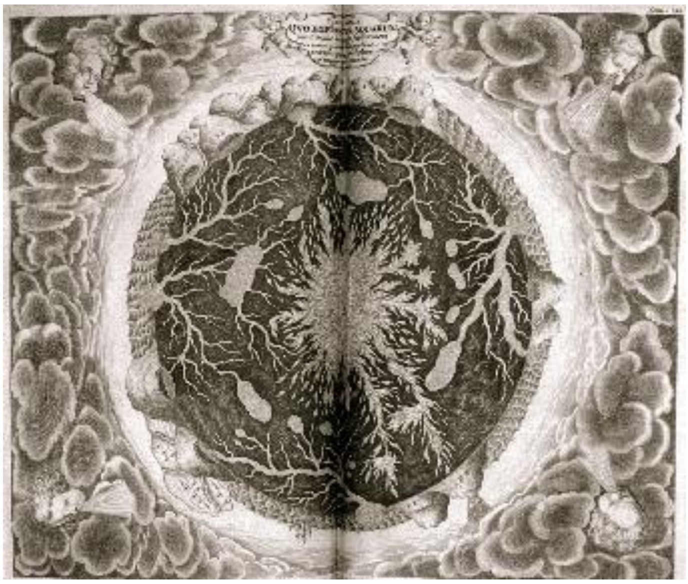
Royal Astronomical Society /
British Geophysical Association
Discussion Meeting - 11th November 2011

UKSEDI:

Study of the Earth's Deep Interior

Royal Astronomical Society Lecture Theatre
Burlington House
London, UK



Abstract Book

10:30 – 11:00 **Carolina Lithgow Bertilloni, UCL (invited)**

What is a plume? An experimental perspective

The concept of mantle plumes has had a significant impact on our ideas about mantle geochemical heterogeneity and evolution. And yet many aspects remain controversial from their geochemical signature, excess temperature and seismic delectability to their very existence. We take an experimental approach not to tackle the question of plume survival in the mantle, but rather to characterize quantitatively the temperature and velocity structure of a single thermal plume and hence define unambiguously and objectively the structure of the plume (head, conduit and source material) and the degree of entrainment. We have developed an automated Stereoscopic Particle Image Velocimetry and Thermometry (SPIVeT) non-invasive visualization system to measure the 3-D velocity and temperature structure of thermal plumes in very viscous fluids. We augmented existing techniques of velocimetry by developing a hybrid particle tracking/particle image velocimetry method for better removal of spurious vectors. Thermochromic liquid crystals were used to extract temperature, but because of their limited color play, a finite volume numerical model using the SPIV velocities as inputs aided in the reconstruction of the 3D temperature field in the tank.

We performed a series of experiments in a cubic tank (30 cm on the side) with corn syrup and a circular heater 2 cm in diameter, set to temperatures ranging from 38-80 C. We analyze the results using the concepts of dynamical systems analysis and in particular Lagrangian Coherent Structures (LCS). The unstable manifold defines the boundary of the head with respect to the surrounding fluid as well as the point of maximum stretching. The stable manifold bounds all the material that will ever be entrained in the plume structure and does away with arbitrary divisions between source and plume material. We determine, by advecting tracers with the experimentally measured velocities mass maps that show the radial and vertical origin of plume material. We have developed a stretching metric that quantifies the degree of stirring and identifies the origin of the head and conduit material. We have reproduced our results numerically using Fluidity, a finite element package with adaptive mesh refinement.

Our results illustrate new features. A plume conduit defined by velocity rather than temperature contours is significantly thinner. The excess temperature is concentrated in this narrow core and decays quickly away from it. The material that makes up this core and is at the top of the head represents source material from less than .5 mm away from the heater. Our most interesting observation is a confirmation that thermal plumes do not have well-developed scroll heads. These are a characteristic of injection-type experiments, which we simulated numerically. We confirmed that the flows are dynamically distinct by analyzing their stable and unstable manifolds using numerical simulations. All our results have important implications for the geodynamical and geochemical signatures of mantle plumes, which I will explore during the presentation.

