Thursday 7\textsuperscript{th} to Friday 8\textsuperscript{th} January 2016

Meeting Programme
This meeting could not have taken place without the generous contributions from our supporters:
### Meeting Schedule

**Thursday 7th January**

<table>
<thead>
<tr>
<th>Time</th>
<th>Event</th>
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<tr>
<td>12:00</td>
<td>Registration and buffet lunch, G41 Royal School of Mines Building</td>
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<tr>
<td>13:25</td>
<td>Welcome, G39 Royal School of Mines Building</td>
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<td>13:30</td>
<td><strong>Andy Biggin, University of Liverpool</strong></td>
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<td></td>
<td>Palaeomagnetic field intensity variations suggest Mesoproterozoic</td>
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<td>inner-core nucleation</td>
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<td>14:00</td>
<td><strong>Mark Hounslow, Lancaster University</strong></td>
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<td></td>
<td>Polarity reversal rates following the Palaeozoic superchrons- slow or</td>
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<td>fast recovery?</td>
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<td>14:20</td>
<td><strong>Louise Hawkins, University of Liverpool</strong></td>
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<td></td>
<td>Geomagnetic field behaviour preceding a Superchron: new evidence</td>
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<td>for a weak Devonian geomagnetic field</td>
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<td>14:40</td>
<td><strong>Anita di Chiara, Plymouth University</strong></td>
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<td></td>
<td>Preliminary paleomagnetic study of the Thetford Mines Ordovician</td>
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<td>Ophiolite (Canada)</td>
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<td>15:00</td>
<td>Coffee break, G41 Royal School of Mines Building</td>
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<tr>
<td>15:30</td>
<td><strong>Claire Nichols, University of Cambridge</strong></td>
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<td>Paleomagnetic and compositional insight into the formation and</td>
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<td>impact history of the IAB parent body</td>
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<td>15:50</td>
<td><strong>Josh Einsle, University of Cambridge</strong></td>
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<td>Multi scale imaging of the Cloudy Zone in the Tazewell IIICD Meteorite</td>
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<td>16:10</td>
<td><strong>Jay Shah, Imperial College London</strong></td>
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<td></td>
<td>In-situ heating holography of chondrule dusty olivine</td>
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<td>16:30</td>
<td><strong>Robert Blukis, University of Cambridge</strong></td>
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<td></td>
<td>Synchrotron Mössbauer spectroscopy of magnetic phases in Fe-Ni</td>
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<td>meteorites</td>
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<td>16:50</td>
<td><strong>Ioan Lascu, University of Cambridge</strong></td>
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<td></td>
<td>Unmixing magnetic domain states in natural and synthetic samples</td>
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<tr>
<td>17:20</td>
<td>Poster session, G41 Royal School of Mines Building</td>
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<tr>
<td>19:00</td>
<td>Conference dinner, 58 Princes Gate (opposite Imperial College)</td>
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# Meeting Schedule

**Friday 8th January**

<table>
<thead>
<tr>
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<tbody>
<tr>
<td>08:30</td>
<td>Coffee in G41 Royal School of Mines Building</td>
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<td>09:00</td>
<td><strong>John Piper, University of Liverpool</strong></td>
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<td></td>
<td>Some recollections of Palaeomagnetism at Imperial College 50 years ago</td>
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<tr>
<td>09:20</td>
<td><strong>Trevor Almeida, Imperial College London</strong></td>
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<td></td>
<td><em>Direct visualization of CRM and TRM of pseudo-single-domain magnetite particles</em></td>
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<td>09:40</td>
<td><strong>Pádraig Ó Conbhui, University of Edinburgh</strong></td>
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<td><em>Simulated electron holography of PSD particles: Examples and Caveats</em></td>
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<td>10:10</td>
<td><strong>Miguel Valdez Grijalva, Imperial College London</strong></td>
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<td><em>Simulated 'early-onset' PSD behaviour: size and shape effects in non-interacting greigite nanoparticles</em></td>
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<td><em>Palaeomagnetic dates of Irish Zn-Pb deposits record regional remagnetization related to Variscan fluid flow</em></td>
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<td><strong>Radchagrit Supakulapos, Imperial College London</strong></td>
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<td><em>The palaeomagnetic field properties at high northern latitudes: preliminary results from Eyjafjardardalur valley</em></td>
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<td>11:30</td>
<td><strong>Neil Suttie, University of Birmingham</strong></td>
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<td><em>Magnetic susceptibility recording of nanoparticle transport in porous media</em></td>
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<td>11:50</td>
<td><strong>Frantisek Hrouda, Agico</strong></td>
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<td></td>
<td><em>Anisotropy of out-of-phase magnetic susceptibility of rocks and its potential for rock fabric studies</em></td>
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<tr>
<td>12:10</td>
<td>Business meeting and farewell</td>
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## Poster Presentations

**Rabiu Abubakar, Imperial College London**  
*Mapping Petroleum Migration Pathways in Wessex Basin Using Magnetics and Seismic Mapping*

**Trevor Almeida, Imperial College London**  
*Effect of maghemization on the magnetic properties of non-stoichiometric pseudo-single-domain magnetite particles*

**Helena Bates, Imperial College London**  
*Using X-rays to Map the Magnetism in the Vigarano Carbonaceous Chondrite Meteorite*

**Matthew Galvin, Lancaster University**  
*Transverse and flow parallel AMS in Eocene turbidites, Ainsa Basin, northern Spain*

**Sam Greenwood, University of Leeds**  
*Testing the Speed of the Last geomagnetic Reversal*

**Samuel Harris, University of Bradford**  
*Archaeomagnetic Studies in the Scottish Neolithic: evaluating the potential of the Ness of Brodgar, Mainland Orkney, UK*

**Susannah Maidment, Imperial College London**  
*A chronostratigraphic framework for the Morrison Formation, western USA: a sequence stratigraphic and magnetostratigraphic approach*

