. PATERSON[1], ANDREW J. BIGGIN [2], YUHJI YAMAMOTO[3] & YONGXIN PAN[1]

[1] Key Laboratory of Earth's Deep Interior, Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing 10029, China
(greig.paterson@mail.iggcas.ac.cn)
[2] Geomagnetism Laboratory, Geology and Geophysics, School of Environmental Sciences, University of Liverpool, Oliver Lodge Laboratories, Oxford Road, Liverpool L69 7ZE, UK
[3] Center for Advanced Marine Core Research, Kochi University, Kochi 783-8502, Japan

The process of data selection in paleointensity studies is an essential step to ensure data fidelity. Despite the birth of modern paleointensity data analysis some 30–40 years ago, there is no consensus as to the best approach to consistently select data with most studies using arbitrarily defined thresholds for selection. We present a new numerical model that simulates the variability of paleointensity data from hypothetical ideal samples acquiring a thermoremanent magnetization (TRM) by incorporating experimental noise, which has been constrained using over 75,000 data measurements. Using Monte Carlo analyses, we investigate the relative contributions that each source makes to the variability of paleointensity data and and characterize the distributions of parameters typically used to select paleointensity data. We define threshold limits for detecting non-ideal behaviour by taking the the 95^{th} percentiles of the parameter distributions. In effect these represent values below which we cannot distinguish non-ideal behaviour from noise. Our results indicate that a number of parameters are sensitive to the applied laboratory field strength and noise. This sensitivity is likely to diminish the ability of these parameters to identify non-ideal behaviour. The fractional (f) dependence of some parameters and the proportion of inaccurate results provide justification for $f \geq 0.35$ when selecting data from both Thellier-Thellier and Coe protocol experiments. For the original Thellier method, however, the manifestation of noise is different to the Coe, Aitken and IZZI methods. Our ability to detect non-ideal effects using the original Thellier method differs from other methods and suggests that the data selection procedure for the Thellier method should be different. The accuracy and scatter of results from the Thellier method, however, are more sensitive to noise than methods that use zero-field heating steps The model developed here is a powerful means of understanding the behaviour of selection parameters and is currently being extended to models incorporating non-ideal behaviour resulting from alteration and multidomain grains.

Turbulent magnetoconvection experiments in liquid gallium

A.Ribeiro[1], J.Cheng[1], E.king[2] & J.Arnou[1]

[1] SPINLAB, Earth & Space Sciences, UCLA, Los Angeles, CA,USA.
[2] Earth and Planetary Science, JC Berkeley, CA, USA.

Astrophysical and planetary dynamos are typically produced by turbulent convection that occurs in the presence of strong rotational and magnetic forces. These forces each individually act to inhibit the convective motions and can fundamentally alter the structure of the turbulence. A great deal of previous attention has focussed on rotationally-constrained convection (e.g., Rossby [1], Julien *et al.* [2], King *et al.* [3],[4]). In contrast, very little is known about the behavior of turbulent convection that is strongly constrained by magnetic forces, even though it is of paramount importance in geophysical and astrophysical settings (K.Bhattacharjee *et al.* [5], Cioni *et al.* [6]). To address this issue, we are presently carrying out a systematic survey of turbulent magnetoconvection in a cylindrical tank of liquid gallium. Our device is capable of reaching Rayleigh numbers $Ra = \frac{\text{buoyancy}}{\text{diffusion}} \lesssim 10^8$, Nusselt numbers $Nu = \frac{\text{heat transfer}}{\text{conduction}} \lesssim 15$ and Chandrasekhar numbers $Q = \frac{\text{Lorentz}}{\text{viscous}} \lesssim 10^6$. In particular, we will use our magnetoconvection survey results to first test whether the behaviors found in rotationally-constrained convection have analogs in magnetically-constrained systems. In doing so, we will gain insight into the universality of constrained turbulent convection.

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Large and Small Scale Dynamos in Local Rapidly Rotating Convection: The Role of Coherence

STEVEN TOBIAS[1]

[1] Department of Applied Mathematics, University of Leeds, Leeds, UK
(smt@maths.leeds.ac.uk)

It is well known that coherent structures in dynamos lead to enhanced dynamo properties. Here we consider dynamos in rapidly rotating plane layer convection to investigate whether the presence of large-scale field leads to enhanced coherence of the flow and discuss the implications for the strong-field branch at low magnetic Prandtl number.

Measurement of the turbulent diffusivity of magnetic fields: Turbulent Ångström and the "Method of Oscillatory Sines"

STEVEN TOBIAS[1], FAUSTO CATTANEO [2]

[1] Department of Applied Mathematics, University of Leeds, Leeds, UK
(email1@leeds.ac.uk)
[2] Fausto's Address
(email2@leeds.ac.uk)

Determination of the turbulent diffusivity of magnetic field is one of the most important problems in geophysics and astrophysics. It is turbulent diffusion of magnetic field that leads to the reconnection of large flux patches in the Earth's interior and may provide a timescale for the reversals of the Earth's magnetic field. However a convincing method for determining the turbulent diffusuvity, and its dependence on field strength, in experiments and computations remains elusive. Here we present two methods for the determination of diffusivity coefficients that can be used. The first, which we call the turbulent Ångström method can be utilised successfully in laboratory experiments. We also introduce for the first time the "Method of Oscillatory Sines" which works extremely well for numerical experiments in both the kinematic and dynamic regime.

Maximum likelihood modeling of paleomagnetic axial dipole moment: insights and applications

LEAH B. ZIEGLER[1], CATHERINE G. CONSTABLE [2]

[1] College of Earth, Ocean, and Atmospheric Science, Oregon State University, Corvallis, OR, USA (lziegler@coas.oregonstate.edu)
[2] Institute of Geophysics and Planetary Physics, Scripps Instit. of Oceanography, UC San Diego, La Jolla, CA, USA

Growing numbers of relative paleomagnetic field intensity and absolute paleointensity data are becoming available, enabling the development of axial dipole moment models on million year timescales. Such models are useful in geomagnetic studies and for large-scale regional and global stratigraphic correlations for dating sedimentary records. We have developed the continuous, time-varying PADM2M model of Paleomagnetic Axial Dipole Moment (PADM) using a maximum likelihood estimation technique and a joint set of globally distributed relative and absolute paleointensity data. Spanning the last 2 Myr, the PADM2M model has an average dipole moment of $53ZAm^2$ with a significant difference in mean between the Brunhes and Matuyama chrons. Analysis of the model derivatives shows asymmetry in the growth and decay rates of axial dipole moment on time scales of several 10s of thousands of years. We investigate trends in the fit of individual relative paleointensity records to the model and explore the possibility of using a similar modeling technique on regionally clustered data sets. Preliminary efforts involve creating PADM models from data clustered by similar site latitude or by site longitude. We see a greater difference between composite PADM models created from longitudinally clustered sediment records than latitudinally clustered records. However, the comparison is limited by the fact that most high latitude data come from the Atlantic Ocean and most Equatorial data come from the Pacific Ocean, so dividing data into subsets by latitude and longitude separately does not provide fully independent comparisons. As more relative paleointensity data continue to become available, these geographical comparisons will become more conclusive.

S6: CMB - Structure, Dynamics & Composition

Invited Talk

News from the core mantle boundary region

STÉPHANE LABROSSE[1], JOHN HERNLUND[2] & CHRISTINE HOUSER[3]

[1] Laboratoire de géologie de Lyon, ENS de Lyon, Université Lyon-1, Lyon, France
(stephane.labrosse@ens-lyon.fr)
[2] Department of Earth and Planetary Science, University of California, Berkeley, California, USA
(hernlund@gmail.com)
[2] Department of Earth and Planetary Science, University of California, Santa Cruz, California, USA
(cthouser@ucsc.edu)

The core mantle boundary (CMB) puts in contact materials of completely different physical and chemical behaviour, with a metallic liquid alloy on one side and a mostly solid silicate on the other. The contrast are of the same order as that existing between the solid Earth and the fluid envelopes, and we should expect that region to be the seat of many complexities, particularly on the mantle side, as is the case for the lithosphere. Many competing scenarios exist to explain the complex observations and the fact that the term D'' is the only remaining one from the early Earth structure proposed by Bullen shows that it resists simple explanations.

Each of the observations pertaining to D'', taken independently, can have multiple explanations. The goal of this review is to discuss the different observations and the explanations offered in the literature to try and isolate the simplest model to explain the maximum observations. Several arguments in favor of compositional variations in the lowermost mantle have been proposed and are now challenged. For example, the large low shear wave velocity provinces (LLSVPs) observed under Africa and the Pacific have been attributed to temperature dependent attenuation. The anti-correlation observed between tomographic models of P and bulk sound velocity has been attributed to difference in frequency content of S and P waves and finite frequency effects. These arguments are quite justified by themselves but come short in explaining the existence of patchy ultra low velocity zones. These regions, that are found to concentrate around the LLSVPs, have been best explained by the presence of partial melting. Lateral variations of the temperature at the top of the core being of the order of 10^{-4}K, partial melting can be everywhere or nowhere in a compositionally homogeneous lower mantle, which contradicts the observations. Several scenarios have been proposed for the formation of compositional variations in the lower mantle. They could be the residual of a primordial layered structure slowly destroyed by thermal convection or created over time by detachment of the subducted crust. Alternatively, they could be formed by fractional crystallisation of a basal magma ocean, which has the advantage of explaining both ULVZs and LLSVPs.

These issues must also be discussed in relationship with the structure, dynamics and evolution of the core. The question of a stratified uppermost core has been recently revived because of some new seismic observations. The origin of such a stratification can be thermal or compositional, the latter being possibly due to accumulation of light elements from inner core formation or to interaction with the mantle. This last scenario is obviously more important if the lower mantle is indeed partially molten. Recent high pressure experiments show that the core is under-saturated in all potential light elements, which reflects that its bulk composition has not evolved strongly since its formation at lower pressure. Interaction with the mantle must therefore be limited, most likely because of the strong compositional buoyancy of light element rich fluids that can come from the mantle. The fact that FeO is found to be metallic at CMB pressure offers intriguing possibilities that need further exploration. The fractional crystallisation of the basal magma ocean enriches the liquid in FeO that could separate and join the core as a liquid. If, on the other hand, it is solid, it could help to solve the long standing question of core-mantle electromagnetic coupling. Several other issues like the transition from perovskite to post-perovskite, the recent results on melting of silicates, will be discussed in an integrated manner, trying to propose a self-consistent view to integrate independent constraints from seismology, mineral physics and geodynamics.

Invited Talk

Constraints on the structure and dynamics of the core-mantle and inner core boundaries inferred from nutation observations.

LAURENCE KOOT[1]

[1] Royal Observatory of Belgium, Brussels, Belgium.
(laurence.koot@observatoire.be)

The gravitational torque applied on the Earth by the other celestial bodies generates periodic variations in the orientation of the Earth's rotation axis in space which are called nutations. This motion has two normal modes, the Free Core Nutation (FCN) and the Free Inner Core Nutation (FICN), of which the frequencies and dampings depend directly on the Earth's interior structure and dynamics. Both normal modes are characterized by differential rotations of the inner core, the outer core, and the mantle. Their natural frequencies are thus directly affected both by the strength of the mechanical coupling at the outer core boundaries and by the way the three regions deform due to the action of centrifugal forces. Similarly, the damping of the modes reflects the energy dissipated both through the couplings at the outer core boundaries and through anelastic deformation of the mantle and inner core. The mechanical coupling can be of several physical origins such as gravitational, electromagnetic (EM), viscous, or pressure/topographic couplings. Due to the high precision of the nutation observations, the frequency and damping of the normal modes can be estimated from the resonance effect they induce on the forced nutations. Interpretation of these estimated natural frequencies and dampings allows then for insights into the physical properties of the deep Earth and in particular, of the core-mantle and inner core boundaries (CMB and ICB). We review here the constraints that can be inferred from nutation observations on deep Earth's properties. We focus in particular on the magnetic field at the CMB and ICB, we discuss the effect of the field spatial distribution on the strength of the EM torque, and take into account new values that have been obtained for the electrical conductivity of the outer core from 'ab initio' computations. We also discuss the effects of mantle anelasticity and inner core viscous deformation.

Invited Talk

The composition of the base of the mantle and reactions with the outer core

D.J. Frost, and D.C. Rubie[1]

[1] Bayerisches Geoinstitut, Universitaet Bayreuth, D-95447 Bayreuth , Germany. e-mail: Dan.Frost@uni-bayreuth.de

In order to understand reactions at the core-mantle boundary (CMB), it is necessary to be able to determine how oxygen and silicon would partition between the Earth's silicate mantle and metallic core at the current CMB conditions. High pressure and temperature experiments were performed to examine the simultaneous partitioning of these elements between liquid iron-rich metal and silicate melt. Results show that the presence of O in liquid Fe at high temperatures influences the partitioning of Si, causing more Si to partition into the metal than would be expected based on lower-temperature measurements. Although Si and O are mutually exclusive in Fe metal at temperatures <3000 K, the level at which both element concentrations are equal in the liquid metal rises above 1 weight % at temperatures above 3000 K. A thermodynamic model based on these experiments has been developed that accounts for the interaction between O and Si in the liquid metal. Comparison between this model and the results of diamond-anvil cell experiments, previously performed up to 71 GPa, indicates that there may be very little pressure dependence but a strong temperature dependence to O and Si partitioning. Our model predicts that sub-equal proportions of Si and O, sufficient to explain the outer core density deficit, would have partitioned into core-forming metal if equilibration occurred between core-forming metal and a magma ocean with a bulk silicate Earth composition at pressures of approximately 50 GPa. The model also predicts that an O- and Si-enriched buoyant layer may have developed at the top of the outer core as a result of subsequent equilibration with the overlying mantle.

In addition melting experiments in the system MgO-$MgSiO_3$ have been performed to estimate the melting temperature of the base of the mantle. The eutectic composition in this system is found to become progressively more MgO-rich with increasing pressure. A simple thermodynamic model is developed to describe the melting phase relations based on literature models for melting curves of end-members and a symmetric liquid mixing model. It is shown that melting relations of a natural peridotite composition at high pressure can be well described on the basis of phase relations of the simple binary, particularly once the effects of FeO on phase relations and melting temperatures are estimated. The thermodynamic model, extrapolated to pressures covering the entire mantle predicts that the eutectic composition becomes richer in MgO up to about 80 GPa, where it becomes near constant with pressure and has a Mg/Si ratio close to that of a peridotite composition. By applying further experimental results to account for the effect of FeO on the melting temperatures, the model predicts that the solidus and liquidus for a peridotitic composition are never more than ~250 K apart. These results can be used to examine a partial melt origin for the existence of localised zones with ultra low shear wave velocities (ULVZ) at the core-mantle boundary (CMB). The solidus temperature of peridotitic mantle at the CMB is estimated to be 4400 ± 300 K, which would require temperatures at the CMB to be at the very top end of the estimated range for melting to occur. The proximity of the solidus and liquidus temperature predicted by the model, however, implies that large melt fractions could form over small depth intervals as a result of relatively small increases in either temperature or FeO content. This is consistent with a seismically sharp transition in the upper boundary of ULVZ layers. Given the high temperatures required to melt mantle peridotite at the CMB, a partial melt origin due to raised FeO contents seems more plausible.

Simulations of thermal conductivity and heat flux in the lowermost mantle

MICHAEL W. AMMANN[1], ANDREW M. WALKER[2*], STEPHEN STACKHOUSE[3], JAMES WOOKEY[2], JOHN P. BRODHOLT[1] & DAVID P. DOBSON[1]

[1] Department of Earth Sciences, University College London, London, UK
[2] School of Earth Sciences, University of Bristol, Bristol, UK
[3] School of Earth and Environment, University of Leeds, Leeds, UK
* (andrew.walker@bristol.ac.uk)

We have combined atomic scale simulations of thermal conductivity in $MgSiO_3$ perovskite and post-perovskite with a models of texture development and temperature distribution in the lowermost mantle in order to better understand the constraints on the distribution of heat flux across the core mantle boundary (CMB). In order to calculate the thermal conductivity we make use of a simple non-equilibrium molecular dynamics scheme [1] with the interactions between atoms described using density functional theory or one of two parameterised interatomic-potential based models. These simulations yield the thermal conductivity of the two phases as a function of pressure and temperature. Under the conditions expected in the lowermost mantle we find that the thermal conductivity of the post-perovskite phase ($\sim$12 W/mK) is about 1.5 times larger than that of $MgSiO_3$ perovskite ($\sim$8.5 W/mK). This increase in conductivity is similar to that measured for the $CaIrO_3$ analogue and sufficient, in simple models of convection, to increase the velocity of downwelling material and the asymmetry of the convective planform [2].

The approach also yields the anisotropy of thermal conductivity tensor. We find that the perovskite phase is weakly anisotropic with conductivity along the c-axis about 10% higher than conductivity along the a-axis. In contrast the post-perovskite phase is found to be strongly anisotropic at relatively low temperature (1000 K) with conductivity along the a-axis about 40% higher than conductivity along the c-axis. However, the anisotropy decreases with increasing temperature and, by 4000 K, conductivity becomes nearly isotropic. We have used the results of these simulations in combination with a model of the development of lattice preferred orientation (LPO) in D'' [3] to examine the controls on the distribution of heat flux at the CMB. Although the model parameters are not well constrained, we believe they place reasonable upper bounds on the strength of the texture and the magnitude of the temperature variation. We are able to separately consider the effects of: (a) an inhomogeneous temperature distribution in D'', (b) temperature dependent thermal conductivity, (c) the spatial distribution of perovskite and post-perovskite and (d) the development of a LPO in post-perovksite. Our model parameters suggest that the strongest control on the distribution of CMB heat flux is the temperature distribution in the lower mantle. However, the influence of of the development of texture in post-perovskite may be geodynamically significant in particular regions.

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Evolution of the gufm1 main field model within slow and fast S-wave regions on the Core-Mantle Boundary using Slepian functions

CIARÁN BEGGAN[1], JARNO SAARIMÄKI[2], KATHY WHALER[2] AND FREDERIK SIMONS[3]

[1] Geomagnetism Team, British Geological Survey, Edinburgh, UK (ciar@bgs.ac.uk)
[2] School of GeoSciences, University of Edinburgh, Edinburgh, UK
[3] Department of Geosciences, Princeton University, New Jersey, USA

Models of the core magnetic field are typically represented using spherical harmonic coefficients. From them, spherical Slepian functions can be employed to produce a locally and also globally orthogonal basis in which to optimally represent the field in a region up to a given spherical harmonic degree [1]. The region can have any arbitrary shape and size and need not necessarily be connected. Slepian functions can be tailored to be preferentially either band- or space-limited, in theory allowing a trade-off between spectral and spatial concentration in the region and leakage beyond.

We use Slepian functions to optimally separate snapshots from the core field model of *gufm1* [2] into two regions: (1) the non-contiguous regions characterised by anomalously slow deep mantle shear wave velocities and (2) the complementary region characterised by average and fast shear wave velocities [3]. Seismic velocities are affected and partially controlled by temperature. Inhomogeneous temperature and heat flux boundary conditions may affect the geodynamo [e.g. 4], thus motivating this study to investigate if there are regional differences in the CMB field.

