Security of Supply of Mineral Resources Programme

SoS MinErals

Thursday 9 May 2019

The Royal Society, London

Finale meeting

NERC SCIENCE OF THE ENVIRONMENT · Newton Fund · FAPESP · EPSRC Engineering and Physical Sciences Research Council

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The Natural Environment Research Council, Engineering and Physical Sciences Research Council &
Sao Paulo Research Foundation in Association with All Party Parliamentary Group for International Mining Present

Contents

The finale meeting of the NERC Security of Supply of Mineral Resources programme provides an opportunity for research teams to celebrate and share their achievements over the past five years with stakeholders and the wider community. It is aimed at all those with an interest in the raw materials for green growth, particularly the e-tech elements that are used in low carbon power generation and energy storage (e.g. cobalt, rare earths, tellurium and selenium) — which are the focus of this ambitious £15M cross-Council Research Programme.

Recognising that increased demand for these raw materials would put a significant strain on the existing sources of supply, the Natural Environment Research Council (NERC) and the Engineering and Physical Science Research Council (EPSRC) launched the multi-million pound Security of Supply of Mineral Resources (SoS-MR) research programme. In collaboration with industry and our global partner FAPESP — the Brazilian São Paulo Research Foundation, this funded four projects to enhance knowledge on the occurrence and processing of the minerals required. With the aim that the knowledge gained will enable more sustainable production, reduce the potential for supply issues and constrain progress towards a low carbon economy in the UK and globally.

In addition, poster exhibitions will expand on the technical and scientific research of the four projects.

SoS MinErals

Introduction

Global action to protect the environment and to mitigate and adapt to increased atmospheric carbon dioxide (CO_2) is demanding significant changes in the way we generate and use energy. The Security of Supply of Mineral Resources research programme focuses on the science needed to sustain the security of supply of the key elements that underpin current and future green energy technologies — cobalt (Co), tellurium (Te), selenium (Se), neodymium (Nd), indium (In), gallium (Ga) and heavy rare earth elements (HREE) — the 'e-tech elements'.

The aims of the Programme are simple: to enable more sustainable production of e-tech elements through a new understanding of mineral genesis and extraction technologies, to reduce the potential for supply issues and through these ensure progress towards a low carbon economy in the UK and globally.

The programme centres on four competitively won projects that directly involve over 50 industrial partners and some 20 plus universities and research organisations with collaboration between the UK, Europe, the Americas, and Asia. It directly funds 24 postdoctoral research associates and 17 PhD researchers, and seeks to deliver world-leading research — and world-leading scientists — in this emerging area. Furthermore, from Day 1, our industrial partners have played a key role in development of the Programme, and in the accelerating results into practice.

The programme has two high level goals:

Goal 1	Understand e-tech element cycling and concentration in natural systems
Goal 2	Understand how to predict and mitigate the environmental effects of extraction and recovery of e-tech elements.

Advances in the science are needed to:

- understand how strategic minerals are mobilised and concentrated in the crust
- deliver advances in process understanding
- develop models to predict the environmental impact of scaling up on new technologies for low carbon mineral extraction
- evaluate the implications of exploiting deep, more dispersed and/or more inaccessible minerals in the future

Agenda

Time	Item	Speaker
0900	Registration and refreshments	
0930	**Welcome**	*Beth House*, Head of Research – Earth and Energy Sciences, NERC
	Programme overview Video presentation	*Adrian Boyce*, Professor of Applied Geology, University of Glasgow
1000	**Geoscience outputs and achievements** • New geological environments for rare earth elements and their potential to supply demand for power generation and electric vehicles • Crustal cycling of tellurium and selenium • The resource potential of submarine manganese crusts to provide materials for green energy generation • The geology of future cobalt supply – feeding the demand for battery metals	 *Martin Smith & Kathryn Goodenough* *Dan Smith* *Isobel Yeo & Pierre Josso* *Richard Herrington, Agnieszka Dybowska, Steve Roberts, Paul Schofield with others on the CoG³ research team*
1130	Refreshment break	
1200	**Environmental and social perspectives** • Tellurium & selenium: supply, demand and waste • The geomicrobiology of cobalt • Modelling the impact of seafloor mining • Responsible sourcing of raw materials used in the low-carbon economy	 *John Parnell* *Laura Newsome & Geoff Gadd* *Jez Spearman, Lea-Anne Henry & Mike Zubkov* *Frances Wall*
1300	Lunch	

