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UKSEDI:

Study of the Earth's Deep Interior

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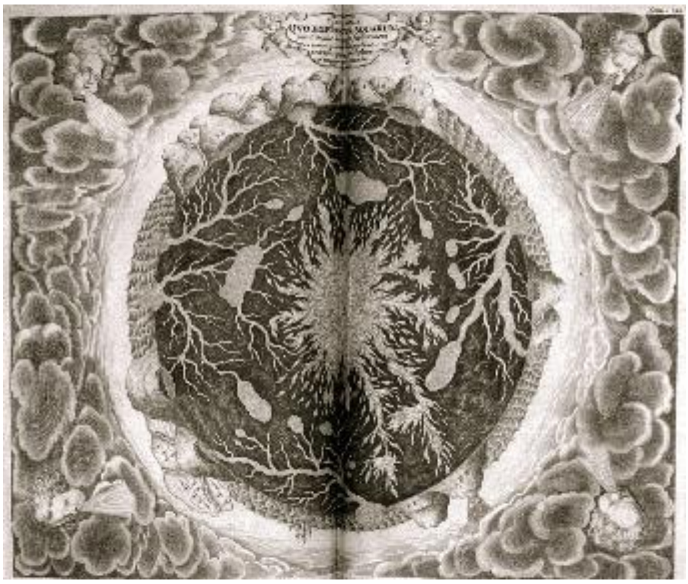

Poster Abstracts

Posters

Susan Macmillan, BGS Edinburgh

Space Weather Impacts of the Developing South Atlantic Anomaly

Macmillan, S., Beggan, C., Clarke, E., Hamilton, B., Thomson, A. and Turbitt C.

British Geological Survey, Edinburgh

The shielding that the Earth's magnetic field provides from solar emissions and cosmic rays is significantly less in the area of the southern Atlantic and South America compared to other areas away from the polar regions. This radiation is known to damage satellites that pass over the area. During the period when global magnetic field observations are available, the South Atlantic Anomaly has been deepening, growing in extent, and moving westwards over the South American landmass. This, combined with (a) the increased reliance on technology that is dependent on satellites and (b) the decline since 1985 of solar parameters that control the shielding that the heliospheric magnetic field provides from cosmic rays, means that damage to satellites is expected to increase in the future. In this presentation we describe efforts to reduce uncertainties in forecasts of both the geomagnetic field and relevant solar parameters. The emphasis is on the provision of timely and good quality measurements and models of the geomagnetic field and maintenance of long-term series of magnetic activity indices and hourly mean data for inferring the solar parameters.

Luis Silva, University of Leeds

Inner core structure caused by quasi-geostrophic core flows

The Earth's inner-core has developed a significant degree of structural complexity since its formation around 1 Ga ago, epitomised by a top 100 km layer that is seismically slow in the western hemisphere and fast in the eastern. Establishing the cause of this hemispheric pattern has significant implications for the evolution of Earth's deep interior and the geodynamo process generating the Earth's magnetic field. Recent results from numerical geodynamo simulations suggest that fluid motions in the liquid outer core can induce heterogeneity at the inner-core boundary in broad agreement with the hemispheric seismic anomalies. The applicability of this mechanism to the present-day outer core has, however, never been established. In this work we show that the fluid motions inside the core can be used to estimate the induced lateral temperature anomalies at the inner-core surface. The flow in the outer core is assumed quasi-geostrophic and is obtained from its tangentially- geostrophic projection onto the core surface, derived from historical observations of the geomagnetic field and its variation with time. Over time, the imposed temperature anomalies lead to a pattern of crystal growth in the inner core which is in striking agreement with the observed hemispherical seismic pattern. In this manner, we link the independent geomagnetic and seismological datasets through a simple dynamical model of the outer core.

Phil Livermore, University of Leeds

Forecasting the geomagnetic field using variational data assimilation

Modern computational models of weather and climate prediction are made as realistic as possible by incorporating past and present observations in a process termed data assimilation. In this presentation, I summarise recent work in applying an identical methodology to Earth's core, where the aim is to produce a realistic model of the complex motion of electrically conducting fluid and its associated magnetic field. In variational assimilation, the technique used in this study, an initial configuration throughout the core is sought which minimises the discrepancy between the output of the subsequently evolved geodynamo model and a set of recent observations of the geomagnetic field on Earth's surface. I will show some promising results of this technique applied to simplified dynamical models of the core and discuss how these might be extended to forecast the geomagnetic field.