In order to investigate the spectral content of each, the *gufm1* spherical harmonic field coefficients are transformed into Slepian coefficients, separated into the appropriate regions and transformed back to spherical harmonic coefficients representing the field over the space-limited extent of the two regions. The spectral power of each region is examined over harmonic degrees L = 2-14. We show that the energy in degree L = 5 coefficients is concentrated almost exclusively into the slow velocity regions as the model evolves from 1590-1990.

However, the results for such a small number of degrees (L = 2-14) must be assessed in conjunction with an investigation of the effects of spectral coupling between the complementary regions. Analysis shows that the leakage of energy into and out of the regions of interest is relatively large compared to the signals observed. This suggests that the concentration of magnetic energy in the slow S-wave region into degree L = 5 may not be as significant as initially indicated. We show how the decompositon of global models into regions using Slepian functions must have considered the coupling between the regions of interest to be valid.

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Libration driven elliptical instability

DAVID CEBRON[1], MICHAEL LE BARS[2], JEROME NOIR[1], JONATHAN AURNOU[3] & STIJN VANTIEGHEM[1]

[1] Institute of Geophysics, ETH Zürich, Zürich, SWITZERLAND
(david.cebron@erdw.ethz.ch)
[2] IRPHE, CNRS and Aix-Marseille University, Marseille, FRANCE
[3] Department of Earth and Space Sciences, Univ. of California, Los Angeles, USA

The longitudinal libration of a so-called synchronized planet or moon, i.e. the oscillation of its axial rotation rate whose mean value is otherwise equal to the orbital rotation rate, arises through its gravitational coupling with its closest neighbors. In the body interior, the interaction of a fluid layer (e.g. an iron rich liquid core or a subsurface ocean) with the surrounding librating solid shell resulting from viscous, topographic, gravitational or electromagnetic coupling, leads to energy dissipation and angular momentum transfer that need to be accounted for in the planet thermal history and orbital dynamics, and possibly in its magnetic state (see e.g. 1).

The fluid dynamics that occurs in a rapidly rotating ellipsoidal cavity has been widely studied in the case of constant but different rotation rates of the fluid and the elliptical distortion. This corresponds in geophysical terms to a non-synchronized body with a constant spin rate Ω_0, subject to dynamical tides rotating at the constant orbital rotation rate Ω_{orb}. In particular, it has been shown that this elliptically deformed base flow can be destabilized by the so-called tidally-driven elliptical instability or TDEI (e.g., 2).

The selected resonances of the TDEI are sensitive to the ratio of the rotation rates of the fluid and the elliptical distortion (3). In particular, the elliptical instability is known to vanish in the case of synchronous rotation $\Omega_0 = \Omega_{orb}$. But theoretical arguments suggest that oscillations around this synchronous state may be sufficient to excite elliptical instability (4; 5; 2). This could be of fundamental importance in planetary liquid cores and subsurface oceans of synchronized bodies, where librations are generically present. In this work, we validate the existence of a libration driven elliptical instability, hereafter referred to as LDEI. To do so, we first extend previous analytical studies (4; 5; 2) using a local WKB approach that allows us to determine a generic formula for the growth rate of LDEI. We then present the numerical and experimental validation of the existence of the LDEI, in good agreement with the theoretical results. Finally, implications for planets and moons are briefly discussed.

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The origin of D'' reflections - a systematic study of seismic data

LAURA COBDEN[1] AND CHRISTINE THOMAS[1]

[1]Institut für Geophysik, University of Münster, Corrensstrasse 24, 49149 Münster, Germany. E-mail: laura.cobden@uni-muenster.de, tine@earth.uni-muenster.de

Regional seismic studies of the Earth's deep mantle indicate the presence of P- and S-wave reflectors at the top of the D'' layer. Such reflectors appear to be laterally intermittent, occur at a range of depths, and produce waveforms whose amplitude and polarity differ at different locations. A number of possible explanations for D'' reflections have been proposed, including: a phase change from perovskite to post-perovskite; thermal or thermochemical discontinuities generated by subducted slabs; alignment of anisotropic minerals; and small-scale chemical heterogeneity arising perhaps from core-mantle interactions or primitive material. However, some of the observed heterogeneity in D'' structure may be related to lack of consistency between the style, quality and number of seismic observations in different regions, as well as complexity in wave propagation due to complex small-scale 3-D structure. In this study we present a compilation of observations of D'' reflections for regions in which (1) a reflector is seen in both P and S wave arrivals and (2) consistent array seismology techniques have been applied to infer the properties of the reflectors. Using a recent Monte-Carlo thermodynamic modelling method to convert changes in chemistry and mineralogy into changes in seismic velocity, we compare the fit of different isotropic thermochemical structures to the observed seismic properties of D'' reflections, namely the polarity and amplitude of the reflectors. We find that it is possible to discriminate between different possible origins for D'' reflections on the basis of polarity observations alone. Amplitude measurements may provide further constraints but must be treated with extreme caution due to a large number of factors which can influence waveform amplitudes. In regions such as the Caribbean, a phase change from perovskite to post-perovskite provides the most likely explanation for the discontinuity, whilst in other regions, multiple explanations for the discontinuity are possible, including subduction-related heterogeneity and anisotropy.

The stratified layer at the core-mantle boundary caused by barodiffusion of Oxygen, Sulphur and Silicon

D GUBBINS[1], C J DAVIES [1]

[1] School of Earth and Environment, Institute of Geophysics and Tectonics, University of Leeds, Leeds, UK
David Gubbins <gubbins@leeds.ac.uk>, Chris Davies <c.davies@see.leeds.ac.uk>

Barodiffusion is the tendency of light elements to migrate down a pressure gradient. In the Earth's outer core, this effect can lead to the development of a chemically stable layer beneath the core-mantle boundary (CMB). Barodiffusion has so far been considered unimportant relative to other effects, but here we show that it dominates at the CMB and inevitably leads to an order-100 km-thick layer that is rich in light elements and stably stratified. Barodiffusion changes not only the equations governing molecular diffusion of light elements in the core but also the boundary condition at the CMB to a non-zero compositional gradient, a point missed by previous studies. This gives the mathematical problem the same form as the recently-proposed migration of light elements passing from the mantle into the core; the effect of barodiffusion is comparable provided all light elements in the outer core are included, not just the light element driving the convection as in previous studies. We therefore conclude that a substantial stable layer exists at the top of the core, and that it does not depend on any mass flux across the CMB. We examine the chemically stable layer by solving the relevant diffusion equations in a thin layer beneath the CMB for barodiffusion of oxygen, sulphur and silicon over the whole history of the core using diffusion constants obtained from first principles calculations. The lower boundary of the layer is defined to be the neutrally stable level where the stabilising barodiffusive gradient is equal and opposite to the destabilising gradients associated with buoyancy sources in the well-mixed bulk of the core. We assume no mass flux across the CMB, and find the compositional gradient imposed by barodiffusion to be so large that its stable density gradient could not be overcome by any destabilising gradient at any time. The light layer therefore develops at the top of the core immediately after core formation; solving the diffusion equations shows it to grow to a thickness of order 100 km. The final thickness is remarkably insensitive to the model of core cooling used to specify the destabilising gradients in the well-mixed region of the core. Furthermore, we consider and dismiss a variety of instability mechanisms and conclude that the stratification is strong enough to inhibit all radial motion within the layer. The variation in composition is sufficiently strong to produce geomagnetic effects and seismic velocity anomalies of a fraction of a percent which could be, and may already have been, detected. Differences in the diffusion parameters for the 3 light elements cause differences in their relative concentrations in the layer, leaving the layer oxygen-rich relative to sulphur or silicon.

Lateral heterogeneities in the lowermost mantle – To what detail can we resolve them seismically?

STEFANIE HEMPEL[1], CHRISTINE THOMAS[1], TARJE NISSEN-MEYER[2]

[1]Institute of Geophysics, University of Muenster, Germany
[2]Institute of Geophysics, ETH Zurich, Switzerland

The D'' layer in the Earth's lowermost mantle has multiple features: tomographic models show lateral variation in elastic properties like density, seismic velocity and anisotropy. In a few areas one or even two reflectors are detected on top and within the D'' layer. This D'' discontinuity exhibits short- and large-scale topography, the width of the vertical gradient of the elastic properties across the discontinuity varies between a few 10ths and 100 kilometers, the polarities of the seismic reflectivity show both positive and negative correlation to the core-mantle-boundary reflection. These complex phenomena are difficult to separate in seismological data. To study their effects separately we use an axisymmetric spectral element method to model the 3D seismic wave propagation in Earth models with 2.5D lateral heterogeneities of different length scales, elastic properties, shapes, or inclinations. We show that some of these features are resolved by seismology and that others are not. E.g. low inclinations of reflectors result in a travel time perturbation that can be mistaken for varying height of the reflector, whereas very steep topography explains e.g. an unexpectedly low amplitude of the reflection off the core-mantle-boundary (PcP, ScS) and a broad arrival of the reflection off the D'' discontinuity (PdP, SdS).

Insights into the Earth's D" layer from normal modes

PAULA J. KOELEMEIJER[1], ARWEN DEUSS[2]

[1] Bullard Laboratories, Department of Earth Sciences, University of Cambridge, Cambridge, UK (pjk49@cam.ac.uk)
[2] Bullard Laboratories, Department of Earth Sciences, University of Cambridge, Cambridge, UK (afd28@cam.ac.uk)

Seismological data provide one of the few tools to study the Earth's deep interior. The use of observations of Earth's free oscillations (normal modes) has many advantages over short period body wave data in studying the deep Earth: the data are global in character; modes are sensitive to density variations in addition to velocity; and no approximations are required to calculate full waveforms. Information on the seismic structures found inside the Earth is obtained from observations of the frequencies, attenuation factors and splitting of these modes.

Normal mode data are particularly useful for investigating the D" layer, where compositional heterogeneities are thought to occur. This region is situated atop the core-mantle boundary (CMB), Earths largest internal boundary, which separates the liquid iron outer core and the solid silicate mantle. The structures found here have a major influence on the nature of mantle convection and the evolution of the core. Seismic observations of features such as topography on the CMB, thin ultra-low-velocity zones (ULVZs), seismic anisotropy and the anti-correlation between shear wave and bulk sound velocity heterogeneities have mainly been made using body waves, which are local in nature. Understanding these complex seismic structures is of fundamental importance for the integration of seismology, mineral physics and mantle convection modelling.

We have modelled the effect of various seismic structures on normal modes with sensitivity to the D" layer. Our results show that modes are sensitive to many of the small scale features found in the deep mantle. However, we are at present limited to structures up to degree 6 due to the uncertainties in the available data. We elaborate on these findings and examine specific modes that are extremely sensitive to the D" layer in detail. In this way, we hope to improve our understanding of the seismic features found in the D" region.

Mapping out features of the Mid-Pacific LLSVP

Dunzhu Li[1], Daoyuan Sun[2], Don Helmberger [3]

[1] Seismological Lab, California Institute of Technology, Pasadena, USA
(dli@gps.caltech.edu)
[2] Department of Earth Sciences, University of Southern California, Los Angeles, USA
(daoyuans@usc.edu)
[3] Seismological Lab, California Institute of Technology, Pasadena, USA
(helm@gps.caltech.edu)

Recent studies of both the African and Mid-Pacific LLSVP display strong secondary (S*) arrivals, especially at diffracted distances. Those complex phases when observed at USArray stations, display strong variation with one dominant S* and several additional phases. The dominant one appears to be associated with the average LLSVP shape and the latters appear to be caused by combinations of LLSVP and more detailed features of the LLSVP structure. In contrast, well observed mantle reverberations from stacked USArray record sections indicate that the upper mantle beneath the Pacific is much more 1D-like than the lower mantle. Thus we can use all the ScS multiples in combination with the Sdiff waveforms to isolate lower mantle structure. Here, we use our newly developed hybrid code, which benchmarks well against normal mode and frequency-wavenumber synthetics, to test several proposed inflated tomographic models. The code uses earth-flattenning transformations, and 2D staggered finite difference to calculate a line dislocation source seismogram first, and then by processing adjacent traces we can determine the ray parameter and correct for point source spreading to obtain realistic seismograms. We use a multi-path detector (MPD) to obtain the timing shifts and amplitudes of S* phases along other late arrivals for both data and synthetics. These shifts and amplitudes patterns provides characteristic structural dimensions as well as a goodness of fit comparisons. We find some of these tomographic models do quite well with inflation factor of 2 to 3 applied to the lower 800km.

Dynamically established structures at the Core-Mantle-Boundary

Mariano Mertens[1] & Ulrich Hansen [1]

[1] Institute of Geophysics, University of Münster, Germany
(m.mertens@wwu.de, hansen@earth.uni-muenster.de)

Mantle convection largely determines the structure and the dynamics of the Earth. Like other strongly nonlinear transport processes, convection in the Earth's mantle acts to establish structures of different scales, particularly in the boundary layers of the convecting systems. While the lithosphere forms the upper boundary layer of the mantle convection system, the Core-Mantle-Boundary (CMB) is usually identified as the lower boundary layer. Seismological studies have demonstrated that a whole spectrum of structures seems to exist at the CMB.

In this study we focus on patterns, as created by convection, at the CMB. In particular we want to analyze line-like structures, which have been numerically and experimentally investigated by several authors in the context of turbulent convection. These structures are intrinsic features of convection. They have a finite height, show a strong increase in the temperature and the vertical velocity and form a kind of flow channels. In these channels hot material flows along the bottom boundary.

We want to explore these structures with respect to their geophysical significance. Especially we want to investigate, whether these features can account for structures at the CMB, as revealed in seismological studies.

A finite volume code is used in order to integrate the equations, describing thermally driven convection of an incompressible Boussinesq-Fluid with infinite Prandtl number. Realistic features of mantle convection, like strongly temperature dependent and depth dependent viscosity, internal heating and a variable thermal expansion coefficient are considered in our model.

We present first results of our work, which show that these structures can be observed over a wide range of parameters. We have analyzed the features of the structures and have shown that they form a topography at the CMB that lies within a reasonable range. What needs to be discussed is, whether or not these structures are visible in seismic data and if so they could provide an alternative explanation for the seismic observations at the CMB.

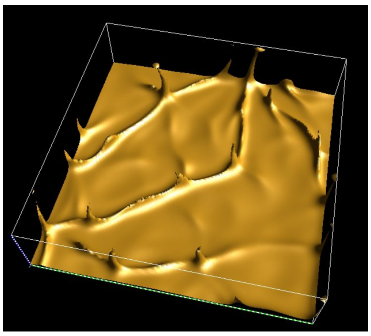

Figure 1: Example of line-like structures with viscosity that depends on depth and temperature.

Anisotropy in D″ from models of mantle flow and texturing of post-perovskite

ANDY NOWACKI[1], ANDREW M. WALKER [1], JAMES WOOKEY[1] & J.-MICHAEL KENDALL[1]

[1] School of Earth Sciences, University of Bristol, Bristol, UK (andy.nowacki@bristol.ac.uk)

The Earth's lowermost mantle—known as the D″ region—exhibits significant seismic anisotropy. This is often attributed to the the development of a lattice preferred orientation (LPO) of $MgSiO_3$ post-perovskite (ppv), believed to be the dominant mineral phase present in the lowermost mantle. There are, however, many other potential causes of D″ anisotropy, such as the alignment of different phases or of seismically distinct material with a shape-preferred orientation (SPO). As yet, no observations have been able to distinguish these cases. We present the initial results of finite-frequency waveform modelling of ScS waves traversing a generally anisotropic, heterogeneous D″. The elasticity we use is derived from a model of texture development in ppv, which in turn is driven by models of mantle flow. We compare these synthetics with regional, multi-azimuth observations of shear wave splitting in ScS made near regions of palaeosubduction—areas where ppv is most likely to exist because of reduced temperatures in D″, using the spectral element method. The synthetics are created with considerable computational expense in order to achieve periods similar to the observations ($\sim$10 s). Where the synthetics and observed splitting match, LPO of ppv can be considered a compatible mechanism.

The input model of mantle flow is the result of an inversion of seismic, mineral physical and other geophysical observations [1]. Particles are traced through the steady-state flow field, driving a viscoplastic self-consistent model of texture development in ppv. The elasticity we produce is fully general, imposing no constraints on the type of anisotropy, and is thus suitable for comparison with regional or global seismic observations of D″. Previous work has compared the model with tomographic inversions which assume radial anisotropy [2], however it is known that in the lowermost mantle, assumptions of this kind of anisotropy are not appropriate everywhere. We pursue an alternative approach by comparing individual source-receiver measurements of shear wave splitting [3–5]. The advantage of this method is that we place no prior constraints on the type of anisotropy present.

The primary difference between the elasticity models we test is the deformation mechanism of ppv—something which is largely unknown at present—whilst mantle viscosity structure and the Clapeyron slope of the perovskite–post-perovskite phase transition produce only minor variation. Three models of dislocation creep in ppv are tested. These are based on both theoretical and experimental considerations, allowing slip mainly on (100), (010) or (001). Preliminary results suggest that one model, where slip is mostly on (010), best agrees with observations; this is also compatible with previous work examining the match with radially-anisotropic shear wave tomography, and with deformation experiments on phases which are structural analogues of ppv.

As the forward modelling methodology is refined, more measurements can be incorporated into the dataset, potentially further strengthening or refuting the current findings. New mineral physical experiments or numerical calculations may also reduce the number of deformation mechanisms in ppv which must be considered, moving us nearer to the goal of constraining mantle flow directly with measurements and models of D″ anisotropy.

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P-wave velocity of the lowermost mantle from high precision array measurements

SEBASTIAN ROST [1]

[1] School of Earth and Environment, Institute of Geophysics and Tectonics, University of Leeds, Leeds, UK (s.rost@leeds.ac.uk)

Tomographic images of the Earth's lowermost mantle show large-scale reductions in seismic S-wave velocities beneath the central Pacific and Africa. These large low shear velocity provinces (LLSVP) are much less constrained in tomographic P-wave models. This discrepancy, together with other geophysical data, led to the interpretation of LLSVPs as thermo-chemical piles. These piles might be long lived, might contain chemically distinct material and might influence convection in mantle and core

The slowness of an incoming wavefront contains direct information on the seismic velocity at the ray's turning point. Especially, for waves diffracted along the core mantle boundary (CMB) the slowness determines the seismic velocity integrated along the path. The slowness of seismic energy can be directly measured using seismic arrays determining both horizontal and vertical incidence angles. This measurement can place constraints on the seismic velocities along the CMB and is independent from traveltime tomography.

Here we measure the slowness of P and P_{diff} using the medium aperture, vertical component Yellowknife array (YKA) in northern Canada. To improve the accuracy of slowness and backazimuth determination of this 20 km aperture array we apply the F-statistic allowing very high resolution measurements of the complete slowness vector. Using more than 1200 high quality records of P and P_{diff} from western Pacific seismicity allows sampling of the northern boundary of the Pacific LLSVP in great detail. Preliminary results show that the boundary of the Pacific LLSVP can be clearly mapped out using this method and we detect a smaller region of reduced velocities beneath the Sea of Okhotsk which might be connected to the main part of the Pacific LLSVP. The detection of this smaller low velocity region is in disagreement with tomographic S-wave velocity models. Events sampling the edges of these low velocity regions also show evidence for multi-pathing indicating very sharp boundaries to LLSVPs in agreement with other seismic studies. Extending this method to measuring S_{diff} slownesses using larger aperture 3-component seismic arrays will allow better insight into the composition of the LLSVPs.