**Maurits Metman, University of Leeds**  
*Magnetic diffusion, reversed flux patches and the Earth’s dipole*

**Joy Muraszko, University of Cambridge**  
*Magnetic properties of micrometeorites from Jurassic stromatolites of Poland*

**Adrian Muxworthy, Imperial College London**  

**Jack Richardson, University of Birmingham**  
*Preliminary study in the anisotropy of magnetic susceptibility of some evaporite samples*
Oral Presentation Abstracts

Palaeomagnetic field intensity variations suggest Mesoproterozoic inner-core nucleation

Andrew Biggin, Elisa Piispa, Lauri Pesonen, Richard Holme, Greig Paterson, Toni Veikkolainen and Lisa Tauxe

1University of Liverpool, 2Victoria University of Wellington, 3University of Helsinki, 4Chinese Academy of Sciences, 5Scripps Institution of Oceanography

The Earth’s inner core grows by the freezing of liquid iron at its surface. The point in history at which this process initiated marks a step-change in the thermal evolution of the planet. Recent computational and experimental studies have presented radically differing estimates of the thermal conductivity of the Earth’s core, resulting in estimates of the timing of inner-core nucleation ranging from less than half a billion to nearly two billion years ago. Recent inner-core nucleation (high thermal conductivity) requires high outer-core temperatures in the early Earth that complicate models of thermal evolution. The nucleation of the core leads to a different convective regime and potentially different magnetic field structures that produce an observable signal in the palaeomagnetic record and allow the date of inner-core nucleation to be estimated directly. Previous studies searching for this signature have been hampered by the paucity of palaeomagnetic intensity measurements, by the lack of an effective means of assessing their reliability, and by shorter-timescale geomagnetic variations. Here we examine results from an expanded Precambrian database of palaeomagnetic intensity measurements selected using a new set of reliability criteria. Our analysis provides intensity-based support for the dominant dipolarity of the time-averaged Precambrian field, a crucial requirement for palaeomagnetic reconstructions of continents. We also present firm evidence for the existence of very long-term variations in geomagnetic strength. The most prominent and robust transition in the record is an increase in both average field strength and variability that is observed to occur between a billion and 1.5 billion years ago. This observation is most readily explained by the nucleation of the inner core occurring during this interval; the timing would tend to favour a modest value of core thermal conductivity and supports a simple thermal evolution model for the Earth.

Polarity reversal rates following the Palaeozoic superchrons—slow or fast recovery?

Mark W Hounslow
Lancaster University

Slow recovery of reversal rates after superchron endings, and asymmetry of rates either side of superchrons have been inferred to be important signatures of mantle superplumes (Olson & Amit, 2015). However, the reversal rates following the Palaeozoic superchrons, have so far only been rough estimates. Here, robust geomagnetic polarity timescales are constructed, following the reverse polarity Kiaman (Permian) and Moyero (Ordovician) superchrons, using a new section-optimisation technique, constrained with best available dates. Higher reversal rates and opposite asymmetry in reversal rates of the Palaeozoic superchrons, compared to the Cretaceous normal polarity superchron, suggests there are important differences between Mesozoic and Palaeozoic superchrons. Like the Cretaceous superchron, unusually long duration chron characterise the ~10 million year interval following the Kiaman superchron, indicating a memory of the superchrons in the reversal behaviour. Possible reasons for these differences in reversal structure are explored.
Geomagnetic field behaviour preceding a Superchron: new evidence for a weak Devonian geomagnetic field

Louise Hawkins¹, Taslima Anwar², Valentina Shcherbakova³, Andy Biggin¹, Vadim Kravchinsky², Andrey Shatsillo⁴, James Holt¹ and Vladimir Pavlov⁴

¹University of Liverpool, ²University of Alberta, ³Geophysical Observatory “Borok IFZ RAS”, ⁴Russian Academy of Sciences

The ~50 million year transition from the peak in reversal frequency in the Middle Jurassic (~170Ma), associated with a weak geomagnetic field, to the stable and apparently strong field during the Cretaceous Normal Superchron (84-121Ma), represents a dramatic change in time-averaged geomagnetic field behaviour during the Mesozoic Era. New evidence from Siberian samples suggests there is a similar transition in geomagnetic field behaviour during the Palaeozoic, with a weak geomagnetic field in the Upper Devonian preceding the Permo-Carboniferous Superchron (262-318Ma). Both sites, the Viluy Traps and the Zharovsk complex of the Patom Margin, have seemingly reliable, published palaeomagnetic directions and new age constraints, 362.3±3.4–377.7±0.48Ma. The samples were measured using the Thermal Thellier-Coe protocol with partial thermoremanent magnetisation (pTRM) and tail checks and the Microwave Thellier-IZZI protocol with pTRM checks. Accepted Arai plots show positive pTRM checks, a clear relation between distinct primary directional and palaeointensity components and little to no zig-zagging. Three distinct magneto-mineralogical types were identified from SEM and rock magnetic techniques; low Ti- and intermediate Ti-titanomagnetite and possible maghemite with magnetite, with mineral type resulting in no significant variation in palaeointensity results. The Arai plots also commonly have a distinct two-slope concave-up shape, although non-heating, pseudo-Thellier experiments have supported this resulting from a strong overprint component rather than alteration or multi-domain effects. Results from these experiments give low site mean values between 2.6–14μT (Virtual Dipole Moments 7–25 ZAm²). These apparently periodic (~180 million years) transitions in geomagnetic field behaviour may indicate the influence of mantle convection changing heat flow across the Core Mantle Boundary.