11:00 – 11:15 Saskia Goes, Imperial College

Synthetic images of dynamically predicted plumes and comparison with global tomography

Elinor Styles, Saskia Goes, Peter van Keken, Jeroen Ritsema, Hannah Smith

Seismic detection of a mantle plume may resolve the debate about the origin of hotspots and the role of plumes in mantle convection. In this work, we test the hypothesis that whole-mantle plumes exist below major hotspots, by quantitatively comparing physically plausible plume models with seismic images following three steps. We (1) simulate a set of representative thermal plumes by solving the governing equations for Earth-like parameters in an axisymmetric spherical shell, (2) convert the thermal structure into shear-velocity anomalies using self-consistent thermo-dynamic relationships, and (3) project the theoretical plumes as seismic images using the S40RTS tomographic filter to account for finite seismic resolution. Simulated plumes with excess potential temperatures of 375 K map into negative shear-wave anomalies of up to 4-8% between 300 and 660 km depth, and 2.0-3.5% in the mid-lower mantle. Given the heterogeneous resolution of S40RTS, plumes of this strength are not easily detectable if tails are narrower than 150-250 km in the upper-mantle or 400-700 km in the lower mantle. In S40RTS, more than half of the forty hotspots we studied overlie low-velocity anomalies that extend through most of the lower mantle. These anomalies exceed 0.6% in the lower mantle, compatible with thermal plume strengths. They have widths mostly with the range 800-1200 km, which is at the high end of plausible thermal plume structures, and at the low end to be resolved in S40RTS. In the upper mantle, the shear velocity is low beneath more than ninety percent of the hotspots. For about ten, including Iceland, the East African hotspots, Hawaii, and the Samoa/Tahiti and Cobb/Bowie pairs, S40RTS low-velocity anomalies extending through the transition zone imply 200-300 K excess temperatures over a ~1000 km wide region. This is substantially broader than expected for thermal plume tails. Such anomalies may be compatible with deep-seated plumes, but only if plume flux is strongly variable due to, for example, interaction with phase transitions and/or chemical entrainment.

11:15 – 11:30 Elizabeth Day, University of Cambridge

P-wave precursor observations of small-scale variations of the 660 km seismic discontinuity

High frequency P-waves are sensitive to small scale structures and sharp transitions within the Earth. We exploit the high frequency nature of P'P' precursors to characterise small scale variations in the 660 km seismic discontinuity, which appears to vary substantially in depth over only a few degrees laterally. We use PP precursor observations of the mantle transition zone in the same region to constrain the thermal and chemical heterogeneities that are responsible for the apparent topography on the `660' to depths below the 410 km seismic discontinuity. This reconciles the apparently contradictory PP and P'P' precursor observations of the 660 km seismic discontinuity under East Africa.

11:30 – 12:00 Jeroen van Hunen, Durham University (invited)

The evolution of subduction throughout the Earth's history

Subduction drives plate tectonics and builds continental crust, and as such is one of the most important processes for shaping the present-day Earth. This talk will address whether subduction was always this important.

Earth cooled from initially very hot conditions to the present-day ~1350^{o}C potential temperature. Today, subduction is driven by slab pull, but in a hot, Earth, more melting probably gave thicker buoyant oceanic crust, perhaps inhibiting new subduction initiation, although eclogitisation of crust resulted in dense deep slabs even when crust was thick. Also plate strength was affected by hotter conditions: directly through temperature-dependent rheology, through dehydration strengthening, and through changing crust-mantle ratios. Although the net effect is somewhat unclear, Archaean plates were probably weaker than today. Combined plate strength and buoyancy differences resulted in different subduction dynamics. Plate tectonics could have been slower or faster and/or intermittent. Linking plate tectonic vigour to Earth secular cooling reveals that plate-tectonic rates were not very different from today. Several of the proposed Archaean subduction rates and styles fit available cooling data reasonably well.

Different types of geological observations are interpreted as subduction-related. Geochemically, a distinct 'arc' signature arises from the fluid-mobile elements. Many Archaean igneous rocks carry such arc signature, although other other causes than subduction have been suggested. They also carry another arc signature that suggest formation (under wet conditions) at depths >50 km. Structural evidence for Archaean subduction includes accreted terranes, thrust belts, and dipping seismic reflectors. The co-existence of paired metamorphic belts is a clear indicator of modern subduction zones, and recent discoveries of such paired belts in the Archaean (although at higher average geotherms) is interpreted as a subduction signature. Blueschists and ultra-high pressure metamorphism (typical for modern collision zones) is absent for the Archaean, indicating either no or different style of subduction.