Zonal wind, inertial waves, instabilities: the rich dynamics of libration-driven flows.

ALBAN SAURET, DAVID CÉBRON, MICHAEL LE BARS & STEPHANE LE DIZÈS

IRPHE, CNRS & Aix-Marseille University, Marseille, FRANCE (sauret@irphe.univ-mrs.fr)

Many astrophysical bodies are subject to harmonic oscillations of their rotation rate, referred to as longitudinal libration [1]. In fluid layers, this boundary forcing leads to a correction to the mean solid body rotation called zonal wind. These oscillations can also be the source of rich dynamics involving instabilities or inertial waves. Here, we combine theoretical, experimental and numerical approaches to study the fluid flows in a sphere or a spherical shell subject to longitudinal libration.

First, we show that for sufficiently large libration amplitude, the oscillating flow is periodically unstable with respect to centrifugal instability [2,3]. The centrifugal instability modifies the torque applied on the different boundaries. In addition, the Taylor-Görtler vortices generated by this instability are shown to become turbulent for small Ekman number or large amplitude of libration. This turbulent flow generates inertial waves in the bulk of the sphere with well-defined characteristics and temporal signatures (figure 1).

Below the centrifugal instability threshold, we consider the zonal wind generated by this harmonic forcing [4]. When the libration frequency is larger than twice the rotation rate, no inertial waves are excited and the zonal wind is well-described by an analytical approach [5]. However, in the presence of inertial waves, the flow patterns in the bulk become more complicated. Its key characteristics are provided.

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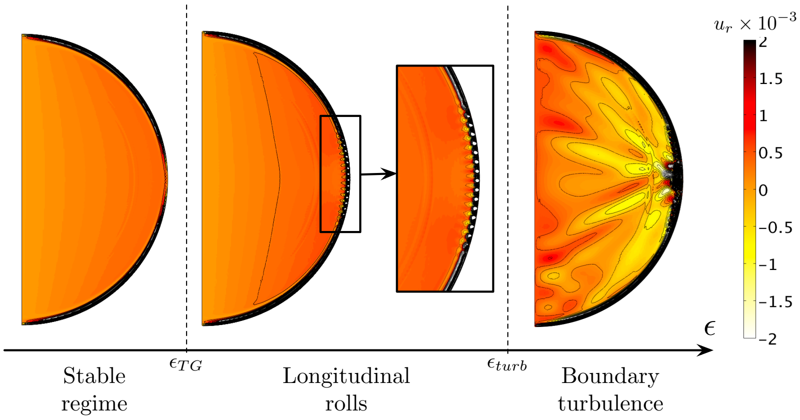

Figure 1: Radial velocity u_r in a librating sphere ($\omega = 3$, $E = 5 \times 10^{-5}$) for different values of the libration amplitude ϵ (from left to right: $\epsilon = 0.3, 0.55, 0.85$). ϵ_{TG} and ϵ_{turb} are respectively the critical value for the apparition of longitudinal rolls (see the zoom) and boundary turbulence. Spontaneous generation of inertial waves are observed for $\epsilon > \epsilon_{turb}$.

Influence of electrical conductivity heterogeneity in the D'' layer on geomagnetic jerks

HISAYOSHI SHIMIZU[1] AND HISASHI UTADA[1]

[1]Earthquake Research Institute, University of Tokyo, Yayoi 1-1-1, Bunkyo-ku, Tokyo, 113-0032, Japan

Geomagnetic jerks are known to have occurred globally around 1969, 1978 and 1991, and these are called as global jerks. Also, those occurred around 1999, 2003 and 2007 are identified as local jerks. One of the most prominent features of the 1969 geomagnetic jerk is the differential delay time of its appearance at the Earth's surface: the sudden change of the first derivatives was observed earlier in Europe compared with that in southern Africa. In this study, we suppose that the cause of the difference as large as two years is attributed to the effect of conductivity anomaly in the D'' layer, and a set of 3-d numerical modeling of electromagnetic induction in the mantle was performed to clarify whether main characteristic features of the geomagnetic jerks can be reproduced by the effect of mantle heterogeneity and magnetic field of a single spherical harmonic mode, both poloidal and toroidal, at the CMB. Numerical results suggest that even an extremely high conductive body in the D'' layer cannot generate differential delay time as large as two years at the surface of Earth by either the poloidal or the toroidal magnetic field at the CMB. On the other hand, it is demonstrated that a geomagnetic jerk originated from the toroidal magnetic field at the CMB is possibly observed as a local jerk. Recently we found that global scale geoelectric voltages observed by transoceanic submarine cables in the northwestern Pacific show jerk-like secular variation around 2006.0, and the variation can be related to the local geomagnetic jerk of 2007. Numerical results indicate that the jerk amplitude and differential delay time of the geomagnetic and geoelectric jerks have potential to constrain the electrical conductivity structure in the D'' layer. Preliminary investigation suggests the most preferable D'' structure consists of localized conducting body (which may be corresponding LLVZ) of 10,000 S/m in laterally uniform 100 S/m layer if the thickness of the D'' layer is 100 km.

D" structure beneath North Pacific

Daoyuan Sun[1], Dunzhu Li[2], and Don Helmberger[3]

[1]University of Southern California, Department of Earth Sciences, Los Angeles, CA 90089 (daoyuans@usc.edu)
[2]California Institute of Technology, Seismological Laboratory 252-21, Caltech, Pasadena, CA 91125 (dli@gps.caltech.edu)
[3] California Institute of Technology, Seismological Laboratory 252-21, Caltech, Pasadena, CA 91125 (helm@gps.caltech.edu)

A lower mantle S wave triplication (Scd) has been recognized for many years and appears to be explained by the recently discovered perovskite (PV) to post-perovskite (PPV) phase change. Seismic observations of Scd display (1) rapid changes in strength and timing relative to S and ScS and (2) early arrivals beneath fast lower mantle regions. While the latter feature can be explained by a Clapeyron slope of 6 MPa/K and a velocity jump of 1.5% when corrected by tomographic predictions, it does not explain the observed rapid variation. *Sun and Helmberger* [2008] expanded on this mapping approach by attempting a new parameterization that requires a sample of D" near the ScS bounce point (δV_S) where the phase height and velocity jump are functions of δV_S. These parameters are determined by modelling dense record sections collected from PASSCAL data where most samples are concentrated beneath Central America. Here, we expand our sampling region beneath north Pacific with the dense USArray records, providing coverage into the shadow zone beyond 90°. Both SH and SV are studied where 1D modelling suggests that a δV_{SH} = 3% increase ~240 km above the CMB with δV_{SV} about half. The distorted waveforms at distances large than 85° require the addition of a strong reduction of shear velocities, 6 to 10%, with a thickness of about 60 km, which could caused by various amounts of iron-rich (Mg,Fe)O-perovskite mixtures. To map-out the lateral variation of D″ layer in this region, we apply a recently developed 2D stagged-grid Finite-difference code to generate synthetics for hybrid D″ models transformed from the latest global tomographic images.

Hunting Ultra Low Velocity Zones: Constructing a Pseudo-automatic Method of Detection

E.A VANACORE[1], S. ROST[2], M. THORNE[3]

[1]School of Earth and Environment, Unversity of Leeds, E.Vanacore@leeds.ac.uk
[2]School of Earth and Environment, Unversity of Leeds, S.Rost@leeds.ac.uk
[3]Dept. Of Geology and Geophysics, University of Utah, michael.thorne@utah.edu

Ultra-low velocity zones (ULVZ's), small-scale areas of strongly reduced seismic velocities along the core-mantle boundary (CMB) , influence multiple aspects of mantle and core dynamics and it has been speculated that these zones are the source of mantle plumes, regions of core material invading the mantle, and/or geochemically distinct regions of either a remnant magma ocean or material such as iron-enriched Perovskite or post-Perovskite. Here we present preliminary work that will ultimately lead to a global study with the aim to determine the global distribution of ULVZs along the CMB and to better constrain the seismic parameters (velocity, density) of ULVZs. We use a two pronged approach to this problem with a combination of computational and observational seismic methods. We are currently applying a 2.5D seismic wave propagation code (PSVAxi) to generate a large library of synthetic seismograms representing a broad model space of ULVZ parameters and their location relative to the seismic raypath. Seismograms are calculated to high frequencies of ~1 Hz. This high frequency synthetic library will then be correlated with observed data phases such as *SPdKS*/*SKPdS* that are highly sensitive to core-mantle boundary structure.
In the development stage of what will eventually be a pseudo-automated method to globally detect ULVZ's, we choose to examine *SKS*/*SKKS* data from ~300 stations within Turkey from the Kandilli Observatory network (KOERI; KO), the National Seismic Network of Turkey (AFAD-DAD; TU), and available IRIS data from the Northern Anatolian Fault experiment (YL) for the period between 2005 and 2010. This data set allows sampling of the expected northern boundary of the African Large Low Shear Velocity Province (LLSVP) from the analysis of SKS and SKKS data from South American and South-Sandwich Island events and provides clear *SPdKS* and *SKPdS* waveforms with excellent signal to noise ratios. The dense network (average station spacing of ~70-100 km) allows testing whether this approach is feasible with other networks (such as USArray). The preliminary *SKKS-SKS* travel-times for this data set indicate the existence of ULVZ structure along the northern boundary of the African LLSVP. Detailed waveform modeling of *SKPdS* waveforms will help to put further constraints on the location and origin of ULVZs in this location.

Lowermost Mantle Radial Anisotropy from S-ScS Separation in Long Period Body Waves.

JAMES WOOKEY[1], ANDREW M. WALKER[1], ANDY NOWACKI[1], T. GUY MASTERS[2], & J-MICHAEL KENDALL[1]

[1]School of Earth Sciences, University of Bristol, Bristol, UK (j.wookey@bristol.ac.uk)

[2]Institute of Geophysics and Planetary Physics, SIO, University of California, San Diego, USA.

As the site of the lower boundary layer of the convecting mantle, the properties of D″ are key to understanding the dynamics of the broader planet. One such property is seismic anisotropy – the variation of seismic wavespeed with direction – which has the potential to be used to study the mineralogy and dynamics of the lowermost mantle. Anisotropy in the lowermost mantle may be the consequence of the lattice-preferred orientation (LPO) of minerals present in the deep Earth, the current most likely candidate being the post-perovskite phase of $MgSiO_3$. Difficulties remain, however, with the confidence in this interpretation. Foremost amongst these is that the mechanism by which post-perovskite deforms is unclear, with different candidates proposed by various experiments and calculations. Furthermore, other potential mechanisms (such as LPO in other minerals or alignment of larger features such as melt pockets or layers) have not been excluded as contributors to the observed signal.

Observations of seismic anisotropy fall into two broad categories: local direct measurement or global tomographic inversions. The former have the advantage of being able to study more general forms of anisotropy, especially where multiple data azimuths are available (e.g., [1, 2]), whilst the latter provide global coverage. To date, however, tomographic inversions have been limited to parameterising radial anisotropy. Furthermore, recent work [3, 4] has shown that tomographic methods are very sensitive to corrections applied for crustal structure. In order to bridge the gap between these two types of study, we present a new set of individual measurements of radial anisotropy in the lowermost mantle which have a much broader coverage than previous studies, yet do not have the same sensitivities as current tomographic models.

In order to measure radial anisotropy in D″ we measure the interphase time between S and ScS on both the radial and transverse components of long period (~20s) waveforms. We first run a series of synthetic experiments that demonstrate that this is sufficient to remove the effect of (even azimuthal) anisotropy in the upper mantle in the region of both source and receiver. We then apply the technique to a large, pre-collated dataset [5], and inforce a set of stringent quality criteria which reduce the final dataset to 167 measurements, distributed broadly across the core-mantle boundary. On average, the SH component of ScS leads the SV by 0.3s, though considerable regional variation is observed. The results are highly compatible with regional measures of seismic anisotropy. We also compare them with geodynamically-derived texture models of D″ [6], tomographic models [4] and simple 1D models, on a global and regional basis.

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S7: Mantle - Observations of Structure & Composition

Invited Talk

Research Frontiers in the Deep Earth

THORNE LAY

University of California Santa Cruz, Department of Earth and Planetary Sciences, Santa Cruz, California, USA (tlay@ucsc.edu)

The large-scale aspherical seismic velocity structure of the lower mantle has been quite well resolved over the past 30 years, and many fine-scale features in localized regions have been mapped or imaged as well. Large low shear velocity provinces beneath the Pacific and Africa contribute strongly to the dominance of low degree heterogeneity, and many investigations support the notion that these regions have relatively abrupt lateral margins and are surrounded by distinct material that may be participating in deep mantle circulation. These regions appear to have some connection to ultra-low velocity zones and have been associated with locations of Large Igneous Provinces for the past few hundred million years. While the progress has been dramatic, given that such features were not even imagined to exist in the early 1980's, many critical issues remain to be resolved. The precise chemistry of these provinces remains an open question along with all aspects of their transport properties and any distinctions from transport properties of the surrounding mantle. The fixity and endurance of the provinces and their relation to upwellings and downwellings has been the subject of some modeling and much speculation, but it will require higher resolution imaging of the structures and their surroundings to distinguish dynamical behaviors.

The challenge of constraining transport properties by direct observations remains a true research frontier for the deep interior. There are many observational challenges to constraining velocity gradients such as might result from a thermal boundary layer, and the thickness of any thermal boundary layer has large implications for overall heat flux from the core into the mantle. Even given seismological estimates of thermal gradients, uncertainties in thermal conduction parameters remain large for both lower mantle mineral assemblages and for outer core alloys. This places overall thermal modeling in a highly uncertain state. Electrical conductivity of the deep materials is even less directly constrained by observations, and large uncertainties in presence of melt fractions and iron properties. Elastic manifestations of Fe spin-transitions are being evaluated to try to make a connection between laboratory measurements and actual in situ processed in the deep Earth. Transition zones in the outermost core and above the inner core boundary pose similare observational, experimental and theoretical challenges.

Recent long-term planning activities sponsored by the U.S. NSF highlight major problems in the deep Earth such as those noted here, and the associated questions of how the system has evolved over time from Earth formation to present. Investment in new observational, experimental and computational facilities to address the research frontiers is recommended, given that significant advances in resolving small-scale structures and processes is required for advancing our understanding of the dynamical systems. The effort required is massive and will require international collaborations and coordination to achieve the goals of solving the grand challenge questions of how the Earth's interior works and has evolved.

Invited Talk

Early planetary differentiation recorded in deep mantle Xenon isotopes

Sujoy Mukhopadhyay[123]

[1] Harvard Univesity, Cambridge, MA, USA, sujoy@eps.harvard.edu

^{129}Xe, produced from the radioactive decay of extinct ^{129}I, and ^{136}Xe, produced from extinct ^{244}Pu and extant ^{238}U, have provided important constraints on early mantle outgassing and volatile loss from Earth[1,2]. The low ratios of radiogenic to non-radiogenic xenon (^{129}Xe/^{130}Xe) in ocean island basalts (OIBs) compared to mid-ocean ridge basalts (MORBs) have been used as evidence for the existence of a relatively undegassed primitive deep mantle reservoir[1]. However, the low ^{129}Xe/^{130}Xe ratios in OIBs have also been attributed to mixing between subducted atmospheric Xe with MORB Xe, obviating the need for a less degassed mantle reservoir[3,4].

I present new noble gas data from OIBs and MORBs that demonstrate for the first time that the lower ^{129}Xe/^{130}Xe ratios in OIBs are derived from a lower I/Xe ratio in the OIB mantle source and cannot be explained solely through mixing between atmospheric Xe and MORB-type Xe[5]. As ^{129}I became extinct prior to 100 Myrs after the start of the Solar System, OIB and MORB mantle sources must have differentiated by 4.45 Ga and subsequent mixing must have been limited.

The new precise xenon measurements also allow us to compute the proportion of Pu to U-derived fission Xe. Our measurements indicate that the plume source has a higher proportion of Pu- to U-derived fission Xe, requiring the plume source to be less degassed than MORBs, a conclusion that is independent of noble gas concentrations and the partitioning behavior of the noble gases with respect to their radiogenic parents. Calculated I/Pu ratios for the plume source is lower than the MORB source. This suggests that early accretion was volatile-poor compared to later accreting material, supporting the hypothesis of heterogeneous accretion[6]. Overall, these results show that the Earth's mantle accreted volatiles from at least two separate sources and that neither the Moon-forming impact nor 4.45 billion years of mantle convection has erased the signature of Earth's heterogeneous accretion and early differentiation. Finally, if noble gases in OIBs are derived from the Large Low Shear Wave Velocity Provinces (LLSVPs), then LLSVPs are stable features that have existed since the formation of the Earth and are not exclusively composed of subducted slabs.

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Invited Talk

A re-analysis of lower mantle tomographic models

LEKIC, V. [1,2], COTTAAR, S.[3], DZIEWSONKI, A.[4], ROMANOWICZ, B.[5,6]

[1]Department of Geology, University of Maryland, College Park, MD
[2]Department of Geological Sciences, Brown University, Providence, RI
[3]Berkeley Seismological Laboratory, University of California, Berkeley, CA
[4]Department of Earth and Planetary Sciences, Harvard University, Cambridge, MA
[5]Collège de France, Paris, France
[6]Institut de Physique du Globe, Paris, France

Earth's lower mantle is dominated by a pair of antipodal large low shear velocity provinces (LLSVPs) that reach >1000 km up from the core-mantle boundary. These are separated by a ring of faster-than-average velocities thought to be related to subduction of oceanic lithosphere. How robustly does global tomography constrain velocity structure in the lower mantle, and are there other robust large scale features that have not been identified? We use cluster analysis to identify structures and seismic characteristics common to a set of recent global tomographic models which have been derived using different data sets, parameterizations, and theory behind approximations used in inversion.

We find that, in all models, there is a clear separation of lower mantle structure into one fast and two slow regions, and that the boundary of the regions is remarkably similar across models even on length scales as small as <1000 km. This inter-model similarity indicates that the dominance of long wavelength features in the tomographic models is not a consequence of lack of fine-scale resolution, but an indication that long-wavelength features truly dominate the structure in the lowermost mantle. We identify a pronounced asymmetry in the velocity gradient with depth between seismically fast and slow regions in the lowermost 500 km of the mantle, which is a consequence of a bimodal distribution of velocities in this depth range.

There is a single exception to this separation: an isolated slow anomaly ~900 km across and extending ~500 km upward from the core-mantle boundary (CMB), which we call the "Permian Anomaly". Though it is far smaller than an LLSVP, waveform analysis confirms that this anomaly is robustly constrained and bounded by rapid lateral velocity gradients like those found around LLSVPs, suggesting that the nature and process of formation of both types of structures may be related.