Preliminary paleomagnetic study of the Thetford Mines Ordovician Ophiolite (Canada)

Anita di Chiara, Antony Morris and Mark Anderson
Plymouth University

Oceanic ridges are extensional environments characterized by brittle to ductile normal faulting and episodic magma supply. Studies in modern oceanic settings suggest that the interplay of low-angle detachments and high-angle normal faults locally lead to the exhumation of lower crust and upper mantle peridotites to the seafloor, known as oceanic core complexes (OCC). OCC are exhumed by movement along long-lived detachment faults that extend for 10s of km, and that are crosscut by high-angle normal faults oriented parallel to the rift axis. Here we present preliminary results from 12 paleomagnetic sites sampled of an example of fossilized Ordovician OCC preserved in the in the Canadian Appalachians, the Southern Quebec ophiolites, which experienced two Paleozoic orogenies after their obduction onto the Laurentian margin. Although locally obscured by tectonic fabrics and structures, the original relationships between the ophiolitic mantle, the overlying plutonic section, and onlapping Ordovician siliciclastic rocks are preserved in the Thetford-Mines ophiolite. Preliminary results from AMS and Thermal demagnetization experiments display an extensive overprint of the last Paleozoic orogeny biasing further study of the rotations along the detachment fault.
Paleomagnetic and compositional insight into the formation and impact history of the IAB parent body

Claire Nichols¹, Geraint Northwood-Smith¹, Julia Herrero-Albillos², Florian Kronast³ and Richard Harrison¹

¹University of Cambridge, ²Centro Universitario de la Defensa, Universidad de Zaragoza, ³Helmholtz Centrum Berlin

Traditionally, it has been thought that only two kinds of bodies formed in the solar system: fully melted bodies and completely unmelted bodies. However, it has recently been argued that some planetesimals may have undergone partial differentiation, forming a metallic core while retaining an overlying unmelted or partially melted rocky crust. If correct, this has profound implications for the origin of meteorite groups, the interior structures of asteroids, and the timescale of planetary accretion. The IABs, a group of iron meteorites, may have formed as metallic pools in the mantle of a partially differentiated parent body. Using X-ray photoelectron emission microscopy, we have studied two IABs, Toluca and Odessa, to examine the composition, structure and magnetisation of several FeNi microstructures. Paleomagnetic analysis suggests neither Odessa nor Toluca experienced a magnetic field, with interesting implications for the presence of an active core dynamo on the parent body. The FeNi microstructures present are also exceptional, including a eutectic intergrowth only observed in two meteorite groups. This provides invaluable insight into the thermal history of the parent body and the timing and effect of early impact events.

Multi scale imaging of the Cloudy Zone in the Tazewell IIICD Meteorite

Joshua F. Einsle¹, Richard Harrison¹, Paul Midgley², Roberts Blukis¹, Paul Bagot³, Alexandar Eggeman², Claire Nichols¹ and Zineb Saghi⁴

¹Department of Earth Sciences, University of Cambridge, ²Department of Materials Sciences, University of Cambridge, ³University of Oxford, ⁴CEA-LETI, Grenoble

Paleomagnetic studies of iron and stony iron meteorites suggest that many small planetary bodies possessed molten cores resulting in the generation of a magnetic field. As these bodies cooled, Fe-Ni metal trapped within their mantle underwent a series of low-temperature transitions, leading to the familiar Widmanstatten inter-growth of kamacite and taenite. Adjacent to the kamacite/taenite interface is the so-called “cloudy zone” (CZ): a nanoscale inter-growth of tetrataenite islands in an Fe-rich matrix phase formed via spinodal decomposition. It has recently been shown (Bryson et al. 2015, Nature) that the CZ encodes a time-series record of the evolution of the magnetic field generated by the molten core of the planetary body. Extracting meaningful paleomagnetic data from the CZ relies on a thorough understanding of the 3D chemical and magnetic properties of the inter-growth focusing on the interactions between the magnetically hard tetrataenite islands and the magnetically soft matrix. Here we present a multi-scale study of the chemical and crystallographic make up of the CZ in the Tazewell IIICD meteorite, using a range of advanced microscopy techniques. The results provide unprecedented insight into the architecture of the CZ, with implications for how the CZ acquires chemical transformation remanence during cooling on the parent body.

Previous 2D transmission electron microscope studies of the CZ suggested that the matrix is an ordered Fe3Ni phase with the L12 structure. Interpretation of the electron diffraction patterns and chemical maps in these studies was hindered by a failure to resolve signals from overlapping island and matrix phases. Here we obtain high resolution electron diffraction and 3D chemical maps with near atomic resolution using a combination of scanning precession electron diffraction, 3D STEM EDS and atom probe tomography.
Using this combined methodology we resolve for the first time the phenomena of secondary precipitation in the tetrataenite islands and chemical partitioning of trace elements between the island and matrix phases. The new crystallographic and compositional measurements present a quantitative picture of low-temperature local equilibrium in the Fe-Ni system. This leads to an improved understanding of the magnetic models used to perform paleomagnetism of the CZ.

**In-situ heating holography of chondrule dusty olivine**

Jay Shah\textsuperscript{1,2}, Adrian R. Muxworthy\textsuperscript{1}, Trevor P. Almeida\textsuperscript{3}, Andras Kovács\textsuperscript{4}, Sara S. Russell\textsuperscript{6}, Matew J. Genge\textsuperscript{1}, Rafal E. Dunin-Borkowski\textsuperscript{4}

\textsuperscript{1}Imperial College London, \textsuperscript{2}Natural History Museum, London, \textsuperscript{3}Ernst Ruska-Centre for Microscopy and Spectroscopy with Electrons and Peter Grünberg Institute, Forschungszentrum Jülich

Dusty olivine grains found within unequilibrated chondrites have the potential to have recorded early Solar System magnetic fields. Understanding of the magnetic fields present during this period is crucial to models of the protoplanetary disk. Estimates of the palaeomagnetic field from dusty olivine suggest magnetic fields played an important role in turning the protoplanetary disk into a planetary system. Off-axis electron holography is a transmission electron microscopy technique that can be used to generate a magnetic induction map of the sample at the nanoscale. Using electron holography, synthetic dusty olivine has proven to be a credible recorder of palaeomagnetic fields. A recent study demonstrates that vortex state magnetite is capable of recording reliable thermoremanent magnetization. Dusty olivine was prepared for TEM analysis by focused ion beam milling lamellae from a polished section of Bishunpur (BM 80339) onto DENS Solutions heating chips. We find highly magnetic, non-interacting vortex structures within the chondrule dusty olivine Fe metal. By heating the lamella in-situ up to 800°C and cooling back to room temperature, we present observations of the remanent magnetisation of dusty olivine up to the Curie point to investigate its nanoscale thermoremanent stability and credibility as a palaeomagnetic recorder.