Combining geodynamical models and geochemical evidence suggest that 1) shallow flat subduction (as often proposed as the dominant style of subduction) is geodynamically not viable and geochemically not necessary. Instead, subduction was perhaps more episodic in nature, as suggested by Archaean subduction models and geochemically evidenced by brief (few Myrs) arc signatures embedded in non-arc signatures.

12:00 – 12:15 Huw Davies, Cardiff University

Earth's Surface Heat Flux - 47 +- 2 TW

JH Davies (Cardiff University) and DR Davies (Imperial College London)

The global surface heat flux is a fundamental constraint on solid earth dynamics. Unfortunately deriving an estimate of the total surface heat flux is not easy due to limitations related to the measurements – especially hydrothermal circulation issues and the inhomogeneous distribution of measurements.

We have derived a revised estimate using a large data-base and GIS methods (Davies & Davies, 2010). For young ocean crust to account for hydrothermal circulation we have used a model estimate of the heat flux following the work of Jaupart et al. (2007) while for the rest of the globe, to try to overcome the inhomogeneous distribution, we have developed an average for each different geology and multiplied by its area.

We used 38 347 measurements, provided by G. Laske and G. Masters, a 55% increase on the number of measurements used previously. While this improves the global coverage significantly there are still many regions of the globe with few measurements. We have followed the idea of previous workers and assumed that the geology of a region can be a guide to its heat-flow. The raw data does suggest that this does have some power, for example displaying a relationship with age of the geology.

We used two digital geology data sets to define the geology everywhere. These were the Global GIS data set of continental geology Hearn et al., (2003) from AGI; and the global data-set, of CCGM – Commission de la Carte Géologique du Monde (2000). This led to over 93,000 polygons defining the Earth’s geology. To limit the influence of clustering, we intersected the geology polygons with a 1 by 1 degree (at the equator) equal area grid. For every geology class the average heat flow in the resulting polygons is evaluated.

For Antarctica we use an estimate based on depth to Curie temperature and include a 1TW contribution from hot-spots in young ocean age. Geology classes with less than 50 readings were excluded.

The total estimate arrived at is 47 ± 2 TW, which is similar but slightly higher than previous estimates e.g. Pollack et al., 1993 – 45 ± 1 TW; and Jaupart et al., 2007, - 46 ± 3 TW. Such high heat flows are a challenge to understand given current estimates of internal heat sources in a thermally monotonically cooling mantle.

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Pollack, H. N., Hurter, S. J., and Johnson, J. R.: Heat-Flow from the Earths Interior – Analysis of the Global Data Set, Rev. Geophys., 31, 267–280, 1993.

12:15 – 12:30 Andy Nowacki, University of Bristol

Flow-induced anisotropy in D″: predictions and observations of shear wave splitting

Andy Nowacki, Andrew M. Walker, James Wookey, J-Michael Kendall, and Alessandro M. Forte[1]
[1] (GEOTOP, Université du Québec a Montreal, Canada)

A commonly-made assumption is that the observed anisotropy in D00 is caused by the alignment of MgSiO3 post-perovskite (ppv). However, there are many other potential causes such as the alignment of other mineral phases or of seismically distinct material in a shape-preferred orientation (SPO), and as yet no observations have been able to distinguish these cases. We present initial results of modelling ScS waves traversing a generally anisotropic, heterogeneous lowermost mantle. The input elasticity is derived from a model of texture development in ppv, driven by flow in D″. We compare these synthetics with regional, multi-azimuth observations of shear wave splitting in ScS made along the same paths. Synthetic waveforms are made using ray theory, where the predicted splitting is calculated at finely-spaced points along observed paths in the anisotropic region, and these multiple splitting operators are applied in the frequency domain to a waveform of the same period as the observations. Where the observed and modelled splitting agree or disagree, ppv LPO can be considered a compatible or incompatible mechanism, within the assumptions and approximations we make.