Mantle heterogeneities in Western Pacific subduction zones - implications for subduction mechanisms and mantle mixing

HANNAH L.M. BENTHAM[1] & SEBASTIAN ROST[2]

[1] School of Earth and Environment, Institute of Geophysics and Tectonics, University of Leeds, Leeds, UK (h.bentham@see.leeds.ac.uk)
[2] School of Earth and Environment, Institute of Geophysics and Tectonics, University of Leeds, Leeds, UK (s.rost@leeds.ac.uk)

In recent years array seismology has been used extensively to detect and locate the small scale (∼10 km) structure of the Earth. In the mantle, small scale structure likely represents chemical heterogeneity and is essential in our understanding of mechanical mixing processes within mantle convection. As subducted crust is chemically distinct from the background mantle, imaging this crust provides a tracer for convectional flow. Seismic heterogeneities have been found in the lower mantle beneath Western Pacific subduction trenches in previous seismology studies [1, 2, 3] but the arrivals associated with such heterogeneities are difficult to detect as they are typically low amplitude and exist as a small fraction of the total number of observed arrivals in the seismogram.

In this study we find seismic heterogeneities in the mantle by processing teleseismic earthquake data through array seismology methods. We use the small aperture array of ILAR (Eielson Array, Alaska) and target the “quiet” window prior to the PP arrival for earthquakes with epicentral distances of 90-110°. Within this time window, we enhance the weak coherent energy that arrives off great circle path by calculating the observed directivity (slowness and backazimuth) and using a semblance weighted beampower measure. We use the directivity and travel times of suitable precursors to back-trace the energy to the origin of P-to-P reflections, using a 1D raytracer. A total of 283 mantle P-to-P reflections are found within Western Pacific subduction zones, 90% of which are in the upper mantle and transition zone. The scattering origins from 300-600 km depth show a good correlation with subduction zone contours that are derived from subduction zone seismicity, and correlate well with tomography gradients of 0.01-0.5% per degree interpreted as the edge of the slab. Observed deep mantle reflections (>1000 km) are combined with previously observed deep seismic heterogeneities to discuss subduction scenarios as proposed from geodynamical and numerical modelling of mantle convection. Such subduction features include: 1) a planar subducted slab that is undisturbed as it reaches the CMB; 2) a slab that has been deformed through buckling but remains as one structure as it enters the lower mantle; 3) a decomposed slab with crust that has been segregated from the underlying subducted lithosphere and may collect in reservoirs.

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A Bayesian approach to infer temperature in the transition zone from surface waves

MÉLANIE DRILLEAU[1], ÉRIC BEUCLER [1], ANTOINE MOCQUET[1], OLIVIER VERHOEVEN[1], GAEL BURGOS[2] & JEAN-PAUL MONTAGNER[2]

[1] Laboratoire de Planétologie et Géodynamique, UMR 6112, Université de Nantes, Nantes, France (melanie.drilleau@univ-nantes.fr)
[2] Institut de Physique du Globe de Paris, Paris, France

Seismic observations like body waves or fundamental mode surface waves do not contain enough information to accurately image the transition zone, which plays a key role in the dynamics of the Earth's mantle. Phase transitions, convective motions, upwelling and downwelling materials make the 400 - 1000 km depth range highly heterogeneous and anisotropic from a seismological point of view. The new tomographic methods involving 3D kernel computations often use, as reference models, 3D large wavelength V_P, V_S models obtained by linearized inversions. These models are based on small perturbations of 1D global models such as PREM or iasp91 and are used secondly to derive temperature and composition profiles. From a geodynamical point of view, the degree of heterogeneity and anisotropy in the transition zone can be strong enough that the concept of a one-dimensional reference seismic model might be addressed.

We develop a non-linear inverse approach to directly interpret surface wave waveforms or phase velocities in terms of 1D temperature and mineralogical distributions. Starting from numerous realisations of the temperature and the mineralogical fields, the seismic velocities are computed using a Birch-Murnaghan-like equation of state. The model space is sampled thanks to a Markov Chain Monte Carlo (MCMC) method. In order to both reduce the computing time and generate a self-adaptating model space, with respect to the resolution power of the data, polynomial Bézier curves are chosen for the parameterization. An additional advantage of this parameterization is that it is able to describe smoothly varying models and first-order discontinuities, both. Up to now, the parameters are the temperature and the mineralogical composition; other parameters, such as iron content and/or macroscopic anisotropy, will be taken into account in the near future.

This approach is tested using synthetic data sets for a given mineralogy. The temperature output models are very close to the expected ones for all tested cases. The joint inversion of the temperature and the mineralogical composition tends to conclude that the olivine content has a second order effect on the data. The procedure is tested with path-averaged fundamental mode and overtone phase velocities between California and the Vanuatu region. The influence of the uppermost layers in the Earth on the surface wave dispersions and waveforms, is taken into account through a two-step procedure. A first non-linear inversion is performed to obtained the V_S distributions between the surface and 1000 km depth. The median of the a posteriori distribution is secondly used as a prior to model the uppermost part of the mantle, down to 300 km depth, which is not inverted in temperature. Although both fundamental and higher surface wave modes are included in the inversion down to 50 s periods, our results tend to indicate that the resolution of the models strongly degrades below 700 km depth.

PKKP Scattering: Towards a global study of the Core-Mantle Boundary

DANIEL A FROST[1], SEBASTIAN ROST [1], NEIL SELBY[2]

[1] School of Earth and Environment, Institute of Geophysics and Tectonics, University of Leeds, Leeds, UK
(eedaf@leeds.ac.uk)
[2] Blacknest, Atomic Weapons Establishment, Reading, UK
(neil@blacknest.gov.uk)

The scattered seismic wavefield contains information about the small-scale structure of the Earth's interior. Scattering of high-frequency ($\sim$1 Hz) seismic energy samples heterogeneities on scale-lengths of $\sim$10 km. Although most scattered energy is generated in the crust, several probes of deep Earth scattering (PKP, Pdiff, PcP, PKiKP, PKKP) have been used previously. Here we use scattering related to the phase PKKP. Scattered PKKP energy (PK•KP) arrives off great-circle path and scattering typically originates from two symmetric areas off great -circle path, either side of the turning point at the Core-Mantle Boundary, with characteristic slowness/back-azimuth values. Due to the unusual raypath of PKKP and PK•KP this probe offers the potential to sample regions previously unstudied for small-scale structure.

We collect data from all operational International Monitoring System arrays for magnitude $\geq$6.0 events recorded between 1970 and the present day. The PKKP precursor time window is analysed using the fk technique and the higher accuracy F-statistic, a procedure to identify scattered energy and determine its slowness vector. The F-statistic has been used in forensic seismology and has been shown in previous work to be capable of resolving low amplitude coherent energy effectively. The source of the scattered energy is found using ray-tracing and the results from all events and all stations are summed to find a global distribution of scatterers near the Core-Mantle Boundary. This can be linked with other scattering studies and tomography maps to infer chemical heterogeneities within the deep mantle.

PKP Scattering: Detecting a Heterogeneous Ridge Above the Core-Mantle Boundary

DANIEL A FROST[1], SEBASTIAN ROST [2], NEIL SELBY[3] & GRAHAM STUART[4]

[1] School of Earth and Environment, Institute of Geophysics and Tectonics, University of Leeds, Leeds, UK
(eedaf@leeds.ac.uk)
[2] School of Earth and Environment, Institute of Geophysics and Tectonics, University of Leeds, Leeds, UK
(s.rost@leeds.ac.uk)
[3] Blacknest, Atomic Weapons Establishment, Reading, UK
(neil@blacknest.gov.uk)
[4] School of Earth and Environment, Institute of Geophysics and Tectonics, University of Leeds, Leeds, UK
(g.w.stuart@leeds.ac.uk)

Anomalous, small amplitude arrivals prior to the core phase PKP_{df} have been attributed to scattering of waves by small-scale heterogeneities in the lowermost mantle since the early 1970's. We present a new array processing technique utilising the F-statistic in beam-forming to precisely determine travel-times, slownesses and back-azimuths of relatively large amplitude precursors to PKP_{df}. 154 seismic events, many of which are spatially correlated with gold mines near Johannesburg, South Africa, have been recorded at Yellowknife Array, Canada between 1978 and 2011, of which 98 show high amplitude arrivals 3 to 15 seconds before PKP_{df}. The events used are 119.3° to 138.8° away from YKA and most are likely mining induced, with magnitudes of $3.2 \leq mb \leq 6.0$. Previous studies reporting precursors in this distance range used much larger tectonic and explosion events with magnitudes of $5 \leq mb \leq 6.5$. The improved signal processing tools used facilitate study of smaller magnitude earthquakes for PKP_{df} scattering allowing investigation of previously unsampled regions.

Two discrete precursory phases, ~4 s apart, are identified with amplitudes between 10% and 200% of PKP_{df}. Recorded slownesses indicate that PK is scattered on the source-side to PKP_{ab} and PKP_{bc}. Ray tracing is used to determine the location of scatterers within the mantle assuming single scattering from a point source. Anomalously high amplitude scatterers are located along a 1200 km by 300 km ridge trending North-North-East, South-South-West, with topography up to 80 km above the Core-Mantle Boundary, associated with regions of large velocity gradient in global S-wave tomography models. Scattered energy varies systematically with location along the ridge and the scattering volume implies a significant P-wave velocity change from ambient lower-mantle into the scattering body. Considering the location of the scattering ridge and its unusual height above the CMB compared to Ultra-Low Velocity Zones, it is proposed that the scattering body comprises dense, partially molten mantle swept to the edges of the African Large Low Shear Velocity Province (LLSVP) and entrained into the upstream, supported by viscous forces at the edges of the LLSVP, as has been observed in analogue and numerical geodynamical experiments.

A non-linear method estimating source parameters, amplitude and travel times of teleseismic body waves

RAPHAËL F. GARCIA[1,4], LEWIS SCHARDONG[2,4], SÉBASTIEN CHEVROT[3,4]

[1] Université de Toulouse; UPS-OMP; IRAP; Toulouse, France (raphael.garcia@irap.omp.eu)
[2] Université de Toulouse; UPS-OMP; IRAP; Toulouse, France (lewis.schardong@irap.omp.eu)
[3] Université de Toulouse; UPS-OMP; IRAP; Toulouse, France (sebastien.chevrot@irap.omp.eu)
[4] CNRS; IRAP; 14, avenue Édouard Belin, F-31400 Toulouse, France

We present a non-linear waveform inversion method of teleseismic records in order to determine the source parameters (depth, source time function, centroid moment tensor and seismic moment), but also the travel times and amplitudes of body waves.

The method is applied to a set of earthquakes in the Japan subduction area which are properly located by regional arrays. The source parameters obtained by our method are compared to the ones obtained by regional (NIED and JMA) and global (GlobalCMT, ISC, USGS) seismological institutions.
We demonstrate that our source time function estimates improve significantly the correlation between the data and synthetics at high frequencies. This allows to get better travel time residuals by cross-correlation.

In addition, the lengths of the source time functions suggest a different scaling with seismic moment for deep and shallow events.

We also compare event depths and moment tensors.
This comparison reveals that our method gives hypocentral depths closer to those obtained with regional array than other teleseismic methods.

The high quality travel times obtained will be exploited to obtain more precise locations, and higher resolution tomographic models.

Influence of the viscosity contrast on the metal diapir breakup in primitive magma oceans

MICHAEL LE BARS[1], JULIEN MONTEUX[2] & ORIANE AUBERT[1]

[1]IRPHE, CNRS & Aix-Marseille University, Marseille, France
(lebars@irphe.univ-mrs.fr & aubert@irphe.univ-mrs.fr)
[2]Université de Nantes, Laboratoire de Planétologie et de Géodynamique, Nantes, France
(julien.monteux@univ-nantes.fr)

The latest stages of planetary accretion probably involve giant impacts of differentiated bodies and the occurrence of large scale melting events. A subsequent metal/silicate separation can occur via negative diapirism and contributes to core formation. In this context, it is of fundamental importance to understand the sinking dynamics of iron diapirs and their potential emulsification during their sinking towards the bottom of an early magma ocean. A global description of the involved processes would help to put realistic constraints on metal–silicate equilibration processes (e.g. [1]) and on the initial heat distribution within the young planet (e.g. [2]).

The persistence of large iron diapirs down to the bottom of a silicate magma ocean is still debated. While most models presume that all sinking diapirs would rapidly break up into centimeter-sized droplets (e.g. [3]), this scenario was recently questioned by analytical [4] and experimental study [5]. The purpose of our present work is to participate in the debate in focusing on the influence of the viscosity contrast between the silicate magma ocean and the iron diapir, which was up to now neglected for simplification. It is indeed expected that this viscosity contrast should not affect the sinking dynamics significantly. On the contrary, by combining results from published theoretical, experimental and numerical studies on bubble dynamics with our own ongoing investigations, we will show that a low diapir viscosity relative to the surrounding magma ocean influences the time evolution of its shape and sinking velocity, increases the typical time before break up into small droplets and enlarges the equilibrium size of the resulting iron droplets.

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Sampling upper mantle seismic discontinuities with PP and SS precursors – Sensitivity for effects of temperature, mantle composition and reaction kinetics

STEPHAN LESSING[1], DAVID DOBSON[2], SEBASTIAN ROST[3], CHRISTINE THOMAS[4]

[1] Institute of Geophysics, University of Münster, Münster, Germany,
(email: stephan.lessing@uni-muenster.de)
[2] Department of Earth Sciences, University College London, London, United Kingdom,
(email: d.dobson@ucl.ac.uk)
[3] School of Earth and Environment, Institute of Geophysics and Tectonics, University of Leeds, Leeds, UK,
(email: s.rost@leeds.ac.uk)
[4] Institute of Geophysics, University of Münster, Münster, Germany,
(email: tine@earth.uni-muenster.de)

The seismic discontinuities in the Earth's mantle transition zone at 410 and 660 km depth are mainly attributed to the solid-solid phase transitions of olivine. High-pressure mineral physics experiments and ab-initio thermodynamical calculations show that the olivine phase transitions interact with the pyroxene-garnet system, thus influencing the pressure and pressure interval of the phase transitions. Furthermore, phase transitions of the pyroxene-garnet system give rise to additional seismic discontinuities, as recently shown supported by several seismic studies. Despite improvements in seismic imaging and mineral-physical modeling of the upper mantle discontinuities, discrepancies between seismological and mineral-physical results prevent a detailed understanding of these structures.

Recently, studies of the kinetics of the mantle transition zone phase transitions/reactions in a subduction zone environment yielded insights to the density structure and rheology of the subducting slab [1], [2]. Nonetheless, the effect of kinetics on the seismic structure has not been studied in detail so far. Studying the kinetics of phase transitions and reactions in a hotspot environment as well as their influence on its seismic structure would add further constraints on mantle dynamics.

In this study, we want to investigate whether and to what extent the effects of varying temperature and mantle composition, as well as the effects of reaction kinetics can be resolved with PP and SS precursors. PP or SS precursors are underside reflections of P- or S-waves off the discontinuities, halfway between the source and the receivers. We calculate equilibrium phase assemblages for a pressure-temperature grid for three bulk compositions (pyrolite, harzburgite, MORB), using the Perple_X program package [3]. We use isentropic geotherms [4] to extract depth profiles of density, P wave and S wave velocity. We also investigate the influence of mantle composition (Al, Ca and Fe content) on the elastic properties separately. Furthermore, we use phase assemblages from kinetic experiments of the reaction of ringwoodite to perovskite and magnesiowuestite and combine them with equilibrium solutions for the used bulk composition. From the profiles of density, P wave and S wave velocity, we calculate 1D reflectivity synthetic seismograms for a range of dominant frequencies. We analyse the frequency dependence of the amplitudes and constrain the sharpness of the discontinuities.

Comparing the results from calculations for different scenarios will allow us to constrain how seismic underside reflections sample the upper mantle discontinuities and will give constraints on the sensitivity of the seismic probes to the discontinuities' fine structure.

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Joint inversion of free air gravity, geoid and topography data sets to obtain lithospheric density structure

SEYED-HANI MOTAVALLI-ANBARAN[1,2], HERMANN ZEYEN [3] & VAHID EBRAHIMZADEH-ARDESTANI[4]

[1] UMR8148 IDES, University Paris Sud, 91405 Orsay Cedex, France
(seyed-hani.motavallianbaran@u-psud.fr)
[2] Institute of Geophysics, University of Tehran, Tehran, Iran
(motavalli@ut.ac.ir)
[3] UMR8148 IDES, University Paris Sud, 91405 Orsay Cedex, France
(hermann.Zeyen@u-psud.fr)
[4] Institute of Geophysics, University of Tehran, Tehran, Iran
(ebrahimz@ut.ac.ir)

We present a 3D algorithm to obtain the density structure of the lithosphere from joint inversion of free air gravity, geoid and topography data sets. Potential field data are sensitive to the lateral density variations which happen across Moho and Lithosphere-Asthenosphere Boundary (LAB). The algorithm delivers the crustal and lithospheric thicknesses and the average crustal density. Stabilization of the inversion process may be obtained through parameter damping and smoothing as well as through the use of a priori information like crustal thicknesses from seismic profiles or density information.

The algorithm is applied to synthetic models in order to demonstrate its possibilities. A real data application is presented for the area of northern Iran, the South Caspian Basin and adjacent areas. We use potential field data which are globally available by satellite measurement and free accessible on the internet.The resulting model shows an important crustal root (up to 55 km) under the Alborz Mountains and a thin crust (ca. 30 km) under the southernmost South Caspian Basin, thickening northwards until the Apsheron-Balkan Sill to 45 km. Central and NW Iran is underlain by a thin lithosphere (ca. 90-100 km). The lithosphere thickens under the South Caspian Basin until the Apsheron-Balkan Sill where it reaches more than 240 km. Under the stable Turan platform, we find a lithospheric thickness of 160-180 km.

Mid-mantle anisotropy in regions of subduction

ANDY NOWACKI[1], J.-MICHAEL KENDALL[1] & JAMES WOOKEY[1]

[1] School of Earth Sciences, University of Bristol, Bristol, UK
(andy.nowacki@bristol.ac.uk)

The boundary layers of the Earth's mantle are where seismic anisotropy is concentrated, a phenomenon believed to be caused by the enhanced deformation present in these regions. This deformation may in turn may lead to texture development in the mineral phases present there, or to the alignment of seismically-distinct material such as melt. Whilst anisotropy is well studied and documented in the lithosphere and in D''—the lowermost mantle—it is much less well established to what degree the 600 km discontinuity might act as a boundary to mass exchange. If it does so, this has important implications for how mantle convection occurs and the nature of mass exchange between the upper and lower mantle. The presence of seismic anisotropy in this part of the Earth is thus a strong indicator of strain-induced fabric in the mantle material at this boundary. In this work we present the results of a systematic search of mid-mantle anisotropy using deep subduction zone earthquakes.