Authors: Phil Livermore, Kuan Li, Andy Jackson at Leeds, ETH, ETH respectively.

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

Ciarán Beggan[1], Jarno Saarimäki[2] and Kathy Whaler[2]

[1]British Geological Survey, Edinburgh, UK
[2]School of GeoSciences, University of Edinburgh, UK

Models of the core magnetic field are typically represented using spherical harmonic coefficients. Rather than spherical harmonics, 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 degree. The region can have any arbitrary shape and size and not necessarily be connected. Slepian functions can be tailored to be 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* (Jackson *et al.*, 2000) into two regions: (1) the non-contiguous regions described by anomalous slow shear wave velocities zones and (2) the complementary region described by average and fast shear wave velocities zones. In order to investigate the spectral content of each, the *gufm1* spherical harmonic main field and SV coefficients are transformed into Slepian coefficients, separated into the appropriate regions and transformed back to spherical harmonic coefficients representing the space-limited extent of the two regions. The spectral power of each region is examined over degrees L = 2-14. We show that the energy in degree L = 5 coefficients is concentrated almost exclusively into the slow velocity regions for the main field coefficients as the model evolves from 1590-1990.

Kathy Whaler, University of Edinburgh

Core surface flows with acceleration and their ability to forecast the magnetic field

Kathy Whaler[1] and Ciarán Beggan[2]

[1]School of GeoSciences, University of Edinburgh, UK
[2]British Geological Survey, Edinburgh, UK

On the decadal and shorter timescale, the magnetic field generated in the liquid core can be assumed to change purely by advection. This forms the basis for inverting the observed secular variation (SV) for the core-mantle boundary flow. Steady flows are able to model the gross features of the SV over extended periods with a small number of parameters, but are unable to reproduce the finer detail. We improve the fit to the data by allowing in addition steady flow acceleration. We invert 'virtual observatory' satellite-derived and ground observatory estimates of the SV and secular acceleration over the last decade directly for a steady flow and steady flow acceleration, using spherical harmonic expansions of the toroidal and poloidal flow scalars. We include steady flow coefficients up to degree 14, and steady flow acceleration coefficients to degree 8. Regularising the inversion, using different damping parameters for the flow and its acceleration, ensures the solution is not sensitive to this choice. The steady flows are similar to those obtained without acceleration, dominated by toroidal flow. The models fit the SV data much better than the secular acceleration data. However, there is significant power in the poloidal flow acceleration at degree 4, which is also the degree at which the toroidal flow acceleration power peaks. These large accelerations are not sustainable over long periods, but may be related to the magnetic 'jerk' that is thought to have occurred around 2004.

The IGRF-11 model released in 2010 gives a description of the geomagnetic field and a prediction of the annual SV in the period 2010-2015. While retrospective modelling of the field has greatly improved in the past decade with the availability of satellite magnetic field measurements, the ability to correctly predict SV has not. For example, the root-mean-square (RMS) difference between the prediction of the previous IGRF-10 model and the IGRF-11 model for 2010.0 was 119nT. Beggan and Whaler (2010) have shown that the predictions of a steady flow are better: after five years, the RMS difference between the forecast model and the 'true' field had reduced to 85nT. Here we show that models of core flow and acceleration can improve the prediction still further. We compare the RMS and spatial differences between retrospective models of the magnetic field for 2005.0-2010.0.

Ceri Nunn, University of Cambridge

P and S wave tomographic structure of NE Tibet

Chris Davies, University of Leeds

A buoyancy profile for the Earth's core

The dynamo process generating the geomagnetic field in Earth's outer core is driven by a combination of thermal and compositional convection, which in turn draws its power from Earth's continued slow cooling. The detailed nature of the geodynamo, and in all probability of the observed field, depends on the `buoyancy profile' driving the convection, the variation of the buoyancy force with depth that acts as a thermodynamic reference state about which geodynamo simulations are evolved. Previous geodynamo simulations have incorporated simple buoyancy profiles (internal heating, bottom heating, compositional sinks) and combined thermochemical buoyancy, however a general profile for the outer core has not been developed. Of particular importance is the intimate link between the buoyancy profile and the thermochemical evolution of the core; a general profile must reflect the gross energy and entropy balances in the core, which evolve slowly over time. The objective of this work is to produce a universal buoyancy profile for the outer core that:
1) expresses individual thermal and compositional contributions to the overall buoyancy profile;
2) allows quantitative comparisons between thermal and compositional effects and between internal and basal effects;
3) can be implemented in geodynamo simulations.
Buoyancy profiles are produced for three different core evolution models, which set the relative amplitudes of individual terms, and implemented in geodynamo simulations. Simulation outputs differ significantly between the Cases in the parameter range considered.