**Synchrotron Mössbauer spectroscopy of magnetic phases in Fe-Ni meteorites**

Roberts Blukis and Richard Harrison

University of Cambridge

Mössbauer spectroscopy provides a unique way of studying solids containing Mössbauer active nuclei, mostly 57-Fe. The method allows for investigation of magnetic phases which is not common for most spectroscopic or diffraction methods. As Fe is the most abundant element in Fe-Ni meteorites and they contain multiple different metallic phases, they are a perfect system to be studied with Mössbauer spectroscopy. However, conventional Mössbauer spectroscopy using a radioactive gamma ray source has limited spatial resolution of about 100 microns.

A synchrotron Mössbauer source (SMS) has been developed at ESRF, Grenoble to improve the spatial resolution, providing a beam spot size of about 10 microns.

There is a debate about the magnetic properties of taenite and “antitaenite” as well their location in meteorites relative to better known phases such as kamacite and tetrataenite. Mössbauer spectroscopy has been used previously to attempt to answer these questions,
however, results have been ambiguous due to poor spatial resolution effectively examining the bulk rock properties.

Metallic Fe-Ni phase of the Tazewell (IIIICD iron) and Estherville (mesosiderite) were investigated using SMS in ESRF and initial spatially resolved spectra of different phases were obtained. The obtained data show changing proportions of magnetic and other metallic phases when crossing a kamacite lamellae. The location of "antitaenite" does not appear to be exclusively associated with the spinodal decomposition structure known as a "cloudy zone". The results show a potential in resolving the actual association of the "antitaenite" phase with other metallurgical phases.

Unmixing magnetic domain states in natural and synthetic samples

Ioan Lascu, Richard Harrison and Joy Muraszko
University of Cambridge

We have developed a magnetic unmixing method based on principal component analysis (PCA) of first-order reversal curve (FORC) diagrams. PCA provides an objective and robust statistical framework for unmixing, because it represents data variability as a linear combination of a limited number of principal components that are derived purely on the basis of natural variations contained within the dataset. For PCA we have resampled FORC distributions on grids that capture diagnostic signatures of magnetic domain states. Individual FORC diagrams were then recast as linear combinations of end-member (EM) FORC diagrams, located at user-defined positions in PCA space. The EM selection is guided by constraints derived from physical modeling, and is imposed by data scatter. To test our model, we have investigated temporal variations of EMs in North Atlantic sediments containing a mixture of magnetosomes and granulometrically distinct detrital magnetite. We calibrate EM fractions using a series of synthetic mixtures of three sizes of magnetite.

Some recollections of Palaeomagnetism at Imperial College 50 years ago

John Piper
University of Liverpool

Palaeomagnetism studies at Imperial College were initiated by Lord Patrick Blackett, a remarkably versatile scientist who was Professor of Physics from 1953 to 1963. Whilst formerly at Manchester he had designed sensitive astatic and parastatic magnetometer systems to determine whether magnetism was naturally associated with rotating bodies. Although that experiment proved to be negative he appreciated that his magnetometer was well suited to measuring the weak magnetisations in rocks and this stimulated the pioneering palaeomagnetic investigations of the 1950s. In 1966 Professor Ronald Mason was Professor of Geophysics in the Royal School of Mines. Together with A.D. Raff he had mapped the extensive magnetic lineaments in the NW Pacific whilst at Scripps. These are now known as Raff-Mason anomalies and their geological significance was later to be recognised by Vine and Matthews in 1963. The mid-1960’s was an exciting time for developments in the Earth Sciences because palaeomagnetic research on the continents had by then resolved some apparent polar wander paths with confidence to support the theory of continental drift. In a seminal 1968 paper Isaacs and colleagues were then able to bring together sea floor spreading and continental drift into the theory of Plate Tectonics. In 1966-1967 I constructed a simple palaeomagnetic laboratory in the Geophysics Department comprising a parastatic magnetometer and a.f. demagnetiser and applied it to
the study of young volcanic domains in the Gulf of Guinea Volcanic Province and Iceland. The former study was part of a regional investigation that Imperial College was then conducting into the magnetic signature of Atlantic oceanic islands. The latter study aimed to map zones of normal and reversed polarity to construct ground models and test how sea floor spreading was reflected on land in Iceland. A model of inward-dipping lava wedges sourced in dyke feeders at depth proved able to explain magnetic anomalies across SW Iceland using a spreading rate comparable to that deduced from the sea floor to the south.

Direct visualization of CRM and TRM of pseudo-single-domain magnetite particles

Trevor P. Almeida¹, Adrian R. Muxworthy¹, Wyn Williams², Andras Kovács³, Rafal Dunin-Borkowski³

¹Imperial College London, ²University of Edinburgh, ³Ernst Ruska-Centre for Microscopy and Spectroscopy with Electrons and Peter Grünberg Institute, Forschungszentrum Jülich

In order to reliably interpret palaeomagnetic measurements, the mechanisms of chemical remanent magnetization (CRM) and thermoremanent magnetization (TRM) must be fully understood. Currently, most models of CRM and TRM processes only exist for the smallest, uniformly magnetized grains, termed single domain (SD). However, the magnetic signal from rocks is often dominated by slightly larger grains containing non-uniform magnetization states, termed pseudo-SD (PSD) grains.

Magnetite (Fe₃O₄) is the most magnetic naturally occurring mineral on Earth, carrying the dominant magnetic signature in rocks and providing a critical tool in palaeomagnetism. The oxidation of Fe₃O₄ to other iron oxides, such as maghemite (γ-Fe₂O₃) and hematite (α-Fe₂O₃), is of particular interest as it influences the preservation of remanence of the Earth’s magnetic field by Fe₃O₄. Further, TRM in Fe₃O₄ grains is acquired in the direction of the ambient geomagnetic field as they cool below their Curie temperature (TC) of ~ 580 °C. The latest transmission electron microscopy (TEM) techniques like electron holography and environmental TEM (ETEM) allows for the imaging of magnetization in nano-scale minerals during in situ heating under vacuum and controlled atmospheres.