The use of source-side anisotropy as a technique for investigating near-source processes has only relatively recently become possible. Vitally, one must account for anisotropy in the upper mantle beneath the recording stations. We use stations in North America and Ethiopia where many SKS splitting measurements have been made, and where little variation of splitting parameters is apparent with source backazimuth; this suggests a simple, homogeneous form of upper mantle anisotropy. The source-side splitting measurements rely both on very well-characterised upper mantle anisotropy beneath the receiver, and on using only the highest quality observations beneath the source. Additionally, we militate against the chance of unintentionally incorporating the effects of free-surface reflection phases by using only measurements where the estimate of source-side S wave initial polarisation matches that predicted by the event's Global CMT solution.

We consider all events from 1979 to the present with magnitude greater than 5.7, and with depth $>$200 km. This gives $\sim$1000 splitting measurements. The splitting delay times in general show little variation with depth. This rules out metastable olivine or a high-pressure, low-temperature pyroxene–ilmenite phase transition within the slab as potential causes of the anisotropy. The amount of splitting varies from very little ($<$0.5 s) in some subduction zones, to very large elsewhere ($>$3 s). In the absence of detailed modelling, it is hard to distinguish the cases of transverse isotropy in the uppermost lower mantle and variable subduction-related supraslab anisotropy. Notably however, ringwoodite is essentially isotropic and is the major phase at the base of the transition zone, suggesting that the anisotropy may be concentrated in the region beneath the 660 km discontinuity.

MANTLE AND CRUSTAL DEFORMATION BENEATH THE AEGEAN REGION

GULTEN POLAT[1] and NURCAN MERAL OZEL[2]

[1]Geophysics Section, Dublin Institute for Advanced Studies-Dublin/Ireland.
gulten@cp.dias.ie
[2]Department of Geophysics, Kandilli Observatory and Earthquake Research Institute Bogaziçi University, Istanbul - Turkey
ozeln@boun.edu.tr

The geometry and amount of seismic anisotropy is generally estimated by using shear wave splitting. In this study, we have measured the source –side shear wave splitting parameters of local and teleseismic S waves which are determined from intermediate and shallow earthquakes occurred in the Aegean region. In addition to source-side anisotropy, receiver-side anisotropy is also measured from teleseismic SKS and SKKS waves. Constrains on the orientation and depth distribution of the anisotropy particularly both below and above the subducted slab in the region area are constructed by using both receiver side and source side anisotropy. We have found that a pattern of S-wave fast polarization directions are parallel to the direction of maximum crustal extension strain in the crust of the Aegean region. Also, we observe that the polarization anisotropy is predominantly located below the subducting slab. This is likely related to the LPO (Lattice Preferred Orientation) induced anisotropy is a product of asthenospheric flow or deformation within the down-going slab. The observed coherence in the direction of crustal extension and the direction of asthenospheric flow that might extend to depths of more 100 km. Additionally, the measured anisotropy provides evidence to explain the direction the retreat or rollback of the subducting African Lithosphere along the Hellenic Arc because asthenospheric flow patterns in the vicinity of the slab probably reflect an abrupt change in fast polarization directions.

Evidence for the Stability of the 660 km Mantle Transition Zone Phase Change from Central Europe

Yong Ren[1], Gregory Houseman[2] & Graham Stuart[3]

[1] School of Earth and Environment, Institute of Geophysics and Tectonics, University of Leeds, Leeds, UK (Y.Ren@leeds.ac.uk)
[2] School of Earth and Environment, Institute of Geophysics and Tectonics, University of Leeds, Leeds, UK (G.A.Houseman@leeds.ac.uk)
[3] School of Earth and Environment, Institute of Geophysics and Tectonics, University of Leeds, Leeds, UK (G.W.Stuart@leeds.ac.uk)

New images from a regional seismic tomography experiment in Central Europe (the South Carpathian Project) confirm an extensive region of relatively fast seismic wave-speeds in the mantle transition zone (MTZ) beneath the Pannonian Basin. This fast anomaly has been variously attributed to Tethyan subduction related to the closure of the Vardar Ocean, Alpine-style continental collision, or Carpathian subduction / gravitational instability of the mantle lithosphere related to extension of the Pannonian Basin. Whatever the cause, a massive overturn of the upper mantle has occurred in this region, resulting in relatively slow velocities in the upper 250 km and relatively fast velocities between 410 and 660 km. Receiver function studies of the upper mantle discontinuities moreover suggest a depression of the 660 km discontinuity consistent with the load created by a relatively dense mass directly beneath the Pannonian Basin. It seems likely that (a) these anomalies are at least partly associated with lithospheric extension of the Pannonian Basin and convergence of the Carpathians in the period 17-11 Ma, and (b) the process continues today with active mantle downwelling beneath the Vrancea region of the South-east Carpathians. The massive transition zone fast anomaly appears to have spread outward beneath the centre of the Pannonian Basin, creating a strong contrast with the surrounding slower MTZ beneath the Bohemian Massif, the West Carpathians and the Moesian Block. These peripheral contact zones in the MTZ are potentially sites where volatiles are evolved which, moving upward to asthenospheric depths, generate magmas. These new tomographic models have important consequences for the evolution of the European continental lithosphere, but also have significant implications for the processes which connect upper and lower mantle convection domains. In contrast to the Hellenic subduction zone further south, where subducted material is thought to flow continuously into the lower mantle, this large volume of relatively fast material occupying the Pannonian transition zone demonstrates that upper and lower mantle convection circulations beneath Central Europe are only weakly interacting. The negative Clapeyron slope of the spinel to perovskite phase transition clearly should inhibit flow across this boundary. The contrast between Hellenic and Pannonian mantle transition zones therefore suggests that the establishment of a downward flow across the 660 km discontinuity is a process that requires firstly that a considerable unstable mass is accumulated above the 660 km boundary and that it persists during the slow growth of an avalanche-type instability in the more viscous lower mantle layer beneath.

Investigation of upper mantle seismic discontinuities beneath the Canary Islands and Azores

Morvarid Saki [1], Christine Thomas [1], Stuart Nippress [2]

[1] Institute of Geophysics, University of Muenster, Germany

[2] School of Environmental Science, University of Liverpool, UK

The upper mantle seismic discontinuities provide important constraints on models of mantle composition and dynamic. Due to the opposite sign of the Clapeyron slope of the phase changes of Olivine to Spinel and Spinel to Pervoskite located at these two discontinuities, we would expect to have a thinner transition zone comparing with the normal state in case of intersecting by a mantle plume. It is however, also possible that the base of the transition zone in upwellings is dominated by the Majorite-Pervoskite transition which would lead to a deeper discontinuity depth. Underside reflections of PP and SS seismic waves from these discontinuities arrive as precursors to the PP and SS phases. Their travel time is indicative of the depths of the reflectors. Dense coverage in both oceanic and continental regions, allow us to obtain the variations of the depth to the reflectors. In this study we map the topography of the transition zone discontinuities beneath Canary Islands and Azores using seismic events from South America recorded in the Kyrgyz and GHENGIS seismic network in Kyrgyzstan. Such source-receiver combinations provid bouncepoints of the underside reflected PP and SS waves and their precursors along a profile between Western Sahara and Greenland. We analyzed over 1000 records from events with M_w >6. Array seismology methods e.g. vespagrams, slowness-backazimuth were applied to stack the signal seismic traces and enhance their signal-to-noise ratio. The stacks show several transition zone discontinuities at 410, 520 and 660 km and we measure the differential travel times between the precursors and the PP and SS arrivals in each event. Our preliminary results indicate that there is a depression of the 410 km discontinuity beneath the Canaries which is in agreement with the expected depth of the olivine phase boundary in an upwelling warm mantle. A first evaluation of the 660 km reflections seems to suggest an average depth around 660 km. Furthermore beneath North Atlantic Ocean, we observe a thickening of the transition zone near Greenland.

Tomography of the lowermost mantle from core-diffracted body waves

LEWIS SCHARDONG[1,6], RAPHAËL F. GARCIA[2,6], SÉBASTIEN CHEVROT[3,6], NOBUAKI FUJI[4,6,7] & MARIE CALVET[5,6]

[1] Université de Toulouse; UPS-OMP; IRAP; Toulouse, France (lewis.schardong@irap.omp.eu)
[2] Université de Toulouse; UPS-OMP; IRAP; Toulouse, France (raphael.garcia@irap.omp.eu)
[3] Université de Toulouse; UPS-OMP; IRAP; Toulouse, France (sebastien.chevrot@irap.omp.eu)
[4] Université de Toulouse; UPS-OMP; IRAP; Toulouse, France (nobuaki.fuji@irap.omp.eu)
[5] Université de Toulouse; UPS-OMP; IRAP; Toulouse, France (marie.calvet@irap.omp.eu)
[6] CNRS; IRAP; 14, avenue Édouard Belin, F-31400 Toulouse, France
[6] now at Institut de Physique du Globe de Paris, Saint Maur, France

The *D”* layer plays a key role in the global dynamics of the Earth, as a thermal and chemical boundary layer. Thus, constraining in detail its structure is an important objective of seismic tomography.

For this purpose, we have constructed a global data set of travel time and amplitude perturbations of many seismic phases, measured in various frequency ranges. The method consists in cross-correlating observed with synthetic seismograms, computed with the GEMINI method. In order to compute synthetic seismograms as accurately as possible, we convolve GEMINI synthetic seismograms with high frequency source time functions, determined by waveform inversion of globally distributed body wave records.

We present some results of the analysis of travel time residuals of diffracted waves (P_{diff} and S_{diff}), which possess a strong sensitivity to *D”* layer heterogeneities, and are thus crucial to decipher the fine structures within this layer. A high resolution tomography of the lowermost mantle, including both *P* and P_{diff} phases, and following the ray theory, will be presented, along with sensitivity kernels computed with new techniques, in prelude to the final high resolution finite frequency tomography.

Seismic Imaging of the Oceanic Lithosphere-Asthenosphere Boundary

NICHOLAS SCHMERR[1], CATHERINE RYCHERT[2], NICHOLAS HARMON[2]

[1]NASA Goddard Space Flight Center, Code 698 Greenbelt, MD 20771 USA nicholas.c.schmerr@nasa.gov
[2]University of Southampton, European Way, Southampton, Hants, SO14 3ZH UK c.rychert@soton.ac.uk, N.Harmon@noc.soton.ac.uk

The lithosphere-asthenosphere boundary (LAB) separating the rigid lid from the underlying weaker, convecting asthenosphere is a fundamental interface in mantle dynamics and plate tectonics. However, neither the depth nor the defining mechanism producing the LAB is globally understood. Oceanic plates are ideal for testing hypotheses regarding the nature of a plate since they make up 70% of Earth's surface area and have a relatively simple geological history. However, seismically imaging the oceanic LAB at high resolution is challenging. Recent receiver function imaging using buried borehole seismometers and stations located on land surrounding the edges of the ocean plates has expanded coverage. The SS waveform has also been used to image discontinuity structure as shallow as the LAB across the oceanic plate where station coverage is sparse. These results in combination with multiple bounce S-waves, ScS reverberations, and surface waves have now imaged discontinuity structure beneath much of the Pacific. We summarize recent seismic results from these various seismic phases and interpretations of the oceanic LAB. Overall, there is much agreement in the depth of the LAB where it is reported. Many of the discrepancies are explained by the sensitivity and different seismic wavelengths that sample structure. However, a simple thermally driven age-depth relationship of the LAB is not clearly identified, nor is a single defining mechanism for the boundary. Discrepancies between different techniques in the presence vs. the absence of the boundary provide an essential clue. Here we show that anisotropy plays an important role in locating and defining the oceanic LAB seismic discontinuity. Using SS precursors, we identify an azimuthally dependent, sharp LAB discontinuity beneath two oceanic regions, including the Hawaiian hotspot and well-sampled central Pacific corridor. In particular, a sharp seismic discontinuity appears when SS azimuths are perpendicular to absolute plate motion (APM) and fossil spreading directions. We propose alignment of mantle minerals in the APM direction and overlying fossil anisotropy acquired at the mid-ocean ridge produce a strongly anisotropic lithospheric lid that discontinuously overlies weaker anisotropy in the asthenosphere. Seismic phases sampling perpendicular to these alignments will image a sharp negative seismic discontinuity, while other azimuths only detect a weak or no discontinuity. This anisotropy may be enhanced by the presence of aligned melt at the top of the asthenosphere underneath hotspots.

Study of the western edge of African Large Low Shear Velocity Province

DAOYUAN SUN[1] AND MEGHAN S. MILLER[2]

[1]Department of Earth Sciences, University of Southern California, daoyuans@usc.edu
[2]Department of Earth Sciences, University of Southern California, msmiller@usc.edu

It is well established that there is a large low shear velocity province (LLSVP) in the lowermost mantle beneath Africa, extending from beneath the southeastern Atlantic Ocean to the southwestern Indian Ocean. From seismic tomography and many studies, it has been estimated that the African LLSVP has dimensions of ~7000 km by ~1000 km and it extends 1200 km up into the lower mantle from the core-mantle boundary [1-3]. Various studies have suggested that African LLSVP has sharp vertical boundaries [4-6]. The detailed 3D geometry of the LLSVP is crucial to understand how LLSVP developed and evolved. Previously, most studies have concentrated on mapping the southern and eastern edges of African LLSVP. Here, we use data from recently deployed PICASSO array in Morocco and Spain to study its western edge. Travel time and waveform modeling of S and SKS phases suggest the existence of two distinct patches of low velocity anomalies in the lowermost mantle beneath the eastern Atlantic Ocean, which agree with global tomography models. However, the S-SKS differential time changes up to 6 sec azimuthally. To match this large travel time variation we observe, existence of a sharp lateral boundary for the southern patch is required. For westernmost stations in the PICASSO array, SKS samples the northern patch and exihibit delays up to 8 sec. If we assume uniform -3% lower S-velocity inside the LLSVP, the height of this anomaly is 1200 km, which is comparable to those observed for southern and eastern part of African LLSVP. These observed features provide information about how far African LLSVP can extend to north and further argue its thermo-chemical origin. The detailed volume information also gives better constraints for the thermo-chemical convection modeling.

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Thermochemical state of the mantle transition zone beneath East Africa

DAVID THOMPSON[1,*], JAMES HAMMOND[2], J-MICHAEL KENDALL[3], GRAHAM STUART[1], GEORGE HELFFRICH[3], DEREK KEIR[4], IAN BASTOW[3], ATALAY AYELE[5] & CINDY EBINGER[6]
(*eardth@leeds.ac.uk)

[1] School of Earth and Environment, Institute of Geophysics and Tectonics, University of Leeds, Leeds, UK
[2] Department of Earth Science and Engineering, Imperial College London, London, UK
[3] School of Earth Sciences, University of Bristol, Bristol, UK
[4] National Oceanography Centre, University of Southampton, Southampton, UK
[5] Institute of Geophysics, Space Science and Astronomy, Addis Ababa University, Addis Ababa, Ethiopia
[6] Department of Earth And Environmental Sciences, University of Rochester, Rochester, NY, USA

The mantle transition zone (MTZ, roughly 410-660 km depth) beneath East Africa is a key region to our understanding of mantle convective processes, upper-lower mantle mass flux and, ultimately, continental rifting. How the African Superplume interacts with this region is still a matter of considerably debate, and the presence of either a broad zone of upwelling vs. a narrow plume-like feature remains unresolved. Here, we present new constraints on the MTZ beneath the region by integrating seismic data from the EAGLE, EKBSE, RLBM and Afar Rift Consortium experiments, along with new deployments in Eritrea and permanent stations across the horn of Africa. The combination of these networks provide us with unprecedented spatial coverage of the MTZ discontinuities across a suspected plume affected region. The relative positions of the 410 km and 660 km seismic discontinuities, along with their frequency-dependent amplitude characteristics, will give insights into the thermochemical state of the MTZ beneath East Africa. Comparison with complimentary seismic, geochemical and geodynamical studies will also provide an opportunity to link the results to the regions tectonic evolution. Interestingly, preliminary results from 1D and 3D migrations suggest that the MTZ is thinnest towards NE Afar/SW Arabia, where a recent study has claimed to resolve a tabular low-velocity feature interpreted as the continuation of the Afar plume into the lower mantle.

A Matlab toolbox for the analysis and modelling of seismic anisotropy in the deep interior

ANDREW M. WALKER[1] & JAMES WOOKEY[2]

[1] School of Earth Sciences, University of Bristol, Bristol, UK
(andrew.walker@bristol.ac.uk)
[2] School of Earth Sciences, University of Bristol, Bristol, UK
(j.wookey@bristol.ac.uk)

Probes of seismic anisotropy offer some of the most powerful methods to reveal the nature of convection in the uppermost and lowermost portions of the mantle. However, studies of seismic anisotropy rarely end with measurements of shear-wave splitting – additional modelling is needed to yield useful geophysical information. We describe a Matlab toolbox designed to aid the modelling needed for this interpretative step of the analysis of seismic anisotropy. Provision of key building blocks for modelling in this modern integrated development environment allows the rapid development and prototyping of explanations for measured anisotropy. The Matlab graphical environment also permits plotting of key anisotropic parameters. Furthermore, this work complements the SplitLab toolbox [1] used for measuring shear wave splitting and the MTEX toolbox [2] used for the analysis of textures in rocks.

MSAT (the Matlab Seismic Anisotropy Toolkit) version 1.0 includes a wide range of functions which can be used to rapidly build models of seismic anisotropy [3]. Available functions allow: the determination of phase velocities as a function of wave propagation direction, the analysis of multi-layer splitting, several effective medium approaches to the prediction of the anisotropy caused by aligned inclusions, layering or cracks, and the measurement of the degree of anisotropy exhibited by an elastic material. We include a database of elastic properties of rocks and minerals and functions to plot seismic anisotropy as a function of wave propagation direction in the form of pole figures or as three-dimensional plots. The toolkit includes extensive documentation and example applications which integrate with the Matlab documentation system alongside automated test cases for all functions. All code is open source and available freely to all [3]. We encourage users to feed back any changes they may need to make.

Some key examples of the use of this software include: (1) Calculation of the pattern of backazimuthal variation of shear wave splitting caused by the interaction a horizontal and dipping layer of partially-aligned olivine, for example, from SKS measurements behind a subduction zone. This shows that the orientation of the fast direction for the two layers is more important than the dip of the lower layer. (2) Analysis of the effect of the change in the elastic constants of clinopyroxenes with pressure as calculated using density functional theory. This shows that despite the overall anisotropy decreasing with increasing pressure, the measured shear wave splitting for particular wave propagation directions is expected to dramatically increase downwards through the upper mantle. (3) Calculation and simplification of the seismic anisotropy in D'' derived from polycrystalline modelling of texture development in the lowermost mantle. By combining MTEX with our toolbox we are able to take the output of visco-plastic self-consistent calculations, calculate the elastic anisotropy without imposing any particular symmetry, and estimate how well this can be explained as a layer exhibiting vertical transverse isotropy.