We have developed an integrated model of mantle ow and the resulting LPO of ppv, derived from seismic and mineral physics observations. Particles are traced through a steady-state flow field, driving a visco-plastic self-consistent model of texture development in ppv. Our model produces fully anisotropic elastic constants which can be used for comparison with global and regional seismic observations of anisotropy in D″. Comparisons with global inversions for vertical transverse isotropy, a common assumption, can be made, but in order to accurately account for azimuthal sampling bias, we require detailed knowledge of each raypath used in the inversion. An alternative approach we pursue is to compare individual source-receiver measurements. This has the advantage that there are no constraints on the type of anisotropy we examine.

By far the largest difference between the models we test is the deformation mechanism of ppv, something which is still largely unknown. We test three models of dislocation creep in ppv, based on theoretical and experiment considerations, with slip mainly on (100), (010) or (001). No single deformation mechanism can reproduce all the observations, but by far the best match is found for models with slip mainly on (010), which is that inferred from deformation experiments on structural analogues of ppv and from dislocation modelling.

The results suggest one or more of several things: ppv LPO with slip on (010) may account for anisotropy in many parts of the lowermost mantle, but other phases, slip systems or other causes entirely may be responsible elsewhere; ppv may have several deformation mechanisms depending on the conditions; some of our assumptions or approximations are not su_ciently accurate. As further constraints are placed on mantle flow, and especially the deformation mechanisms of lowermost mantle phases, the number of possibilities will be reduced, and we will move closer to being able to constrain mantle flow directly with measurements and models of D″ anisotropy.

12:30 – 14:00 Poster viewing / lunch

14:00 – 14:30 George Helffrich, University of Bristol (invited)

Causes and consequences of outer core compositional stratification
George Helffrich, Satoshi Kaneshima

We report on the structure of the topmost outer core using SmKS-SnKS differential travel times. These seismic waves travel across the outer core at depths between 60-700 km and reflect (m-1) or (n-1) times from the underside of the core-mantle boundary. The data are array recordings of earthquakes in South America and the southwest Pacific at distances around 150 degrees. The arrays, located in Europe and Japan, yield high-precision measurements of differential travel times and differential slownesses that average over structure at the core-mantle boundary and so are a methodological improvement over studies using measurements of individual seismograms.

The uppermost 300 km of the core is 0.3% gradationally slower than the PREM model. Applying Birch's homogeneity test to the velocity profile shows that it differs at more than the 95% confidence level from compression of a simple liquid of fixed composition. Thus the outer core is stratified in its composition. The layer's thickness rules out diffusion of material into the core from the core-mantle boundary, given known diffusivity of core liquids. Consequently, light element addition within the core, probably from the growth of the inner core, probably causes the stratification.

These results are independent of any particular compositional model for the core. Using a core liquid model in the Fe-O-S system to estimate the amount of light element transferred from the deeper core suggests a 3-5 wt% light element concentration increase. A rough material balance may be made between the density jump at the inner core boundary and the thickness of the layer. Maintaining a 300 km thick layer against convective mixing in the outer core suggests that the shallowest core is stagnant. One way to suppress convection there is by lowering the thermal gradient in the topmost core, compensated by a significant thermal boundary layer at the base of the mantle.

14:30 – 14:45 Jessica Irving, University of Cambridge

Small and regional scale heterogeneities in Earth's inner core

Earth's inner core is not the homogeneous single crystal it was once thought to be; instead its complex nature is becoming clearer. The hemispherical variation in the inner core is its most striking structure; we use high frequency seismic body waves to observe the hemispherical differences between the "eastern" and "western" hemispheres of the inner core. We find that the spectra of normal mode oscillations of the whole earth are affected by the presence of hemispherical structure in the inner core. Observations of splitting functions of these low frequency normal modes support our understanding of the hemispherical nature of the inner core as a global phenomenon.

Using a new, high ray-density dataset, we are able to illuminate small scale features in the inner core, such as the precise location of the boundary between the two hemispheres, and the presence of small-scale scatterers in the uppermost inner core.

A better understanding of the seismic structure of the inner core will provide helpful constraints on the permissible magnetic and thermal fields present in the core.