In the present study, synthetic Fe₃O₄ particles in the PSD size range (< 200 nm) were heated in situ in an ETEM under an O₂ atmosphere. Close examination of Fe₃O₄ particles after in situ heating revealed surface degradation, whilst electron energy-loss spectroscopy confirmed their oxidation. The effect of CRM was visualized using electron holography, in the form of reconstructed magnetic induction maps, where the oxidized grains exhibited a loss of overall remanence and change in remanent direction.

The thermomagnetic behaviour of Fe₃O₄ particles in the PSD size range is also investigated using off-axis electron holography. Magnetic induction maps, which are recorded during in situ heating up to above the TC, reveal the PSD nature of several Fe₃O₄ grains by visualizing their vortex domain states. The vortex states in small Fe₃O₄ grains are shown to rotate close to its unblocking temperature, rather than remaining thermally stable as seen in the vortex states of larger Fe₃O₄ grains.
Simulated electron holography of PSD particles: Examples and Caveats

Pádraig Ó Conbhuí and Wyn Williams
University of Edinburgh

Electron holography is an experimental technique that is capable of observing magnetic microstructures on the same scale as can be determined using numerical modeling and thus bridge the gap between experimental measurements and theory. I will present a technique for simulating holographic images from the results of micromagnetic models and demonstrate an easily used tool for generating holograms on the fly in an interactive environment (ie in ParaView). Since holography flattens 3D information onto a 2D image, some useful information can be lost. By looking at some examples of holograms of interesting 3D magnetizations (ie PSD structures), particularly how they change as they're rotated, along with comparisons of different structures, I will examine what information can be retrieved and what might be lost. The existence of an external dipole can be indicative of an in-plane component of a seemingly out-of-plane vortex core. It is also seen, however, that two quite different structures (in this case a [111] vortex core and a [111] uniform magnetization) can sometimes be quite indistinguishable.

Simulated 'early-onset' PSD behaviour: size and shape effects in non-interacting greigite nanoparticles

Miguel A. Valdez-Grijalva and Adrian R. Muxworthy
Imperial College London

A micromagnetic finite element method of greigite has allowed us to construct a phase diagram of the SD and PSD states for a variety of shapes in the SD-PSD transition regime. Our zero-field results suggest a minimum size of 40 nm for the PSD states and a maximum of 80 nm for the SD states. Hysteresis simulations are consistent with an early PSD behaviour driven mostly by vortex states aligned with hard axes beginning from 50 nm and a more standard PSD behaviour (with vortices aligned with easy directions) from around 70 nm. This difference is explained by the intersections of the size vs. energy curves for the different domain states and particularly how the PSD curves intersect the SD curve.

Palaeomagnetic dates of Irish Zn-Pb deposits record regional remagnetization related to Variscan fluid flow

Conall Mac Niocaill\(^1\), Adrian Muxworthy\(^2\), Katie Vowles\(^2\) and Jamie Wilkinson\(^2\)
\(^1\)University of Oxford, \(^2\)Imperial College London

Hydrothermal ore deposits hosted within sedimentary rocks are a major source of the world’s lead, zinc and copper. The origins of these ores are believed to be diverse, ranging from formation at the same time as their host rocks from fluids that may have vented at the sea floor (“Sedex” deposits), through deposits that formed during burial and diagenesis, to those that are thought to be syntectonic. In many cases ore genetic processes and the geodynamic setting of mineralization remain controversial, due to the lack of minerals that can be easily dated by radiogenic isotopic methods. This is because a key question – the timing of mineralization with respect to sedimentary host rock deposition – can only be inferred from often ambiguous textural relationships between ore minerals and sedimentary structures.
Published palaeomagnetic “ages” for Irish Pb-Zn deposits have been used to argue for a secondary origin for these deposits, and against a “Sedex” origin. We present new results from both mineralized and un-mineralized Carboniferous rocks in central Ireland that indicate that they have all been remagnetized at about 310Ma. There is no spatial association between mineralization and remagnetization, and the overprint has also been previously identified in Silurian and Devonian rocks. There is a temporal association with Variscan deformation. Hence the published palaeomagnetic ages for Irish Pb-Zn deposits are dating Variscan fluid flow – but should not be taken as prima facie evidence against a primary origin for such deposits.

The palaeomagnetic field properties at high northern latitudes: preliminary results from Eyjafjardardalur valley

Radchagrit Supakulopas¹, Adrian Muxworthy¹, Arne Døssing² Conall Mac Niocaill³ and Morten Riishuus⁴
¹Imperial College London, ²Technical University of Denmark, ³University of Oxford, ⁴University of Iceland

The geocentric axial dipole (GAD) hypothesis is essential to palaeomagnetic research as it underpins palaeogeographic plate reconstructions. Previous palaeomagnetic data conclusively reveal that the time-averaged field during 10 ka is not the GAD while over long period of time, e.g. 200 Ma, the GAD seems to hold. However, the time scale during 10⁴-10⁶ Myr is still in doubt as the deviations from the GAD were reported. This research intends to palaeomagnetically study 3-7 Ma basalts in Eyjafjardardalur valley, Northern Iceland in order to test the GAD hypothesis. The preliminary results are presented herein including rock magnetic, palaeodirectional and palaeointensity data.

Magnetic susceptibility recording of nanoparticle transport in porous media

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Manufactured nanoparticles are increasingly used in a wide variety of applications. Once released into the environment they can be toxic to a range of organisms and there is concern over their long-term effects once they enter groundwater. To assess the risk posed by these new contaminants we are developing models of nanoparticle transport in groundwater.