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[2] http://www.gm.univ-montp2.fr/splitting/
[3] http://www1.gly.bris.ac.uk/MSAT/

W isotopic constraints on ancient mantle mixing

Matthias Willbold[1], Tim Elliott[1], Stephen Moorbath[2] and Stephen Mojzsis[3,4]

[1]Bristol Isotope Group, School of Earth Sciences, University of Bristol, BS8 1RJ, UK
[2]Department of Earth Sciences, South Parks Road, Univeristy of Oxford, OX1 3AN, UK
[3]Laboratoire de Géologie de Lyon, Université Claude Bernard Lyon 1 & Ecole Normale Supérieure de Lyon, 69622 Villeurbanne, France
[4]Department of Geological Sciences, University of Colorado, Boulder, Colorado 80309-0399, USA

We have undertaken high precision (±5ppm) W isotope measurements on a suite of ca. 3.8 Ga samples from Isua, West Greenland [1]. These samples notably show $^{182}W/^{184}W$ isotope ratios ~15ppm higher than values for the modern silicate Earth and a 2 Ga crustal sample, suggesting that the $^{182}W/^{184}W$ of the silicate Earth has decreased by this small but significant amount between the time the ancient Isua source was isolated, and 2 Ga. Existing data on the coupled $^{147,146}Sm/^{143,142}Nd$ isotope systematics of Isua rocks require that they were derived from a source which formed before about 4.4 Ga [2]. Our W isotopic data may reflect the isotopic consequence of a Late Veneer wherein a late accretionary flux to the Earth resupplied the silicate Earth with highly siderophile ("iron-living") elements following segregation of the core. It is widely held that the siderophiles should have otherwise been sequestered during core formation. The Late Veneer hypothesis derives from the observation that mantle abundances of highly siderophile elements (HSEs) are higher relative to the vanishingly small values expected in the accessible silicate Earth from effective silicate-metal separation due to core formation. That HSE abundances are enhanced suggest that at least 0.5% by mass of the terrestrial mantle was contributed by a Late Veneer of primitive meteorite composition(s). The consequence of this flux for the W isotopic signature is a lowering of the $^{182}W/^{184}W$ by between 10-25ppm, depending on the impactor type. The consistency of the effects of the Late Veneer on HSE abundances and results from W isotopes lends support to this model. It is difficult to reconstruct the HSE contents of the past mantle, but W isotopic compositions of ancient rocks should provide a faithful record of mantle evolution. Thus we have a new tracer to monitor to mixing of chondritic material into the ancient mantle. An independent study has found an equally elevated $^{182}W/^{184}W$ in a mantle sample at 2.8 Ga but not at 3.5 Ga [3]. We interpret this observation as imperfect mixing of the mantle and preservation of some domains uninfluenced by the Late Veneer until 2.8 Ga. We are analysing more Archean samples to document better the record of homogensiation of Late Veneer material into the mantle and hence to provide constraints on the style of ancient mantle convection.

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S8: Mantle - Modelling & Dynamics

Invited Talk

Geophysics of Chemical Heterogeneity in the Mantle

LARS STIXRUDE[1]

[1] Department of Earth Sciences, University College London, London, UK
(stixrude@ucl.ac.uk)

Chemical heterogeneity, produced by the near-surface rock cycle and dominated volumetrically by subducted oceanic crust and its depleted residue, is continuously subducted into the mantle. This lithologic-scale chemical heterogeneity may survive in the mantle for as long as the age of Earth because chemical diffusion is inefficient. Estimates of rates of subduction and mantle processing over geologic history indicate that most or all of the mantle may be composed of lithologically heterogeneous material. Mineralogical models of the mantle show that chemical heterogeneity over many decades in length scale may be detectable by geophysical probes via its influence on seismic-wave propagation. Grain-scale heterogeneity influences the aggregate absolute seismic velocity and its lateral variation with temperature. The elastic-wave velocity contrast associated with lithologic-scale heterogeneity may be sufficient to produce observable scattering of short-period seismic waves.

Invited Talk

Generation of Plate Tectonics on Earth & Other Planets

DAVID BERCOVICI[1]

[1] Department of Geology and Geophysics, Yale University, New Haven, CT, USA
(david.bercovici@yale.edu)

The plate-tectonic mode of mantle convection on Earth is thought to provide the fundamental conditions for habitability, from stabilizing the carbon cycle and climate, to supplying energy for early chemosynthetic life, to cooling the core enough to power the dynamo. The emergence of plate tectonics versus stagnant-lid behavior, as on the other terrestrial planets of our solar system, relies on mechanisms for shear localization in the lithosphere. I first present a new theoretical model for lithospheric shear-localization through damage, grain evolution and Zener pinning in two-phase (polycrystalline) lithospheric rocks. Grain size evolves through the competition between coarsening (which drives grain-growth) and damage (which drives grain reduction). In a two-phase medium, however, the interface between phases induces Zener pinning, which impedes grain growth and facilitates damage. The size of the pinning surfaces is given by the roughness of the interface, and damage to the interface causes smaller pinning surfaces, which in turn drive the grain-size down eventually into the grain-size-dependent diffusion creep regime. This process allows damage and rheological weakening to co-exist, which is nominally precluded in single phase assemblages. Pinning also inhibits grain-growth and shear-zone healing, which is much faster in single phase materials. Hence, the resulting shear-localization is rapid (less than 1Myr), but the healing time for a dormant weak zone is very slow (greater than 100Myrs); these effects therefore permit rapidly forming and long-lived plate boundaries, in both simple shear and two-dimensional source-sink flows that generate plate-like toroidal motion. The essential damage model is then incorporated into numerical simulations of mantle convection, which are used to develop scaling laws for predicting conditions at which super-Earths would have plate tectonics. The resulting scaling law is based on the criterion that plate-like behavior occurs when damage reduces the viscosity of lithospheric shear zones to the asthenospheric viscosity. The theory is scaled to super-Earths in order to map out the transition between plate-like and stagnant-lid convection in a "planetary plate-tectonic phase" diagram in planet size-surface temperature space. Both size and surface conditions are found to be important, with plate tectonics being favored for larger, cooler planets. This gives a natural explanation for Earth, Venus, and Mars, and implies that plate tectonics on exoplanets should correlate with size, incident solar radiation, and atmospheric composition.

Invited Talk

Seismic Tomography and Mantle Convection – a window into the past

ROBERT MOUCHA[1]

[1]Department of Earth Sciences, Syracuse University, 204 Heory Geology Laboratories, Syracuse, NY, 13244, USA

Over the past few decades many significant advances have been made in understanding the Earth's internal structure and its role in shaping its surface. These advances have been spurred by developments in seismic body wave and surface wave tomography [e.g. 1-4] in conjunction with progress made in computational geodynamics [e.g. 5-9]. Subsequently, numerical models of mantle convection driven by buoyancy inferred from seismic tomography models have contributed significantly to our interpretations of the driving forces behind present-day tectonic plate motions, the non-hydrostatic structure of the planet's gravitational field, as well as the present-day surface deformation (i.e. dynamic topography) of the planet.

Recent efforts of using these present-day convection models to infer the past mantle structure and associated surface deformation has ushered in a new era, bringing us a step closer to a unified understanding of the Earth as a system [e.g. 10-13]. Using examples from southwestern US, the North American east coast and Africa, I will review backward-in-time mantle convection calculations that are based on a high-Rayleigh approximation to the time-dependent equation for conservation of (thermal) energy. In this approximation, the temperature variation due to thermal diffusion in upwelling and downwelling plumes is treated as negligible compared to the effect of heat transport by advection, where the latter is a reversible process. Consideration of modeling limitations and associated uncertainties will also be addressed.

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Modeling the thermal evolution of subcontinental mantle since Pangea dispersal

LEA BELLO[1], TOBIAS ROLF[2], NICOLAS COLTICE [1,3] & PAUL TACKLEY[2]

[1] Laboratoire de Géologie de Lyon Terre Planètes Environnement, Université de Lyon - Ecole Normale Supérieure - CNRS, Lyon, France (lea.bello@ens-lyon.fr)
[2] Institut fur Geophysik, Eidgenoessische Technische Hochschule Zurich, Zurich, Switzerland (tobias.rolf@erdw.ethz.ch) (ptackley@ethz.ch)
[3] Institut Universitaire de France, France (nicolas.coltice@univ-lyon1.fr)

The assembly and break-up of Pangea, the last supercontinent, is relatively well documented. Since its dispersal, which started approximately 190 My ago [6], numerous Large Igneous Provinces (LIPs) have appeared. Among them, the Central Atlantic Magmatic Province (CAMP) which is the largest one, formed at ∼200 Ma, the Karoo at ∼180 Ma, the Parana-Etendeka at ∼130 Ma, and the Deccan at ∼65 Ma [2]. For the first two, geological, geophysical and geochemical observations suggest that the large-scale melting associated with these provinces is not caused by mantle plumes, but could rather be a consequence of the continent distribution at the top of the convecting mantle. Besides the absence of a domal uplift and a hotspot track on the oceanic floor, the large area over which magma erupted for CAMP ($>10^6$ km^2), the elongated shape of the province, the Ti content and the Nd-Sr isotopic composition of CAMP basalts suggest shallow-mantle sources and do not bear a deep plume origin [1]. We propose here to study the origin of melting anomalies following the break-up of Pangea using dynamic simulations of mantle flow [3]. By imposing reconstructed plate motions, we simulate the dispersal of Pangea in a 3D spherical model of mantle convection that includes plate-like behavior and floating continents, which are simplified as strong Archaean cratons [5]. So far, convection models with forced surface velocities have not considered the effect of floating continents [7]. Our numerical experiment is mostly heated from within and the cratons differ from oceanic lithosphere in density and rheology. The prescribed distribution of continents and surface velocities are based on the tectonic reconstructions of the Earth [4]. The initial continental assembly correspond to the Pangean supercontinent before its dispersal and the kinematic history is imposed until the present day in 10 My intervals. Plate boundaries naturally emerged from the interactions between rheology and convective flow, mostly driven by the imposed velocities at the surface. We will present the numerical experimental set-up and preliminary results of simulations of Pangea dispersal, and discuss the limitations of the model and the choice of initial conditions.

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The Influence of Plate Motion History on Thermochemical Structures in Earth's Lower Mantle

ABIGAIL L. BULL[1] & TROND H. TORSVIK[2]

[1] Physics of Geological Processes, University of Oslo, NO-0316 Oslo, Norway (a.l.bull@fys.uio.no)

[2] Physics of Geological Processes, University of Oslo, NO-0316 Oslo, Norway (t.h.torsvik@geo.uio.no)

Understanding the first-order dynamical structure and temporal evolution of Earth's mantle is a fundamental goal in solid-earth geophysics. Recent tomographic observations reveal a lower mantle characterised by higher-than-average shear-wave speeds beneath Asia and encircling the Pacific, consistent with cold slabs of descending lithosphere beneath regions of ancient subduction, and lower-than-average shear-wave speeds in broad regional areas beneath Africa and the Central Pacific (LLSVPs). The LLSVPs, although not as easily understood from a dynamical perspective, are inferred to be broad upwelling centres between Mesozoic and Cenozoic subduction zones. Heterogeneous mantle models place these anomalies into the context of thermochemical piles, characterised by an anomalously dense (2-3% more dense) component, with their location and geometry being controlled by the movement of subducting slabs.

The origin and temporal evolution of the LLSVPs remain enigmatic. Recent numerical studies propose that the LLSVP beneath Africa formed as a result of return flow in the mantle due to circum-Pacific subduction beneath the Pangean supercontinent. In contrast, palaeomagnetic studies which show that 80% of Kimberlites from the last 540 million years erupted at locations on the present day margins of the LLSVPs, require the LLSVPs to have remained in their present positions for at least such a time period.

In this work, we investigate the temporal evolution and possible long-term persistence of LLSVPs by integrating plate tectonics into numerical models of mantle dynamics. In the numerical models of McNamara and Zhong (2005)[1] and Bull et al., (2009)[2], a dense component in the lower mantle was focused into LLSVP-like structures beneath Africa and the Pacific due to the imposed subduction history. In both cases the calculations were carried out for 119 million years of model time and employed surface velocity boundary conditions consistent with 11 stages of plate history. In this work, we improve upon these studies by employing a new global plate motion data set to impose surface velocity boundary conditions for 250 million years of plate motion history on numerical models of thermochemical convection in Earth's mantle. We aim to understand the role that Earth's plate motion history plays on the development of LLSVPs within Earth's mantle. Specifically, we investigate the effect of 250 million years of plate history on the degree-2 structure of the mantle and explore the possibility that both LLSVPs existed prior to the break-up of the Pangean supercontinent.

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Spontaneous initiation of one-sided subduction in complex rheology fluid

ERIKA DI GIUSEPPE[1], ANNE DAVAILLE [1], & ERIC MITTLESTAEDT[1]

[1] FAST Laboratory, UPMC Univ. Paris 06/ Univ. Paris-Sud/ CNRS, Orsay, FR
(digiuseppe@fast.u-psud.fr)

To understand the physics of plate tectonics remains difficult due to the large range of scales involved from the crystal to the lithospheric plate. In particular, the initiation of one-sided subduction is probably one of the least understood aspects of plate tectonics. To *allow* subduction, two major prerequisites seem to be the capability of geological material to localize stress and the related ability of the lithospheric plate to deform and bend to facilitate subduction. However, what is really needed to *trigger* subduction, and to sustain it in a self-consistent convective model remains poorly known, especially one-sided subduction away from continents.

Here we show that one-sided subduction also naturally occur in the laboratory during the drying-induced convection of thick layers of colloidal suspensions. This system is appealing since a) the interesting phenomena occur within the "human" dimensions of a fishtank, b) the rheology of the solutions can be measured accurately, and c) we can measure and study all the processes occurring from the colloidal particle-scale to the "plate" scale.

The rheology of these colloidal solutions depends on their solid particles fraction ϕ and their ionic contents. As water is removed, several behaviours are identified: newtonian at low ϕ, then viscoelastic shear thinning with increasing elastic modulus, to end with an elastic brittle solid at high ϕ. By analogy with the mantle, water content in our solutions is similar to temperature in the mantle. So thick layers of these suspensions were dryed from above. The evaporation of water from the upper surface generates a solutal boundary layer (SBL), with a strongly varying rheology from newtonian at its bottom to brittle at the surface. Humidity rate, ambient temperature, solution's thickness and concentration were systematically varied, resulting in the variation of the convection intensity and SBL structure. Due to the visco-elasticity of the concentrated suspensions, folds always appear on the surface, but the existence of a brittle film on the surface of the SBL seems necessary to observe asymmetric subduction.

Seismic anisotropy and *SKS* splitting in subduction zones predicted from 3-D mantle flow models

JEANETTE F. DI LEO[1], JAMES WOOKEY[1], ANDREW M. WALKER[1], J.-MICHAEL KENDALL[1], ZHONGHAI LI[2], NEIL M. RIBE[2], ANDRÉA TOMMASI[3]

[1]School of Earth Sciences, University of Bristol, Bristol, UK (jd7479@bristol.ac.uk)
[2]Laboratoire FAST, UPMC/Univ Paris-Sud/CNRS, Orsay, France (lzhhai@gmail.com)
[3]Geosciences Montpellier, CNRS & Université Montpellier 2, Montpellier, France (deia@gm.univ-montp2.fr)

Observations of shear wave splitting are often interpreted as being due to strain-induced crystal alignment of olivine in the convecting upper mantle. In these studies the polarisation of the fast shear wave is frequently taken to directly indicate the direction of mantle flow. However, caution must be exercised when making these inferences, as the relationship between lattice-preferred orientation (LPO) of olivine and fast splitting orientation is dependendent on a number of factors, including the entire history of defomation. This is especially the case in regions where complex mantle flow is expected, such as subduction zones, where the interpretation of trench-parallel fast directions as trench-parallel mantle flow remains a topic of controversy. Observations of shear wave splitting at subduction zones are highly varied, ranging from trench-perpendicular to trench-parallel or, as is most often the case, a combination of both [1]. A truly coherent pattern has not been identified to date.

Rigorously interpreting this variety of shear-wave splitting results requires modelling which properly accounts for the development of LPO in the near-slab mantle environment. To this end, we simulate olivine LPO development caused by the defomation of polycrystalline aggregates as they deform and move along streamlines extracted from a 3-D model of mantle flow model at a subduction zone. The flow model is based on 3-D boundary-element numerical simulations of a dense fluid sheet (representing the slab) with a thickness corresponding to ~85 km and a width of ~900 km sinking in an ambient mantle down to the a depth of ~660 km. This geometry approximates that of the Sangihe subduction zone in eastern Indonesia [1]. The model shows return flow around the edges of the slab and partial return flow around its leading edge as it descends. The effect of defomation and development of an LPO is simulated assuming the defomation of each olivine crystal is governed by the motion of dislocations. Interactions between crystals are descibed using the visco-plastic self-consistent (VPSC) approach [2, 3].

After calculating the elastic properties associated with the LPO at multiple depths, we estimate the resulting shear wave splitting parameters (fast direction, ϕ, and delay time, δt) for synthetic *SKS* phases. This enables us to predict behaviour such as backazimuthal dependence of splitting. We then compare these splitting measurements with observations of shear wave splitting in real subduction zones, such as the Sangihe subduction zone. Our model shows that complex behaviour in fast direction appears in even an apparently simple model of mantle flow in a subduction zone, and that making robust dynamic inferences requires proper consideration of the geometry of subduction.

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Coupling the evolution of plate tectonics and magnetic fields

Peter Driscoll [1], Dave Bercovici [1], & Brad Foley[1]

[1] Department of Geology and Geophysics, Yale University, New Haven, CT, USA
(peter.driscoll@yale.edu)

We explore the influence of plate tectonics on the cooling history of the deep interior, with a focus on the two end member cases of Earth and Venus. In particular we make use of the influence of atmospheric ground temperature on lithospheric damage. It has been demonstrated in numerical models using grain-damage that high surface temperature can suppress shear localization and subduction by promoting rapid grain grown (i.e. healing). We develop scaling laws based on the results of numerical models and use them to compute whole planet thermal history models, giving magnetic dipole field intensity over time. Earth's mantle is cooled by heat conduction through thin oceanic plates at the surface fast enough to drive thermal and compositional convection in the core, and maintain a strong dipole field. Paleomagnetic evidence indicates that the geodynamo has been active for at least the past 3 Gyr, implying a sufficient cooling rate of both the mantle and core over this time. However, thicker plates and slower cooling rates could result in sub-adiabatic core heat flow and decay of the dynamo, which may explain the current lack of plates and magnetic field at Venus.

Layering Processes in the Early Earth's Mantle - Consequences for Thermal History and Reservoir Formation

Sabine Dude[1] & Ulrich Hansen [1]

[1] Institut für Geophysik, University of Münster, Münster, Germany
(sabine.dude@uni-muenster.de)

The dynamical evolution of the Earth and other planets, their chemical differentiation and reactions of their interior with the atmosphere is largely determined by convective processes within the Earth's mantle. Convection does not always tend to homogenize the interior. It can rather establish structures such as layers which can stay intact for geological significant time. We will demonstrate that distinct convective layers can form as self-organized structures from an initially non-layered state, without pre-existing density jumps, once the effects of thermal and compositional contributions to the density are taken into account (double-diffusive convection). We carried out a series of two dimensional numerical experiments, ranging from a constant viscosity fluid to a strongly temperature and stress dependent viscosity fluid, to first study the process of layer formation and the finally evolving structures. A stable compositional gradient, due to magma ocean differentiation, heated from below and cooled from above resembles one reasonable scenario for the Earth's mantle after core formation. In this configuration a layered mantle emerges with the individual layers displaying different stabilities (see Fig. 1). The intermittent breakdown of individual layers leads to a strong episodicity in the thermal and chemical evolution of the system.