...Continued

Agenda

Time	Item	Speaker
1400	**Industry and stakeholder engagement** ***Keynote 'Industry perspective'*** • Geometallurgy for industrial solutions • Industrial applications of deep eutectic liquids in metal extraction • Stakeholder engagement, outreach and input to the policy and regulatory framework for deep-sea mining • Targeting near-term critical metal deposits after speculative bubbles: An example from Namibia	*Alex Lemon, President, Mkango Resources Ltd.* *Hylke Glass & Barrie Johnson* *Gawen Jenkin & Andy Abbott* *Paul Lusty* *Ed Loye*
1545	Refreshment break	
1615	***Keynote 'Climate change and green growth'*** ***Keynote 'International perspective'***	*Baroness Brown (Julia King)*, Vice Chair of the Climate Change Committee *Darryn Quayle*, Department for International Trade
17:05	**Minerals resources for green growth — panel discussion**	Chaired by *Professor Frances Wall*, University of Exeter, Camborne School of Mines
	Closing remarks	
1730	**Drinks reception**	
1900	Event closes	

Keynote speakers

The Baroness Brown of Cambridge DBE FREng FRS

Deputy Chair Climate Change Committee

Baroness Brown of Cambridge (Julia King) is a crossbench member of the House of Lords and an engineer. Her career has included senior engineering and leadership roles in industry and academia. She also holds the following positions:

- Chair of the Committee on Climate Change's Adaptation Sub-Committee
- Non-executive director of the Offshore Renewable Energy Catapult
- Chair of the Carbon Trust
- the UK's Low Carbon Business Ambassador

She was non-executive director of the Green Investment Bank and she led the King Review on decarbonising transport (2008). Baroness Brown is currently supporting the UK offshore wind sector as Sector Champion for the development of the Sector Deal as part of the Government's Industrial Strategy. She is a Fellow of the Royal Academy of Engineering and of the Royal Society, she was awarded DBE for services to higher education and technology.

Alex Lemon

President and Co-Founder, Mkango Resources Ltd.

Alex Lemon is a graduate of the Royal School of Mines, Imperial College, London (MSc DIC in Mineral Exploration) and Oxford Brookes University (BSc Geological Sciences). He has 24 years' experience in mineral exploration and business development. Mr Lemon is a founding Director and President of Mkango and Mkango's major Shareholder, Leominex. From 1994 to 2001 was the Managing Director of a gold mining company, which owned and operated a producing gold mine in Central Asia, where he gained extensive operating experience in emerging markets including government negotiations and project management. From 2001 to 2005, he worked for a family office, Allied Commercial Exporters as an investment adviser. Since 2005 has been involved in the exploration and evaluation of a variety of projects throughout Africa, Central Asia and Europe. He is a Fellow of the Geological Society, Fellow of the Geographical Society and a Member of the Southern African Institute of Mining & Metallurgy.

Darryn Quayle

Mining Engineer & Specialist at the Department for International Trade

Darryn Qualye is a mining engineer from the West Australian School of Mines in Kalgoorlie, Darryn has amassed substantial international experience in underground and open pit operations associated with many commodities

including gold, copper, iron ore and lead, tin and zinc. Darryn was appointed the Department for International Trade's Mining Engineer and Specialist in 2014 providing technical support to the Department as well as looking after the UK's mining interests in the Americas, especially Latin America. His role expanded last year to be included in a cross UK Government team aiming to ensure a secure supply chain of metals and minerals for the UK's own industries and global trade.

Introductory speakers

Beth House

Head of Research – Earth and Energy Sciences, Natural Environment Research Council (NERC)

Dr Beth house will introduce the programme from a UKRI perspective.

Speaker biography

Dr Beth House has worked for the Natural Environment Research Council (NERC) for 9 years and is currently the Head of Research for Earth and Energy Science. Her main responsibility is for the delivery of current and new strategic research investments in energy and earth science. The Natural Environment Research Council is the UK's leading funder of environmental science, and is part of UK Research and Innovation (UKRI).

Professor Adrian Boyce

Professor Adrian Boyce will give an overview of the development and execution of the Security of Supply of Mineral Resources programme.