Contaminant transport is often characterised in the laboratory by experiments where the contaminant is injected into a column and the breakthrough curve at the outflow is recorded. Here we exploit the ferrimagnetic properties of certain nanoparticles to monitor their progress throughout the column using a susceptibility bridge, leading to improved understanding of the processes occurring within the porous medium, such as attachment and straining. As the nanoparticles that are suspended in the pore fluid have an enhanced susceptibility and different frequency response compared to those that are attached, we show how further magnetic measurements such as frequency dependence of susceptibility, high-field magnetisation and thermomagnetic curves, have the potential to yield additional information regarding the attachment process.
Anisotropy of out-of-phase magnetic susceptibility of rocks and its potential for rock fabric studies

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The magnetic susceptibility measured in alternating field can in general be resolved into a component that is in-phase with the applied field and a component that is out-of-phase. While in non-conductive diamagnetic, paramagnetic and many ferromagnetic materials (including pure multi-domain magnetite) the phase is effectively zero, in some ferromagnetic minerals, such as pyrrhotite, hematite, titanomagnetite or ultrafine magnetically viscous magnetite, it is clearly non-zero. The anisotropy of out-of-phase susceptibility (opAMS) can then be used as a tool for the direct determination of the magnetic sub-fabrics of the minerals with non-zero phase. In some specific cases, the opAMS provides us with similar data to those provided by anisotropies of low-field dependent susceptibility and frequency-dependent susceptibility. The advantage of the opAMS compared to the other two anisotropies is its simultaneous measurement with the standard (in-phase) AMS during one measuring process, while the other two anisotropies require the AMS measurements in several fields or at least at two operating frequencies. A disadvantage of the opAMS may be its imprecise determination in specimens with very low phase angle. Consequently, it is highly recommended to inspect the results of the statistical tests for anisotropy of each specimen and to exclude the specimens whose opAMS is determined with insufficient precision from further processing.
Poster Presentation Abstracts

Mapping Petroleum Migration Pathways in Wessex Basin Using Magnetics and Seismic Mapping

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Potential hydrocarbon migration pathways from the hanging wall of the Purbeck fault into Sherwood Sandstone reservoir at Wytch Farm have been identified during this study via the interpretation of sixty two (62) 2D seismic lines. Furthermore, Magnetic characterisation of reservoir (Bridport Sandstone and Inferior Oolite) core material revealed variations in magnetic signatures along potential migration routes, with variations also observed with depth of sampling. Increases in magnetic signals were observed based on low-temperature magnetic measurements in terms of magnetic remanence carrying materials and also in coercivity values from the Kimmeridge area, via Creech to Wytch Farm, which is a potential oil migration route. A detailed magnetic study revealed variations in magnetic mineralogy along potential oil migration routes; magnetite predominates in the hydrocarbon proximal plume, pyrrhotite in the distal plume environment with mixed pyrrhotite and magnetite in shallow proximal plume environment. Magnetic susceptibility measurements carried out on cores also reveal increases in magnetic volume susceptibility in core materials with oil stains. It is suggested that magnetic mineralogy can be used as a proxy for hydrocarbon migration identification in the future.

Effect of maghemization on the magnetic properties of non-stoichiometric pseudo-single-domain magnetite particles

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During formation, magnetic minerals record the direction and intensity of the Earth’s magnetic field. Paleomagnetists use this information to investigate, for example, past tectonic plate motion and geodynamo evolution. However, subsequent to formation the constituent magnetic minerals are commonly exposed to a range of weathering conditions and environments. One of the most common weathering processes is maghemization, which is the oxidation of magnetite (Fe3O4) at ambient temperatures, i.e., the slow oxidation of Fe3O4 to maghemite (γ-Fe2O3), and is known to alter the original remanent magnetization.

Of the constituent magnetic minerals, particles in the single domain (SD) grain size range (< 100 nm) are regarded as ideal paleomagnetic recorders because of their strong remanence and high magnetic stability, with potential relaxation times greater than that of the age of the Universe. However, magnetic signals from rocks are often dominated by small grains with non-uniform magnetization that exhibit magnetic recording fidelities similar to those of SD grains (termed pseudo-SD (PSD)).
In this context, the effect of maghemization on the magnetic properties of Fe$_3$O$_4$ grains in the PSD size range is investigated as a function of annealing temperature. X-ray diffraction and transmission electron microscopy confirms the precursor grains as Fe$_3$O$_4$ ranging from ~150 nm to ~250 nm in diameter, whilst Mössbauer spectrometry suggests the grains are initially near-stoichiometric. The Fe$_3$O$_4$ grains are heated to increasing reaction temperatures of 120 – 220 ºC to investigate their oxidation to γ-Fe$_2$O$_3$. High-angle annular dark field imaging and localized electron energy-loss spectroscopy reveals slightly oxidized Fe$_3$O$_4$ grains, heated to 140 ºC, exhibit higher oxygen content at the surface. Off-axis electron holography allows for construction of magnetic induction maps of individual Fe$_3$O$_4$ and γ-Fe$_2$O$_3$ grains, revealing their PSD (vortex) nature, which is supported by magnetic hysteresis measurements, including first-order reversal curve analysis. The coercivity of the grains is shown to increase with reaction temperature up to 180 ºC, but subsequently decreases after heating above 200 ºC; this magnetic behavior is attributed to the growth of a γ-Fe$_2$O$_3$ shell with magnetic properties distinct from the Fe$_3$O$_4$ core.

**Application of magnetic techniques to lateral hydrocarbon migration - Lower Tertiary reservoir systems, UK North Sea**

Sope A. Badejo, Adrian R. Muxworthy, and Alastair Fraser

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High-wavenumber magnetic anomalies discovered over oil fields have been linked to the precipitation of near surface magnetic minerals due to the reducing environment generated by hydrocarbon seepage. Pyrolysis experiments have been carried out in Imperial College have shown that magnetic minerals are precipitated in the oil-kitchen and are small enough to get through the pore spaces in the reservoir rocks. This study focuses on the magnetic minerals that should be observed in the reservoir and its application to lateral hydrocarbon migration. The Central North Sea is the study area. The Tertiary reservoir fans of the Central North Sea are regionally continuous, this facilitates lateral hydrocarbon migration over a long distance.