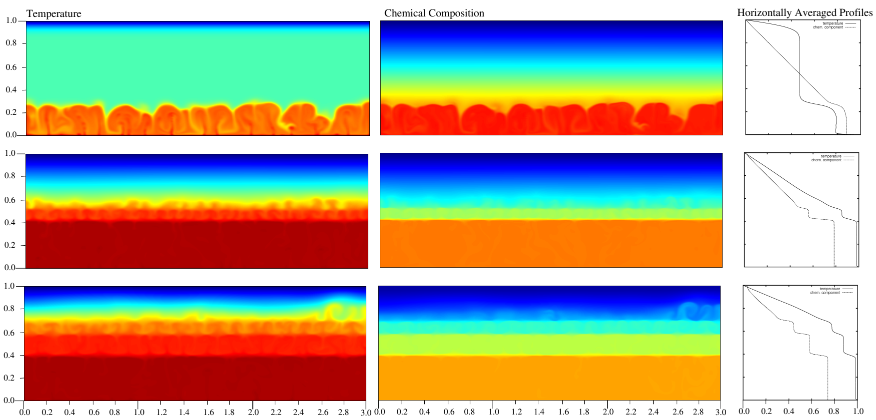

Fig. 1: Evolution of layered structures. Temperature (left), composition (middle) and the associated horizontally averaged profiles (right) for a thermoviscous double-diffusive system with $Ra = 10^5, Ra_C = 2 \cdot 10^5, Le = 100, \eta_{\Delta T} = 10^5$.

Since the Earth's mantle exhibit different phase changes we improved the previous model by the influence of an endothermic phase change. The first results show that the fundamental process is preserved but the stability of layers is strongly influenced by the presents of a phase change. At this point the results indicate that distinct layers in planetary mantles are formed by a dynamical fractionation and are thus likely to appear as a generic feature in the process of planet formation.

Multiple mantle upwellings through the transition zone beneath the Afar Depression.

JAMES O. S. HAMMOND[1], J-MICHAEL. KENDALL[2], GRAHAM W. STUART[3], DAVID A. THOMPSON[3], JAMES WOOKEY[2], CATHERINE A. RYCHERT[4], CYNTHIA J. EBINGER[5], IAN D. BASTOW[2], DEREK. KEIR[4], ATALAY AYELE[6], BERHE GOITOM[7], GHEBREBRHAN OGUBAZGHI[7]

[1]Department of Earth Science and Engineering, Imperial College London, London, UK
j.hammond@imperial.ac.uk
[2]Department of Earth Science, University of Bristol, Bristol, UK
[3]School of Earth and Environment, University of Leeds, Leeds, UK
[4]National Oceanography Centre Southampton, University of Southampton, Southampton, UK
[5]Department of Earth and Environment, University of Rochester, Rochester, US
[6]Institute of Geophysics, Space Science and Astronomy, Addis Ababa University, Addis Ababa, Ethiopia
[7]Eritrea Institute of Technology, Asmara, Eritrea

Plume related volcanism in Ethiopia has long been cited to have instigated continental breakup in northeast Africa. However, to date seismic images of the mantle beneath the region have not produced conclusive evidence of a plume-like structure. As a result the nature and even existence of a plume in the region and its role in rift initiation and continental rupture are debated.

Previous seismic studies using regional deployments of sensors in East-Africa show that low seismic velocities underlie Africa, but their resolution is limited to the top 200-300km of the Earth. Thus, the connection between the low velocities in the uppermost mantle and those imaged in global studies in the lower mantle is unclear. We have combined new data from Afar, Ethiopia with 7 other regional experiments and global network stations across Kenya, Ethiopia, Eritrea, Djibouti and Yemen, to produce high-resolution models of upper mantle P- and S- wave velocities to the base of the transition zone.

Relative travel time tomographic inversions show that within the transition zone two focussed sharp-sided low velocity regions exist: one beneath the Western Ethiopian plateau outside the rift valley, and the other beneath the Afar depression. Estimates of transition zone thickness suggest that this is unlikely to be an artefact of mantle discontinuity topography as a transition zone of normal thickness underlies the majority of Afar. The only location that shows evidence of transition zone thinning, an indicator of increased temperature, is in northeast Afar/south-west Arabia, the location of some of the slowest seismic velocities. Seismic anisotropy studies show that flow in the mantle is dominated by the African superswell, and that little evidence exists of radial flow from a large plume.

The combination of seismic constraints suggests that small weak upwellings may rise from a broader low velocity plume-like feature in the lower mantle. This interpretation is supported by numerical and analogue experiments that suggest the 660km phase change and viscosity jump may impede flow from the lower to upper mantle creating a thermal boundary layer at the base of the transition zone. This allows smaller, secondary upwellings to initiate and rise to the surface.

Our images of secondary upwellings suggest that there is no evidence for a plume in the classical sense (i.e. a narrow conduit). Instead, we propose that secondary upwellings rise from the base of the transition zone and connect with the northwest flowing African superswell in the upper mantle.

Post-supercontinent formation: insulation effects on the mantle from numerical simulations featuring oceanic and continental plates

PHILIP J. HERON[1] & JULIAN P. LOWMAN[2,1]

[1] Department of Physics, University of Toronto, Toronto, Canada
(pjheron@physics.utoronto.ca)
[2] Department of Physical and Environmental Science, University of Toronto Scarborough, Toronto, Canada
(lowman@utsc.utoronto.ca)

Continental insulation during the Mesozoic may offer an explanation as to why the mantle below the African plate, a former site of continental aggregation, is hotter than normal. Numerical modelling studies have shown that the formation of a supercontinent over a mantle downwelling can initiate a reorganization of mantle convection planform, resulting in subcontinental upwellings. Despite continental and oceanic plates having significantly different thermal and mechanical properties, mantle convection models often omit the presence of distinct continental and oceanic regions, or omit the characteristics of oceanic plates altogether. As a result, the effect of interacting oceanic and continental plates and their influence on mantle convection is poorly understood. To isolate the dominant aspect of continental aggregation on mantle evolution, here we examine the evolution of mantle dynamics after supercontinent aggregation along a convergent plate boundary for a variety of mechanical and thermal boundary conditions.

Our models feature high Rayleigh numbers, stratified viscosities and oceanic plates (with time-dependent velocities that are dynamically determined using the total integrated shear stresses at the base of each plate (a force-balance method)). Continental insulation is modelled by varying thermal diffusivity throughout the plates (prescribing a continental region with lower conductivity than an oceanic region). In 3D calculations with supercontinental coverage of the mantle comparable to Pangea's, we find that subcontinental plumes develop as a consequence of subduction patterns rather than continental thermal insulation properties. Moreover, we find that despite the presence of an overlying supercontinent with insulating properties appropriate for modelling terrestrial dynamics, averaged subcontinental mantle temperatures do not significantly exceed sub-oceanic temperatures on timescales relevant to supercontinent assembly. The effect of one or more insulating plates in mantle convection models featuring evolving plate geometries is also discussed alongside the importance of temperature- and pressure-dependent viscosity laws on deep mantle plume development post-supercontinent formation.

Understanding the geodynamic setting of Sao Miguel, Azores: A peculiar bit of mantle in the Central Atlantic

HOULIÉ N[1], WILSON M[1], LITHGOW-BERTELLONI C[2] & KHAN, A.[3]

[1]School of Earth & Environment. University of Leeds, UK – ETH, Zurich
nhoulie@ethz.chb.m.wilson@leeds.ac.uk
[2]Earth Sciences, University College, London,UK
c.lithgow-bertelloni@ucl.ac.uk
[3]ETH Zurich Institut für Geophysik, ETH Zurich, Switzerland
amir.khan@erdw.ethz.ch

The Azores Plateau and Archipelago in the Central Atlantic Ocean has traditionally been considered as the surface expression of a deep mantle plume or hotspot that has interacted with a mid-ocean ridge. It is geodynamically associated with the triple junction between the North American, African and Eurasian plates. Yang et al. [1] used finite frequency seismic tomography to demonstrate the presence of a zone of low P-wave velocities (peak magnitude -1.5%) in the uppermost 200km of the mantle beneath the Plateau. The tomographic model is consistent with SW deflection of a mantle plume by regional upper mantle shear flow driven by absolute plate motions.

The volcanic island of Sao Miguel is located within the Terceira Rift, believed to represent the boundary between the African and Eurasian plates; magmatic activity has been characterised by abundant basaltic eruptions in the past 30,000 years. The basalts are distinctive within the spectrum of global ocean island basalts for their wide range in isotopic composition, particularly in $^{87}Sr/^{86}Sr$. Their Sr-Nd-Pb isotopic compositions [2] show systematic variations from west to east across the island which have been interpreted [2] in terms of melting of a 2-component mantle source. The low melting point (enriched) component in the source has been attributed to recycled ancient (>2 Ga) oceanic crust [2]. Using the thermo-barometry approach of Lee et al. [3] we demonstrate that the pressure and temperature of magma generation below Sao Miguel increase from west (2 GPa, 1425 °C) to east (3.8 GPa, 1575 °C), consistent with partial melting along a mantle geotherm with a potential temperature of ~ 1550 °C. This is consistent with the magnitude of the thermal anomaly beneath the Azores Plateau (ΔT ~ 150-200 °C) inferred on the basis of the seismic tomography study [1]. The site of primary magma generation extends from the base of the local lithosphere (~ 80 km) to ~ 115 km depth.

To understand the geodynamic setting of the Sao Miguel magmatism we combine GPS data [4],and mantle convection models [5] with our intrepretation of the geochemistry of the basalts. We demonstrate strong south-westerly and downward flow in the asthenospheric mantle above the Transition Zone (410 km seismic discontinuity), consistent with upper mantle shear. The maximum flow velocity is broadly consistent with the zone of magma generation. The advection of the mantle with respect to the oceanic plate "moves" an isotopically distinct mantle source component beneath the active volcanoes of Sao Miguel and carries its previous melting residues to the south-west. We discuss the nature of this mantle source and its contribution to the mantle velocity anomalies determined by seismic tomography [1]. This study opens-up new perspectives for seismic tomography and potentially new connections between the fields of geophysics and geochcmistry in oceanic domains.

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Structure-preserving modeling of seismic waves at the global scale

Xiaofan Li, Wenshuai Wang, Mingwen Lu, Shixu Chen, Meigen Zhang
Key Laboratory of the Earth's Deep Interior, CAS,
Institute of Geology and Geophysics, Chinese Academy of Sciences,
Beijing 100029, P.R. China
(Xflee@mail.iggcas.ac.cn)

Most of knowledge on the Earth's deep interior are obtained from seismic waves. High-precision modeling of seismic waves at the global scale is indispensible to studies of the Earth's deep interior, however, it involves long-time and high-precision calculation of seismic wave propagation. The above-mentioned question is one of difficult problems in the seismological research fields. For developing methods of seismic inversion and high-resolution seismic wave imaging, the above-mentioned problem has to be solved as perfect as possible. Moreover, for long-term computations of seismic wave (e.g., Earth's free oscillations modeling and global-scale seismic wave propagation modeling), the capability of seismic modeling methods for long-time simulations is in great demand.

Modeling seismic waves in the time domain using direct methods involves discretization of both space and time derivatives. In the past tens years, the traditional finite difference methods (nonsymplectic schemes) for temporal discretizations has been widely used. Because the classical finite difference methods for temporal discretizations are not structure-preserving schemes, it is extremely difficult to avoid accumulated errors in precise or long-time numerical simulations for partial differential equations using these methods. When solving differential equations numerically, some numerical algorithms can preserve the corresponding structures. This can be called the structure-preserving property of a numerical algorithm. The structure-preserving property of symplectic algorithms is well known. Theoretically, a numerical method for Hamiltonian dynamical systems can be called a symplectic algorithm if the resulting numerical solution is also a symplectic mapping.

In this paper, an alternative method for accurately and efficiently modeling seismic wavefields has been presented, which is based on a symplectic discrete singular convolution differentiator scheme (SDSCD). This approach uses optimization and truncation to form a localized operator. This preserves the fine structure of the wavefield in complex media and avoids non-causal interaction when parameter discontinuities are present in the medium. The approach presented has the structure-preserving property, which is suitable for treating questions of high-precision or long-time numerical simulations. Our numerical results indicate that this method can suppress numerical dispersion and allow for the research into long-time numerical simulations of wavefields. These numerical results also show that the SDSCD method can effectively capture the inner interface without any special treatment at the discontinuity. It can be expected that the structure-preserving approach presented will become one of powerful tools to study the Earth's deep interior.

Mantle dynamics and structure beneath the Western Mediterranean constrained by shear wave splitting and global flow models

MEGHAN S. MILLER[1], LISA A. ALPERT[2], THORSTEN W. BECKER[3], AND AMIR ALLAM[4]

[1]Department of Earth Sciences, University of Southern California, Los Angeles, CA, USA (msmiller@usc.edu)
[2] Department of Earth Sciences, University of Southern California, Los Angeles, CA, USA (lisaalpert4@gmail.com)
[3] Department of Earth Sciences, University of Southern California, Los Angeles, CA, USA (aallam@usc.edu)
[4] Department of Earth Sciences, University of Southern California, Los Angeles, CA, USA (twb@usc.edu)

Seismicity and previous seismic tomography in the western Mediterranean are insufficient to precisely resolve the density structure beneath the Alboran Sea reflected in the complex surface tectonics. Here, we use inferred seismic anisotropy in the mantle to test a range of suggested structures. We analyze shear-wave splitting delay times and fast polarization directions using SKS and S phases recorded by a temporary broadband array in Morocco and southern Spain. In co-located sites, our results substantiate published work, but new sites in Morocco show an approximately 90 degree rotation in apparent fast azimuth, and reduced delay-times, going across the Atlas. This shift occurs south of the spine of the High Atlas. We show that these observations are best reproduced by global mantle flow models that include a continuous, deeply extending, slab structure beneath the Alboran Sea, elongate along the Iberian margin from Granada to Gibraltar, where the slab curves southward toward the High Atlas. The models that include a detached slab beneath the Alboran, a slab with gaps, or drip-like features are generally inconsistent with the splitting measurements. Slab viscosities of ~250 times the upper mantle produce the best match by providing a balance between radial flow induced by cold downwellings and toroidal flow induced by stiff slabs. We suggest that the change in fast polarization direction might be also affected by the existence of a shallow lithosphere-asthenosphere boundary beneath the Atlas, as imaged by receiver functions and surface wave tomography, and mantle flow interacting with the cratonic root toward the south.

Numerical investigations of effects of spatial variations in physical properties on the mantle convection patterns

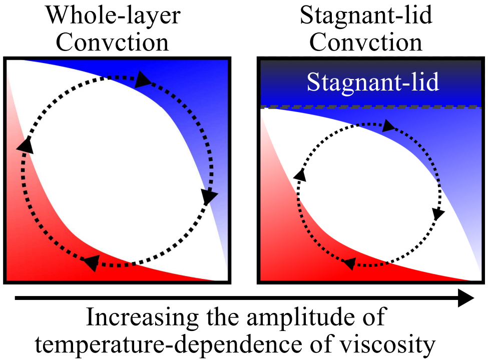
ARATA MIYAUCHI[1], MASANORI KAMEYAMA [2], HIROKI ICHIKAWA[3]

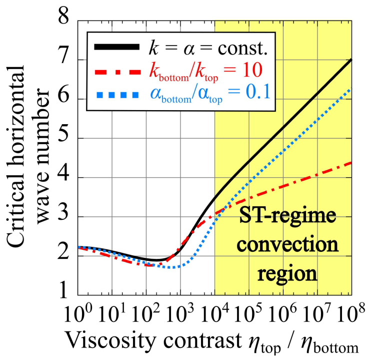
[1] Geodynamics Research Center, Ehime University, Ehime, JAPAN (miyauchi@sci.ehime-u.ac.jp)
[2] Geodynamics Research Center, Ehime University, Ehime, JAPAN (kameyama@sci.ehime-u.ac.jp)
[3] Geodynamics Research Center, Ehime University, Ehime, JAPAN (h-ichikawa@sci.ehime-u.ac.jp)

A series of numerical simulations is carried out on the onset of thermal convection of Boussinesq fluid of an infinite Prandtl number in a planar layer in the presence of spatial variation of physical properties such as viscosity, thermal conductivity and expansivity. The viscosity of the fluid is exponentially dependent on temperature, while thermal conductivity and expansivity are linearly dependent on pressure (or depth). Based on the linear stability analysis, velocity and temperature distributions are solved for infinitesimal perturbations for given horizontal wave number. We seek for the condition for the onset of convection by changing the horizontal wave number of perturbation as well as the amplitudes of spatial variations in physical properties (viscosity, thermal conductivity and thermal expansivity). Then, we examine influences on both the critical conditions and the dominant flow patterns of spatial variations in those physical properties. From the changes in flow patterns with increasing the amplitudes of temperature dependence of viscosity, we successfully identified the transition into the "stagnant lid" (ST) regime, where the convection occurs only beneath a thick and stagnant lid of cold fluid at the top surface (see below conceptual illustrations of two types of convection regimes). We also found that the transition takes place regardless of the spatial variations in thermal conductivity and/or expansivity.

However, detailed analysis of the numerical results showed a quantitative difference in the critical condition for the onset of ST convection due to the presence of spatial variations in thermal conductivity and expansivity. Especially we focused on the horizontal wave number of perturbation which is largely decreased by the introduction of spatial variations in these properties. In particular, the variation in thermal conductivity can significantly reduce the wave number: the horizontal length scale of convection can be enlarged by up to 50% when viscosity is strongly dependent on temperature (see below plots of critical wave number against the viscosity contrast across the layer). We further developed an analytical model of convection cells which consider the thickness of stagnant lid and convective vigor beneath it. The model successfully reproduced the mechanism of increasing horizontal length scale of ST regime convection cells for each conditions of spatial variations in physical properties. Same effects and mechanism induced by the spatial variation in physical properties are confirmed by the finite amplitude convection simulations.

The results of present studies indicate that, under certain conditions, the convection of fluids with strongly temperature-dependent viscosity takes place which is characterized simultaneously by (i) large horizontal length scales of convective cells and (ii) thick stiff lid of highly viscous fluid above it. This is in a stark contrast with earlier numerical studies using constant thermal conductivity and expansivity where the convection beneath stagnant lids is always associated with cells with small horizontal length scales. Our findings therefore highlight the essential roles of the spatial variation of the thermal conductivity and thermal expansivity on the convection patterns in the mantle of terrestrial planets.





The Influence of Rotation on the Settling of Metal Droplets in a Hadean Magma Ocean

ALEXANDRA MÖLLER[1] & ULRICH HANSEN[2]

[1] Institute of Geophysics, University of Münster, Münster, Germany (alexam@uni-muenster.de)
[2] Institute of Geophysics, University of Münster, Münster, Germany

During its evolution, the Earth most likely experienced a 'Giant Impact' in which a Mars size body hit the early planet. Today it seems widely accepted that the origin of the Moon is a result of this Giant Impact. Another consequence of such an impact would be the formation of a 'Deep Magma Ocean', i.e. a layer of molten material, extending to a depth of about $1000km$. In this vigorously convecting environment the separation of iron and silicate takes place. Small iron droplets of a size about $1cm$ can form and fall, due to their higher density through the molten silicate to the bottom of the magma ocean. This scenario is called the 'Metal Rain Scenario'. It is the first step in the core forming processes of the earth.