14:45 – 15:00 Andy Biggin, University of Liverpool
Palaeomagnetism as a probe of long timescale processes occurring in the Earth's deep interior

The palaeomagnetic record provides a signal of core convection and resulting geodynamo activity for the last 3.5 Gyr although it is neither trivial to obtain nor to interpret. Clear variations in geomagnetic behaviour occurring over timescales of 10-100 Myr likely reflect the influence of changes in the core-mantle boundary heat flux resulting from mantle convection. Observations of still longer timescale variations of greater than 1 Gyr may reflect the evolution of the Earth's deep interior in response to its secular cooling. Relevant palaeomagnetic observations of polarity reversal frequency, secular variation and mean intensity variations will be summarised. Efforts to interpret these using a synthesis of geodynamo and mantle convection modelling will also be highlighted. These are at an early stage but, together with improved palaeomagnetic records, have significant potential for providing insight into processes occurring at all levels in the Earth's interior.

15**:00 – 15:30 Julian Aubert, Institut de Physique du Globe de Paris (invited)**
Imaging flow within the Earth's core

Images of flow inside the Earth's core are essential to describe its dynamical state. Inverting geomagnetic data for the flow below the Earth's core-mantle boundary requires assumptions and regularisation to handle the non-uniqueness of the solution. In this talk I will present a new way to approach this problem, based on a stochastic inversion using as a prior the statistics from a numerical model of the geodynamo with output highly resembling the geomagnetic field. The method is not limited to the core-mantle boundary, and yields full outer core flow images. I will briefly discuss its efficiency based on synthetic tests, before analyzing its results with CM4 and CHAOS-4 data over the period 1970-2005.

16:00 James Wookey, University of Bristol (as part of RAS Ordinary meeting)

Between a rock and a hot place: the core mantle boundary

The boundary between the rocky mantle and iron core, almost 2900 km below the surface, is physically the most significant in the Earth's interior. It may be the terminus for subducted surface material, the source of mantle plumes and a control on the Earth's magnetic field. Its properties also have profound significance for the thermochemical and dynamic evolution of the solid Earth. Evidence from seismology shows that D'' (the lowermost few hundred kilometres of the mantle) has a variety of anomalous features. Understanding the origin of these observations requires an understanding of the elastic and deformation properties of deep Earth minerals. Core-mantle boundary pressures and temperatures are achievable in the laboratory using diamond anvil cell (DAC) apparatuses. Experimental work is also done using analogue minerals at lower pressures and temperatures; these circumvent some of the limits imposed by the small sample size allowed by the DAC. A considerable contribution also comes from theoretical methods, which provide a wealth of otherwise unavailable information, as well as verification and refinement of experimental results. Recent advances in the study of the lowermost mantle involve the linking of the ever-improving seismic observations with predictions of material properties from theoretical and experimental mineral physics in a quantitative fashion, including simulations of the dynamics of the deep Earth. While important issues still remain outstanding, this has the potential to dispel much of the mystery that still surrounds this remote but important region.

Posters

Susan Macmillan, BGS Edinburgh
Space Weather Impacts of the Developing South Atlantic Anomaly

Kathy Whaler, University of Edinburgh
Core surface flows with acceleration and their ability to forecast the magnetic field

Phil Livermore, University of Leeds
Forecasting the geomagnetic field using variational data assimilation

Lauren Waszek, University of Cambridge
Earth's inner core: hemispheres, anisotropy and rotation

Luis Silva, University of Leeds
Inner core structure caused by quasi-geostrophic core flows

Ciarán Beggan, BGS Edinburgh
Separation of Main Field and Secular variation signatures within slow and fast S-wave regions on the Core-Mantle Boundary using Slepian functions

Chris Davies, University of Leeds
A buoyancy profile for the Earth's core

Anna Mäkinen, University of Cambridge
Global seismic observations of time variations in the Earth's core, and its rotation

Ceri Nunn, University of Cambridge
P and S wave tomographic structure of NE Tibet

Neil Suttie, University of Liverpool
Interpreting the palaeomagnetic record through geodynamo simulations

Victoria Ridley, University of Liverpool
Jovian Secular variation and Length of Day

Miles Osmaston
A new starting-point for the deep-Earth paradigm, leading to wider insights on today's behaviour

Scoping studies: “The controlling influence of the core and mantle on a habitable planet”:

Integrated subduction zone systems (PI Jon Davidson, Durham University)

Critical metals in the global Earth system: where did all the REEs go? (PI Craig Storey, University of Portsmouth)

The Impact of the Weakening Geomagnetic Field on Space Weather. (PI Kathy Whaler, University of Edinburgh)