**Using X-rays to Map the Magnetism in the Vigarano Carbonaceous Chondrite Meteorite**

Helena Bates, Adrian Muxworthy and Jay Shah

*Imperial College London*

A study of 19 chondrules of the reduced CV3 Vigarano carbonaceous chondrite meteorite has been conducted. Eight chondrules were mutually oriented using micro-CT scans with the aim of perform- ing the paleomagnetic conglomerate test to see if magnetic moments aligned. This is a test to see if magnetisation is pre-accretionary or not and can give information about the parent body from which Vigarano came, specifically if it had an internal dynamo generating a magnetic field. This is impor- tant for understanding of early Solar System planetesimals. The chondrules were removed from the bulk sample using freeze-thaw disaggregation, and then demagnetised using incrementally increasing alternating fields. I reorientated eight samples which had similar paleomagnetic directions at the 95% confidence level, however when split into matrix and chondrule-rich samples the matrix-rich samples had aligned magnetic moments but the chondrule-rich samples did not align (although due to the low number of chondrule-rich samples this cannot be said with much certainty). There are two potential scenarios for the origins of the magnetisations
Transverse and flow parallel AMS in Eocene turbidites, Ainsa Basin, northern Spain

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Understanding sedimentary transport mechanisms in shale-prone basins can be difficult, but anisotropy of magnetic susceptibility (AMS) has the sensitivity and ease of use to be widely applicable. The Ainsa Basin was selected to assess the strengths and limitations of AMS as a palaeoflow indicator, since it has a well characterised palaeoflow and depositional model. The basin is geographically a tightly confined, small turbidite basin, widely used as an outcrop analogue for sub-surface slope/turbidite basins. Sixty-two samples were taken from two sites, 22 from the older Ainsa I (Ainsa Quarry) and 40 from the Ainsa II (Barranco Forcaz) facies. The AMS displays both flow-parallel and flow-transverse Kmax directions, with a weak indication of some flow-aligned Kmin imbrication. Both features match the conceptual grain deposition model of Park et al. (2013). However, the shape and strength of the AMS fabrics diverge from these simple grain transport models, related to the grain interaction regimes. Reasons for these differences are explored.

Testing the Speed of the Last Geomagnetic Reversal

Sam Greenwood and Phil Livermore

University of Leeds

A recent paper by Sagnotti et al. (2014) suggested that only 100 years may have been needed to fully reverse the polarity of the geomagnetic field during the Matuyama-Brunhes transition (the most recent reversal ~780,000 years ago). I test to see how geophysically reasonable this time scale may be by using spherical harmonic models of the field during the time period the reversal occurred. I optimise the flow in the upper outer core constrained by these field models to provide an upper bound on the rate of change of the axial dipole component of the field (represented by the g10 gauss coefficient). Initial results show that at 780.2 ka ago the field had the potential to change at a rate of 280 nT/year, varying g10 by 28,000 nT in 100 years. This may have been enough to produce the signal observed in the palaeomagnetic data however there are several other factors that may change this value. Since they are fully optimised the core flows are not necessarily that realistic, the truncation of the field model at degree 4 removes effects from potentially significant higher degrees and the field models themselves can contain large uncertainties. It seems at the moment that although on the edge of within the limits of the optimised analysis it is not very likely that 100 years would actually be enough to reverse the polarity from one stable state to another.

Archaeomagnetic Studies in the Scottish Neolithic: evaluating the potential of the Ness of Brodgar, Mainland Orkney, UK

Samuel Harris and Catherine Batt
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Here we present an archaeomagnetic study at the Ness of Brodgar; that lies in the midst of the 'Heart of Neolithic Orkney' World Heritage Site. This unique Neolithic complex consists of a deeply stratified sequence of large structures within a monumental walled enclosure. The main aim was to ascertain the complete geomagnetic vector of the ancient geomagnetic field at the time of last firing. Archaeodirectional measurements of 78 samples from four burnt horizons successfully isolated 71 characteristic directions of the ancient geomagnetic field. In order to ascertain the strength of the field, experiments were carried out on pottery sherds from the site. Combining these studies with a complete rock magnetic study showed the stability of the iron oxides in the material and helped to identify hearth temperatures in antiquity. Measurements included: stepwise alternating field demagnetisation of natural remanent magnetisation, 14GHz microwave measurements, susceptibility frequency dependence, isothermal remanent magnetisations, hysteresis loops, thermomagnetic heating and cooling curves, and backfield experiments. The ancient geomagnetic field information from the four burnt horizons were compared to two data sets to ascertain the periods in prehistory when the geomagnetic field reflected that of the field retained by the archaeological features. These included: the global model of CALS10k.1b[1], SHA_DIF_14k[2] and the European palaeosecular variation curve for the Neolithic[3] which yielded a number of complementary date ranges. At present the calibration methods do not allow precise dating of the archaeological features. However, there are a number of date ranges that match the archaeological and radiocarbon evidence. The research demonstrates the potential for material from this site to delineate geomagnetic change in the Scottish Neolithic.


A chronostratigraphic framework for the Morrison Formation, western USA: a sequence stratigraphic and magnetostratigraphic approach