Speaker biography

Adrian Boyce is Professor of Applied Geology, Scottish Universities Environmental Research Centre (SUERC) at the University of Glasgow. He is a Fellow of the Society of Economic Geologists (SEG) and Geology Applied to Mineral Deposits (SGA) and a leader of applied stable isotope Geoscience research in the UK and beyond. Adrian has co-published over 300 peer-reviewed papers, many focused on the application of stable isotope geochemistry to hydrothermal processes. He has run the NERC Isotope Community Support Facility at SUERC for over 20 years, set in one of Europe's leading stable isotope laboratories, through which he has been responsible for the isotopic aspects of over 120 peer-reviewed NERC projects, including over 75 PhD students. He has demonstrated the utility of underpinning stable isotope techniques on research from km- to sub-millimetre scale fundamental hydrothermal processes from crustal fluid flow mechanisms to ocean vents to major ore deposits to geothermal energy. Adrian was Chair of Expert Group for the SoS Minerals Programme and is a member of the associated Programme Executive Board.

Session 1 speakers

Geoscience outputs and achievements

New geological environments for rare earth elements and their potential to supply demand for power generation and electric vehicles

Martin Smith and Kathryn Goodenough

Abstract

Many resources of the rare earth elements (REE) are derived from hard-rock deposits that require large amounts of energy and chemical reagents to mine and process. Potential alternative sources include those formed by weathering, in particular ion adsorption deposits (IADs). In South China, IADs formed by lateritic weathering of granites currently provide much of the world's heavy rare earth element supply. New deposits are under investigation in Myanmar, Brazil, Madagascar, USA and elsewhere. These IADs are relatively simple to process, through in situ or heap leaching, but the details of their genesis and mineralogy have been little studied until recently. In the SoS RARE project, we have studied examples of IADs in Madagascar and find that formation of these deposits represents a complex interplay of bedrock geological history, climate and weathering history, and topography. Bulk rock total REE contents for Madagascar protoliths vary from 400–5000ppm, with 10 to 20% of the total as HREE. Ammonium Sulphate leaches (designed to remove clay-adsorbed REE) of laterite overlying those protoliths show leachable TREE from 130–500ppm, with no preferential HREE adsorption. Within the sequential extraction procedure the reducible fraction (hydroxylammonium chloride leach) showed the highest REE, but this is largely attributable to Ce4+ in oxide layers. Analysis of laterite profiles show that the REE distribution is heterogeneous, with control from both bedrock heterogeneity, and the hydrological variation between pedolith and saprolith. Similar patterns are seen in Chinese profiles from Jiangxi province. X-ray diffraction shows the clay fraction in all sites is dominated by kaolinite and halloysite. This is consistent with experimental data which show that kaolinite is only HREE selective in high ionic strength solutions, and suggest that HREE enrichment in lateritic deposits may be a function of exceptional bedrock conditions. Characterisation of samples from both Madagascar and China using Synchrotron X-Ray absorption spectroscopy (XAS) confirms that the REE are directly adsorbed on kaolinite surfaces, and are present as 8 or 9 co-ordinated, hydrated, complex ions on basal surface sites rather than as interlayer or edge adsorbed ions. This works confirms common genetic mechanisms between Chinese and globally identified deposits, and the improved understanding of the REE incorporation mechanism may help with the development of more efficient and environmentally sensitive extraction techniques.

Speaker biographies

Martin Smith is Professor of Geochemistry in the School of Environment and Technology, University of Brighton. Martin is a geologist, geochemist and mineralogist, with 25 years' experience in geochemistry applied to problems in mineral deposit geology, hydrogeology and environmental mineralogy. He has been a Chartered Geologist with the Geological Society of London since 2012. Martin's research interests can broadly be classified under the heading of water-rock interaction. This covers the chemical and physical interaction of fluids with earth materials from high temperature igneous systems to environment mineralogy and fluid chemistry. Current research interests include the genesis of rare earth element and iron oxide-copper-gold (IOCG) deposits, the influence of unsaturated zone flow on groundwater chemistry, particularly with respect to diffuse urban pollution, and the redox mineralogy of marine steel corrosion. Martin is a researcher on the SoS RARE project for SoS Minerals.