Lauren Waszek, University of Cambridge

Constraining the velocity structure of Earth's upper inner core: hemispheres, anisotropy and rotation

Lauren Waszek*, Dr Arwen Deuss
University of Cambridge, Bullard Laboratories, Department of Earth Sciences
Contact: lw313@cam.ac.uk

Earth's inner core grows through solidification of material from the fluid outer core, freezing in thecore properties as the inner core grows, at a rate of ~1mm/year. This results in an age-depth relationfor the inner core, whereby deeper structure is older. Distinct hemispherical structure in the upperinner core is well-documented: a fast velocity, isotropic east hemisphere and a slow velocity westhemisphere, comprising an isotropic upper layer atop deeper anisotropic structure. However, consensus has not yet been reached on the detailed velocity structure within the hemispheres.
Separately, the inner core is reported to rotate at rates of up to 1°/year. Considering the slow growth of the inner core, rotation rates of this magnitude would completely erase any regional structure created by varying environments at the inner core boundary, and thus are incompatible with theverified hemispheres.

We reconcile the two conflicting properties of hemispheres and rotation through exploiting the age-depth relation of the inner core. Using differential travel time residuals of PKIKP and

PKiKP, we constrain the locations of the boundaries between the hemispherical structure, finding a consistent eastwards movement with depth. This corresponds to an eastwards shift over time, which corresponds to an extremely slow inner core super-rotation of 0.1 - 1°/Ma. We then use our large dataset to derive a velocity model for the uppermost inner core, providing new constraints on the isotropic and anisotropic velocity structures. We observe an upper isotropic layer in the western hemisphere, and constrain its thickness to 57.5 km. We also observe a high velocity region in the top 30 km of the east hemisphere. Sharp boundaries separating the hemispheres and unrelated velocity structures indicate that the hemispheres act independent from one another, suggesting differing compositions and mineral structures.

Anna Mäkinen, University of Cambridge

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

Differential rotation of the Earth's inner core has been predicted in some geodynamo models, and seismic studies over the past fifteen years have resolved rotation rates up to 1 degree/year. Most of these studies have focussed on South Sandwich Islands events recorded at station COL in Alaska. Here, we present a globally extended study into temporal variations in the inner core over some 25 years, using PKPbc-PKPdf travel time residuals. We introduce a new method to remove the effect of spatial variations in residuals from time variations, which allows for the use of both polar, semi-equatorial and equatorial geometries.
Firstly, we re-analyse polar paths from South Sandwich Islands events to stations COL and INK in North America. These stations yield a differential rotation of the inner core at a rate of 0.12-0.38 degrees/year in an eastward direction, in agreement with previous studies. However, the close-lying station DAWY yields at best a westward differential rotation of the inner core, incompatible with the COL/INK results. Secondly, earthquakes in the Aleutian Islands region, observed at BOSA and LBTB in southern Africa, exhibit temporal variations that are incompatible with the South Sandwich Islands-COL/INK inferred rotation rate. Lastly, our strongest piece of evidence for the irreconcilability of differential inner-core rotation with global data comes from using earthquakes in the Vanuatu region, recorded at BCAO/BGCA in Central Africa, an equatorial geometry. These residuals resolve a westward inner-core rotation at a rate of 0.14 degrees/year, over the same time period that South Sandwich Islands events indicate an eastward rotation. As any rigid-body rotation should yield the same direction and rate independent of where the inner core is sampled, our results allow us to reject previously reported inner-core differential rotation rates of up to 0.1-0.5 degrees/year. Instead, our results suggest that structure in either the inner or the outer core is varying with time, over relatively short time scales and in ways that cannot be explained by, and do not support, a differentially rotating inner core.

Reference:
Mäkinen, Anna M. and Deuss, Arwen (2011). Global seismic body-wave observations of temporal variations in the Earth's inner core, and implications for its differential rotation. GJI (187), pp.355-370.