We employed a 3D Cartesian numerical model with finite Prandtl number, in order to study the sinking of heavy particles in a vigorously convecting environment. Differently from most approaches we have included the effect of rotation on the flow dynamics. Due to the low viscosity of the magma ocean and a much faster rotation of the earth at the time after the giant impact the influence of rotation on the fluid flow of the magma ocean can not be easily neglected. Our numerical fluid model is based on a Finite Volume discretization, while the numerical model for the iron droplets is based on a discrete element model for the simulation of granular Material. The particles influence the fluid flow through the chemical component of the fluid model, which is the volumetric ratio of the particle in each fluid cell. The particles themselves experience the force of the fluid through the fluids drag. Also gravitational and Coriolis forces act on the particles. In our simulations unlike to other approaches the particles are much smaller than the numerical fluid cells, thus saving computational effort.

In our present work we study the influence of strong rotation on the iron droplets with a rotation axes parallel to the gravitational acceleration like on the earth pole and with an rotation axes perpendicular to gravity like on the equator. Depending on the Rossby number of the system we find a different behavior of the particles.

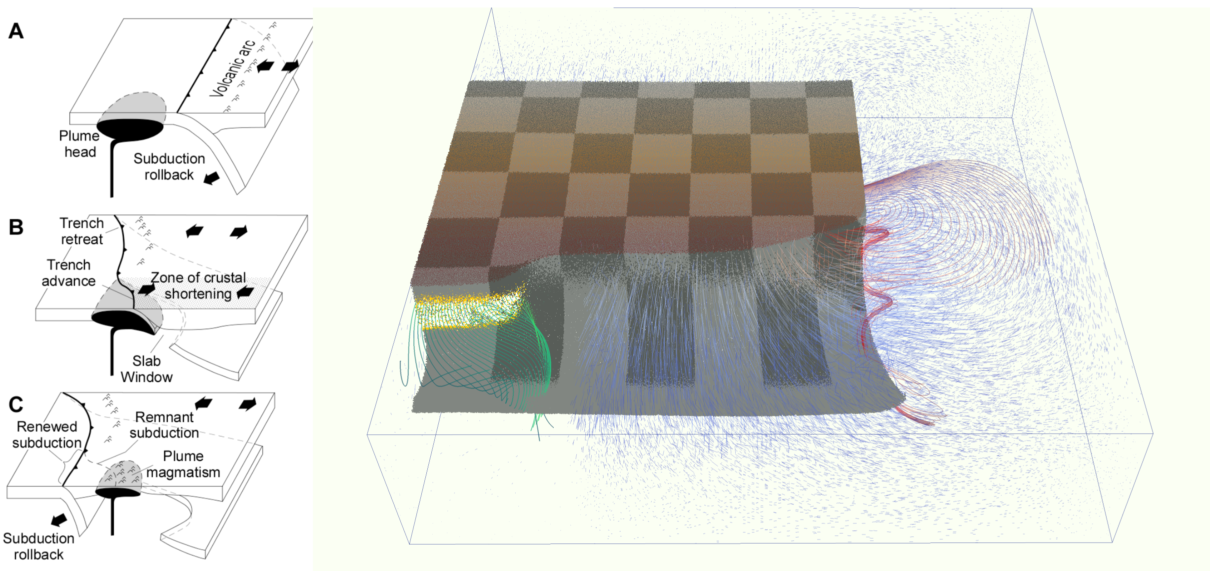
For the poles the particles fall nearly with Stokes' velocity to the bottom. Whereas for the equatorial case the particles can stay suspended depending on the strength of the Coriolis force acting against gravity. We find three regimes depending on the strength of rotation for the equatorial case. At low rotation rates the particles fall to the bottom like at the poles. At higher rotation rates the particles stay suspended in the bottom 1/3 of the box and have an insulating effect on the hot thermal boundary layer. This leads to a layering of the temperature field. At high rotation rates the particles are completely suspended in a ribbon in the middle of the box. In this case there is no layering of the temperature field observable.

If on of these scenario was true for the magma ocean on the earth it leads to an interesting setup for the following core formation processes. A parameter study can show at which fluid and particle parameters these three regimes do occur. This makes it possible to predict a possible scenario for the evolution of the iron settling in the magma ocean.

The Influence of a Mantle Plume Head on Subduction Zone Dynamics

Louis Moresi[1,2], Peter G. Betts[1], Wendy G. Mason[1]

[1]School of Geosciences, Monash University, Clayton VIC 3800, Australia; Email: louis.moresi@monash.edu
[2]School of Mathematical Sciences, Monash University, Clayton VIC 3800, Australia



The geological record and seismic tomography together contain multiple examples of mantle plumes and subducting oceanic slabs colliding, however consequences of these collisions and a mechanism for plumes to pass from the subducting to the overriding plate are uncertain. We present 3D numerical simulations of a retreating subduction zone encountering a mantle plume head. We assess the impact a plume head has on the geometry of the trench and whether it can create a window within the subducted slab. Our models explain slab/plume head collisions as a natural consequence of plume head entrainment by plate motion combined with slab retreat. Strong slabs prevent plume heads from reaching the surface. For weak slabs, strongly buoyant plume heads cause local trench advance, slab windowing and accelerated slab retreat at the margins of the plume head. For large plume heads, this trench advance may contribute to orogenesis. Opening a slab window creates a potential conduit for transfer of plume material from the subducting plate to the overriding plate without terminating an active magmatic arc away from the point where the plume head tears the slab (A-C in the figure are an interpretation of the numerical model which is shown on the right hand side).

Comparison of spherical shell and plane-layer mantle convection thermal structure in viscously stratified models: implications for the incorporation of temperature-dependent parameters

Keely O'Farrell[1], Julian Lowman[1,2], & Hans-Peter Bunge[3]

[1] Department of Physics, University of Toronto, Toronto, Canada
(ofarrell@physics.utoronto.ca)
[2] Department of Physical and Environmental Sciences, University of Toronto Scarborough, Toronto, Canada
(lowman@utsc.utoronto.ca)
[3] Department of Earth and Environmental Sciences, Ludwig-Maximilians University, Munich, Germany
(bunge@lmu.de)

Plane-layer geometry convection models remain a useful tool for investigating planetary mantle dynamics but yield significantly warmer geotherms than spherical shell systems. Uniform property plane-layer and spherical models have provided insight into the role of geometry on temperature in convecting systems but the inclusion of first-order terrestrial characteristics is needed to quantitatively assess the influence of system geometry on planetary scale simulation. Here, we analyze the mean temperatures of over 90 spherical shell and plane-layer convection models featuring a uniform upper mantle viscosity and a lower mantle that increases in viscosity by a factor of 30. With the imposition of the stratified viscosity an effective Rayleigh number is defined based on the average viscosity of the mantle, $Ra_{\overline{\eta}}$. We derive equations for the relationship between the mean temperature, θ, $Ra_{\overline{\eta}}$, and the nondimensional internal heating rate, H, for convection in a fixed spherical shell (with terrestrial mantle geometry) and plane-layer solution domains. These equations predict the mean temperatures in the corresponding systems to an accuracy of a few percent or better. Our equations can be combined to derive the appropriate heating rate for a plane-layer convection model to emulate spherical shell convection mean temperatures for effective Rayleigh numbers comparable to the Earth's value and greater. When comparing cases with the same internal heating rate and effective Rayleigh number, we find that the increased lower mantle viscosity amplifies the mismatch in mean temperatures between spherical shell and plane-layer geometry models. These findings have important implications for studying convection with temperature-dependent parameters in plane-layer systems and may be particularly relevant to the study of convection in super-Earths where full spherical shell calculations remain intractable.

Anisotropy in the Lesser Antilles Arc Subduction Zone

DAVID SCHLAPHORST[1], MICHAEL KENDALL[2]

[1]School of Earth Sciences, University of Bristol, Bristol, UK
(david.schlaphorst@bristol.ac.uk)
[2]School of Earth Sciences, University of Bristol, Bristol, UK
(gljmk@bristol.ac.uk)

The detailed study of the seismic anisotropy is useful for a better understanding of the different tectonic features of the subduction zone along the Lesser Antilles Arc. An observation of a variety of different phases helps to get the most comprehensive insight into the anisotropic features of the region.

Due to an overall eastward drift of the Caribbean plate of around 2cm/year relative to the North American plate, the type of the subduction changes. Compared to the plain subduction of the North American plate in the east, the northern plate boundary zone is far more complex, predominantly characterised by a left-lateral east-west strike-slip motion that includes an oblique convergence of the Bahamas carbonate banks and a pull apart basin in the Mona Passage, the sea gate between Hispaniola and Puerto Rico. The island of Hispaniola is decoupled from the Caribbean plate, which leads to a second subduction zone south of Hispaniola where the Caribbean plate subducts beneath the Hispaniola micro plate. Strictly speaking, the arc only extends to the east of the island of Puerto Rico but since most of the northern Caribbean plate boundary zone is directly linked to it the results become more directly comparable. Fed by the Orinoco the southern part of the Lesser Antilles subduction zone consists of a sediment-rich subduction zone which changes to a sediment-poor subduction zone towards the north as the sediments get blocked by several banks like the accretionary prism containing the island of Barbados.

Seismic anisotropy causes a change in velocity of seismic waves due to their polarisation that can be measured. It is an important feature to characterise the nature of the subduction by indicating the flow regime above the slab. This feature depends strongly on the structure of the subduction zone.

If a seismic shear wave enters an anisotropic medium it will be split into to perpendicularly polarised waves travelling at different velocities through the medium, therefore creating a fast and a slow shear wave. Once the waves leave the anisotropic layer they will retain their polarisation. This effect is called shear wave splitting and can be observed at seismic stations. By entering a second anisotropic layer, the waves can be split up again, thus leaving four individual waves with two different polarisation angles. Since this effect adds up over the whole ray path it is one of the goals to narrow down the possible areas of anisotropy. This can be done by using events with varying depths as well as different phases that penetrate different layers in the subsurface.

The Lesser Antilles Arc provides sufficient data, not only in the fields of seismology but also petrology from an abundance of available xenoliths brought to the surface. Therefore, some geochemical and isotopic studies are already available and can be linked to further results from seismology and petrology to get a more complete picture of the area. Moreover, a great number of seismic broadband stations are currently active around the arc, thus allowing for access to a large number of seismological data with a comprehensive distribution. Additionally, it is possible to monitor the seismic activity not only along the arc but also perpendicular to it, since seismic stations are placed at locations outside the arc, such as on Barbados as, well as Antigua and Barbuda.

Mantle Convection Models Featuring Plates

CLAUDIA STEIN[1], JULIAN P. LOWMAN [2,3], ULRICH HANSEN [1]

[1] Institute of Geophysics, University of Münster, Münster, Germany
(stein@earth.uni-muenster.de)
[2] Department of Physical and Environmental Science, University of Toronto Scarborough, Toronto, Canada
[3] also at: Department of Physics, University of Toronto, Toronto, Canada

Oceanic plates are an integral part of the Earth's mantle and thus play an important role in its dynamics and evolution. Accordingly, plate-like surface motion is the most fundamental property a mantle convection model must possess in order to be considered Earth-like. Recognition of the feedback between mantle dynamics and surface motion has motivated an ongoing investigation into the requirements needed to generate plate-like surface motion. However, modeling approaches have bifurcated and now typically fall into one of two categories.

To allow plate behaviour to arise naturally in numerical mantle convection models, self-consistent plate generation methods apply a fully rheological approach (featuring a temperature-, pressure- and stress-dependent viscosity). However, due to the extreme local viscosity changes that the self-generation of model plates entails, their computational requirements are demanding. Alternative plate modeling methods specify the existence of plates explicitely by imposing this motion as a time-dependent boundary condition (e.g., by employing a force-balance method).

Here, we present modifications to a force-balance model by utilizing a geotherm- and pressure-dependent viscosity. Accordingly, plate viscosity and plate thickness are no longer prescribed by the modeler but now follow as a dynamic consequence of the temperature-dependence of the viscosity and the model's evolution. We describe the new method and present benchmark results for a rheologically self-consistent mantle convection model (plaatjes) and the modified force-balance plate model (MC3D). Our results show that both plate modeling methods lead to the same system behaviour and convection patterns for a wide range of system parameters (cf. Fig. 1). For example, for mixed heating mode systems, we find that both models converge to the same stagnant-lid convection solutions as either the non-dimensional internal heating rate is increased or the Bénard-Rayleigh number is decreased.

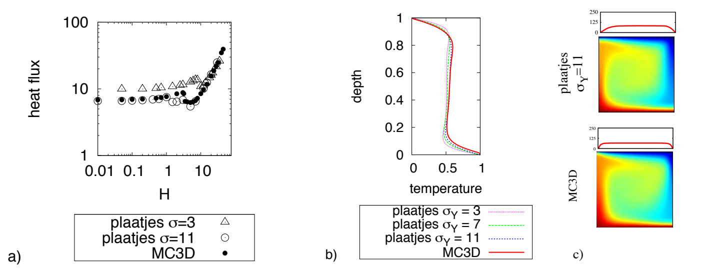


Figure 1: a) Time-averaged surface heat flux as function of the non-dimensional heating rate H, b) temperature-depth profiles for H=0.2 and c) snapshots of the temperature fields and velocity profiles for H=0.2 for the rheological model plaatjes (with different yield stresses) and the force-balance model MC3D.

One advantage of the force-balance models is that they are particularly robust at high Rayleigh numbers and high thermal viscosity contrasts. Accordingly, our new rheology-dependent force-balance method is a useful tool for exploring the dynamics of planets inferred to have deeper mantles or higher internal heating rates than the present-day Earth, such as exo-solar super-Earsths or the Archean Earth.

Modeling melting with particles in whole mantle convection

HEIN VAN HECK[1] & HUW DAVIES [1]

[1] School of Earth and Ocean Sciences, Cardiff University, Cardiff, UK
(vanHeckHJ@cardiff.ac.uk)

Problem: Many outstanding problems in Earth science relate to the geodynamical explanation of geochemical observations. Nowadays, extensive geochemical databases of surface observations exist, but satisfying explanations of underlying processes are lacking. Longstanding problems such as; The possible existence and sustainability of chemically distinct reservoirs in the Earth's mantle; the possible need of layered convection through much of Earth's history to explain chemical observations; and the heat flow paradox remain, on a deep level, unsolved. One way to address these problems is through numerical modeling of mantle convection while tracking chemical information throughout the convective mantle. In the past decade, both numerical mantle convection codes and computer power have grown sufficiently to begin to grasp much of the full problem of the complex interlocking physics, chemistry and thermodynamics of the convecting mantle, lithosphere, continents and atmosphere.

Action: We implemented a new way to track both bulk composition and concentration of trace elements in the well developed mantle convection code TERRA (finite element). Our approach is to track bulk composition and trace element abundance via particles. One value on each particle represents bulk composition, it can be interpreted as the basalt component. The system is set up to track both radioactive isotopes (in the U, Th, K system) and noble gases (He, Ne, Ar). In our model, chemical separation on bulk composition and trace elements happens at self-consistent, evolving melting zones. Melting is defined via a composition dependent solidus, such that the amount of melt generated depends on pressure, temperature and bulk composition of each particle. A novel aspect is that we do not move particles that undergo melting; instead we transfer the chemical information carried by the particle to other particles. Molten material, represented by the particles, is instantaneously transported to the surface, thereby increasing the basalt component carried by the particles close to the surface, and decreasing the basalt component in the residue. For molten material that arrives at the surface, a fraction of its content of noble gases and radioactive elements is moved into separate continent and atmosphere reservoirs.

Results: First results will be presented in which we test and show the success and limitations of our implementation. To this end we choose to use a highly simplified setup with calculations of isoviscous, incompressible, low-Rayleigh number mantle convection in spherical geometry. In these we will avoid complexities such as phase changes, elastic/plastic deformation, and all coupling of variations in material properties to the Navier-Stokes equations. For these calculations we will show: 1: The evolution of bulk composition over time, showing the build up of oceanic crust (via melting induced chemical separation in bulk composition); i.e. a basalt-rich layer at the surface overlying a thin layer of depleted material (Harzburgite), and the transportation of these chemical heterogeneities through the deep mantle. 2: The amount of melt generated over time. 3: The evolution of the concentrations and abundances of different isotopes of the elements: U, Th, K, Pb, He, Ne and Ar, throughout the mantle as well as the atmosphere and continent reservoir. 4: Numerical details on the splitting and merging of particles which is needed to ensure proper coverage and maintain numerical resolution at all times.

Thermochemical Anomaly in the lowermost Mantle and its Evolution

TING YANG RONGSHAN FU LEI BAN CHUAN HUANG

School of Earth and Space Science,University of Science and Technology of China

The large low shear wave velocity structure (LLSVP) beneath Southern Africa is suggested to be a thermochemical anomaly (Ni, Tan et al. 2002). LIP (large igneous province) eruption sites of the last 0.3 Ga and most deep origin hotspots today is observed to correlate well with the boundary of this anomaly on CMB, which suggests the shape of this anomaly can remain largely unchanged for at least 0.3 Ga (Burke, Steinberger et al. 2008). Some authors further suggest the thermochemical anomaly beneath Africa produced early in the Earth's history (Wen 2001) and thus serves as an isolated primordial chemical reservoir (Burke, Steinberger et al. 2008).

We performed numerical models on thermochemical convection to study under which conditions can one thermochemical block in the lowermost mantle survive for 4.6 Ga and keep its shape largely unchanged for at least 0.3 Ga. We keep other parameters earthlike while change viscosity ratio η_{c1} (the ratio of viscosity between anomaly and ambient mantle) from 10~500 or buoyancy ratio B from 0.2 ~0.8 to investigate the effect of the viscosity constract and buoyancy ratio on evolution of chemical blocks.

Our main conclusions are:

(1) The inequality below should be satisfied to keep Th (the time when the residual mass of a chemical block is half its initial) no less than 4.6 Ga:

$$B+\log10(\eta_{c1})\geq 2.4$$

(2) Although chemical blocks with low η_{c1} (as low as 50) endured an fast change in its morpholoy at early time in its evolution, it can keep its morphology largely unchanged for more than 0.3 Ga at most time when the convection reached quasisteady state.

(3) If the LLSVP beneath southern Africa is regarded as a thermochemical block with buoyancy ratio between 0.3~0.6 (Simmons, Forte et al. 2007), the lower boundary of the viscosity ratio η_{c1} required to make its lifetime longer than 4.6 Ga (Th no less than 4.6 Ga) and keep its morphology largely unchanged for at least 0.3 Ga is 63~126.

(4) When the position of chemical blocks remained unchanged, plumes generate from the boundarys of them mostly but does not reject to origin from the ambient mantle and top of the block occasionaly.

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