Susannah Maidment and Adrian Muxworthy
Imperial College London

The Morrison Formation comprises a series of fluvial, overbank and lacustrine sediments deposited in the backbulge depozone of a retroarc foreland basin during the Upper Jurassic. The Formation has been intensively studied since the discovery of its diverse and well-preserved dinosaurian fauna in the latter part of the 19th century. Outcropping from Montana in the north to New Mexico in the south, the Formation covers 12 degrees of latitude, and it was deposited over a time period of approximately 10 million years. The diverse environments represented, and the length of time over which the sediments were deposited, makes the Morrison Formation an ideal candidate for examining biodiversity patterns, population ecology, and evolution at a time when climatic conditions were significantly warmer than today. However, attempts to understand the Morrison dinosaur
fauna are severely hampered by a lack of long range correlation: the chronostratigraphy of the Formation across its outcrop area remains entirely unknown. Magnetostratigraphic sampling and sedimentological logging were carried out at 19 sites across the Morrison Formation in order to produce a chronostratigraphic framework for the Formation. Sampling was carried out using a rock core drill, which restricted sampling to sandstone intervals, because mudstones were too friable for cores to be recovered. This resulted in unsatisfactory sample coverage at many sites. Alternating field demagnetisation was found to be ineffective at separating magnetic components and fully demagnetising the specimens, so thermal demagnetization was carried out. Samples were magnetically weak, with intensities commonly <1x10^-3A/m, and alteration of the magnetic phase was frequently observed at around 400OC. This resulted in noisy data with high α95 values, precluding easy interpretation. Magnetostratigraphic results are therefore or poor quality and somewhat unsatisfactory. However, sequence stratigraphic analysis clearly divided the Formation into three sequences with six systems tracts, and this framework is supported by the magnetostratigraphic results that were recovered, as well as by existing radiometric dates. Preliminary analysis of the dinosaurian fauna indicates homogeneity at the generic level across the 10 million years represented by the Formation, suggesting anomalously low rates of morphological evolution at this time and in this geographic setting.

Magnetic diffusion, reversed flux patches and the Earth's dipole

Maurits Metman, Phil Livermore and Jon Mound

University of Leeds

Changes in Earth’s magnetic field are most often explained by advection of the magnetic field near the core-mantle boundary (CMB). While doing so, it is often assumed that the other process controlling temporal geomagnetic changes, that is magnetic diffusion, is negligible compared to advection.

However, there is reason to believe that diffusion does in fact play a significant role in explaining geomagnetic secular variation. For example, there are areas at the CMB where the sign of the radial field is revered compared to that of the dipole state, also known as reversed flux patches (RFPs). These RFPs are thought to be created by a combination of outward advection of the toroidal field and diffusion (Bloxham, 1986). In turn, these patches are thought to be responsible for the decay in dipole moment over the past four centuries (Gubbins, 2006). Additionally, diffusion might have a stronger control on secular variation than previously thought, as it has been proposed that the outer part of the core is stratified (Pozzo et al., 2012).

In this presentation I will show the secular changes in Earth’s magnetic field and its RFPs over the past four centuries, as obtained from the gufm1 field model (Jackson et al, 2000). Moreover, I will show a method of defining the magnetic equator and how I have used it to find reversed flux patches and their midpoints on the CMB. Lastly, I demonstrate how RFPs have contributed to the decay of Earth’s magnetic dipole moment.

Magnetic properties of micrometeorites from Jurassic stromatolites of Poland

Joy Muraszko¹, Richard Harrison¹, Joshua Einsle¹ and Piotr Ziolkowski²
¹University of Cambridge, ²University of Warsaw

This study aims to determine the rock magnetic properties of micrometeorites from stromatolites of the Kraków-Wieluń Upland in Poland.

These stromatolites are developed as condensed sections or lag deposits of Upper Callovian to Lower Oxfordian age, associated with sub-aqueous elevations in a deep water setting.

Lowe sedimentary rates and lack of detrital input create favourable conditions for increased accumulation of micrometeorites. Cosmic spherules were magnetically extracted from crushed bulk rock and studied using First Order Reversal Curves (FORCs), examined in SEM-FIB dual beam microscope.

A relationship between the surface texture, internal structure and magnetic properties was observed.

Further studies involve a comprehensive study of a larger suite of micrometeorites from the stromatolites using FORCs, SEM-FIB microscopy and Magnetic Force Microscopy for direct imaging of magnetic domains.

How Well Does Preisach Theory Predict Pseudo-Single-Domain Behavior?

Adrian Muxworthy
Imperial College London

Single-domain Preisach theory has been used to quantify the behaviour of natural systems, for example, it has been used to determine paleointensity estimates from first-order-reversal-curve (FORC) measurements on natural samples, but how well does Preisach theory explain the behavior of the particles dominant in many natural systems: pseudo-single-domain (PSD) grains? Using experimental data collected from synthetic samples I investigate this. The samples were generated by electron beam lithography, and consist of two-dimensional arrays of near-identical particles in the PSD grain size range. To generate a Preisach distribution, I measure a FORC diagram and then compare measured responses, e.g., alternating-field demagnetisation, with those predicted by a single-domain Preisach theory.

Preliminary study in the anisotropy of magnetic susceptibility of some evaporite samples

Jack Richardson and Carl Stevenson
University of Birmingham

The mobilisation and intrusion of salt plays a major role in the evolution of basins. Although the geometry and distribution of salt structures can be easily examined, the internal dynamics of salt intrusion are only partially understood. Modelling the influences of salt intrusion in basins, in particular predicting the future structural and thermal evolution of a basin and the related effects on the hydrocarbon habitat, are limited.
In order to overcome this impasse in salt tectonics, detailed and high quality strain data is required from salt outcrops. To obtain structural data we will use anisotropy of magnetic susceptibility (AMS) measurements on oriented samples from mine exposures. This technique measures the distribution and orientation of any detrital magnetite or Fe-bearing clay minerals within the salt. Where these are absent, the crystal lattice of halite or gypsum can also produce a measurable signal.

Block samples containing carnallite, sylvite, gypsum, halite and polyhalite, from the Cabanasses mine in the Suria anticline, NW Spain, are presented here. We have measured the AMS of sample blocks with and without clear fabrics to establish a preliminary method of AMS analysis within environments affected by halokinesis.

Fabric data derived from AMS analysis will provide crucial information about the strain field allowing a comprehensive view of the flow of the salt. Fabrics mapped in 3D from mine exposures will generate the first internal flow model for salt based on empirical data.
The meeting will be held in rooms G39 and G41 of the Department of Earth Science and Engineering, Royal School of Mines Building, SW7 2BP.

The Conference dinner at 19:00 will be in The Garden Room at 58 Prince’s Gate, SW7 1AY opposite the Imperial College London Exhibition Road entrance.