Neil Suttie, University of Liverpool

Interpreting the palaeomagnetic record through geodynamo simulations

Neil Suttie, Andy Biggin, Richard Holme, Julien Aubert

Recent improvements in numerical models of the geodynamo can shed light upon the variation of palaeomagnetic observables throughout Earth's history. Here, simulated datasets of virtual geomagnetic poles and dipole moments are used to interpret the palaeomagnetic record across different time periods. We show that the numerical models are broadly consistent with the palaeomagnetic data and consider which observables might offer the most robust indications of thermal conditions at the core mantle boundary. As a case study, we analyse data from before during and after the Cretaceous Normal Superchron and use dynamo models to infer the possible evolution of this enigmatic event.

Victoria Ridley, University of Liverpool

Jovian Secular variation and Length of Day

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 being used to investigate possible time 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 an alternative, regularised minimum norm approach to modelling the internal planetary field. Regularisation is advantageous as it allows the data to be fit in its entirety with stable models that display higher degree field structure then that previously attained.

Two models of Jupiter's magnetic field have been created: one is time-averaged over the whole dataset, whilst the second permits linear time variation of the field. Comparison of these allow inferences to be made about jovimagnetic secular variation with our favoured model 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}).

Further analysis suggests that the modelled variation could in part be attributed to changes in the reference frame with time. Whilst it has previously been hypothesised that these changes may stem from poor constraint of the System III 1965.0 rotation period, we investigate whether atmospheric variation might induce planetary length of day changes. Our results show that even if the surface winds extend to depths equivalent to the outer 2% of the planet, observed atmospheric changes between 1979-1996 would translate to a ~10º rotation of the planetary interior via angular momentum exchange. We provide this as strong observational evidence against models linking surface winds to deep convection on cylinders.

Miles Osmaston (miles@osmaston.demon.co.uk)

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

The present internal behaviour of our planet necessarily depends on its origin and the evolution of what is going on inside it. So here we outline big changes in our understanding of those, even bearing upon major features of our everyday lives - water, oxygen, serious earthquakes. These understandings could also influence exploration missions to the other terrestrial planets (TPs)

Our starting-point, for all four TPs, is their planetary construction and formation of their iron cores. Their individually very high orbital specific angular momenta, relative to solar material (>5000-fold for Earth), demands the action of the nebula and do it for their feedstock throughout their growth [1]. This short timescale (<5 Ma?) means that the >30 Ma timescales inferred for cores-by-percolation models take far too long and necessitate our reversion to the Ringwood model, with the further great benefit of forming the solar planetary system's water [1]. This gave the early Earth a very wet mantle, dominating the magmagenetic and (via its rheological effect) the dynamical evolution of the Earth [1,2]. Prior to 2.5 Ga this permitted convective extraction of early heating and genesis of komatiite, the predominant high-melting magmatic effusive, without a need for mantle plumes. After that, its non-linear effect upon rheology [3] as the ocean emerged resulted in a complete hiatus in plate tectonics ~2.45-2.2 Ga [2,4,5]. The shut-down of MORs enabled oxygenic life to win its battle against their exhalations, initiating our oxygen-bearing atmosphere, to which we owe our very existence. It also greatly lowered (>3km) sea-level and the resultant weathering of cratons lowered atmospheric CO_2 to the point that Earth's first global glaciations (Huronian) occurred during the hiatus.

Since that time, and globally explicit in the dynamics of plate motions for the past 150 Ma [5], this rheologically 'stiffened' mantle has remained attached to the undersides of craton lithospheres as 'deep keels' reaching to or near the base of the Upper Mantle [2,5]. The '2-layer mantle' implied by these dynamics arises from convective separation precipitated by the hiatus. This >tripled the Upper Mantle chemical depletion rate. We show how the thick-plate (including LVZ [ref 3]) and heat-retaining view for oceanic plate enables this to be reconciled with the apparent, but illusory, penetration of slabs into the Lower Mantle.

Another group of factors - shallow-mantle phase changes - needs attention by geophysical modellers, on account of the very large volume changes, per joule in or out, exhibited by most of them, relative to pure thermal expansivity. As thermally induced volume changes these can have big effects upon topography and are easily confused, using pure expansivity, with convective injection by a large-volume plume. Importantly, the horizontal expression of this solid-state volume increase may split the plate further. We show how narrowly splitting a thick plate is a fertile mechanism for mantle magmagenesis and its segregation at different depths to yield different volcanic compositions [6].

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