Dr Kathryn Goodenough is Deputy Director, BGS Global and Principal Geologist at the British Geological Survey, and is a Co-I on the SoS RARE project. Kathryn's research focus is on studying mineral deposits, particularly deposits of the critical metals, and setting them into their broader geodynamic context. Kathryn is involved in three major international research consortia (EURARE, SoS RARE, and Hitech AlkCarb) that are making major advances in understanding all aspects of the supply chain for the rare earth elements and associated critical metals. These projects encompass field geology, mineralogy, geometallurgy and minerals processing, for a range of potential deposits from carbonatites in Greenland to weathered alkali granites in Madagascar. Kathryn also works on building capacity in African geological surveys to achieve sustainable governance of their natural resources.

Crustal cycling of tellurium and selenium

Dan Smith

Abstract

Tellurium and selenium both have growing demands from advanced and green technologies, including photovoltaic cells, thermoelectric generators and coolers, fibre optic glasses, and potentially next-generation lithium batteries. Both elements are rare in the crust though, and current means of supply — from the processing of copper refinery waste — is poorly responsive to changes in demand.

Tellurium and selenium are often considered 'chemical bedfellows' in geoscience, given that they occur in the same group on the periodic table, and that they are presently recovered from the same source. In the TeaSe project, we are

challenging this idea. Tellurium and selenium have significantly different behaviours as the rock cycle transports them from the Earth's mantle to the surface.

For the most part, geological processes result in very low abundances of Te and Se in typical rocks; however, some environments and processes give rise to spectacular enrichments, typically in one (rather than both) of the elements. These enrichments tell us about Earth processes (melt transport in aqueous fluids, lithospheric fertilisation, hydrothermal fluid pH, distillation, fractionation, redox-controlled transport, microbiological control), but also give us targets for mineral exploration. The ability to target specific ore bodies and ore minerals for tellurium, selenium, or both, gives us more flexibility in meeting demand.

Speaker biography

Dr Dan Smith is an Associate Professor in Applied & Environmental Geoscience at the University of Leicester. Dan's research tackles ore formation, and the crustal magmatic processes that underpin mineralisation. His particular areas of interest are in those deposits where magmas and fluids combine to form metal-rich ores (particularly copper, gold and the critical elements that accompany them). Dan currently leads the SoS Minerals project TeaSe — a consortium of researchers studying tellurium and selenium resources, to support the growth of clean energy (Te & Se being vital ingredients in modern solar panels).In 2018, Dan was one of the Mineralogical Society's Distinguished Lecturers, and toured the UK to talk about his research into ore formation, reducing the environmental impact of resources, and ensuring security of supply of raw materials.

The resource potential of submarine manganese crusts to provide materials for green energy generation

Isobel Yeo and Pierre Josso

Abstract

Hydrogenetic ferromanganese crusts are a potential resource of strategic and critical metals that are essential for the future decarbonisation of the global economy. Formed over millions of years, the processes controlling where and how Fe-Mn crusts grow are poorly understood. Through a study of in situ FeMn crusts growing on a Tropic Seamount in the NE Atlantic, Marine e-tech has been able to show how present-day conditions are reflected in the systematic distribution of growth and erosion that broadly map onto the distribution of mobile sediments, the morphology of the seamount, its depth, and the prevailing hydrographic conditions. Drilling through the FeMn crusts across the summit of the seamount

recovered whole cores from which an age model has been reconstructed extending back for 75 Myr revealing how global oceanographic conditions also affect FeMn crust growth and composition.

Using detailed mapping of seafloor outcrop, hydrographic modelling, and scanning electron microscope imagery of FeMn crusts samples from the Tropic Seamount, we find that just over 35% of the summit is covered by ferromanganese crust, with the rest variably covered by plains of mobile sediment. The steep flanks of the seamount largely expose ferromanganese crust both in situ and as debris flows. The strongest currents are located on the seamount's upper-flanks, central eastern limb, and summit. Three categories of surface erosion textures are identified ranging from pristine to completely polished. In general, the least eroded crusts are found below 2000 m water depth and the most strongly eroded crusts are largely found on the seamount's summit. Pristine samples are restricted to areas that rarely experience current speeds over 0.2 m/s. However, the entire range of crust textures are found across all current speeds. This complexity reflects the availability of mobile sediments as an abrasive agent (i.e. especially at the seamount's summit), and the importance of small-scale geomorphology (<50 m) on the local-scale dissipation of current energy.

While the surface textures yield a snap-shot of current factors controlling growth and erosion, the FeMn crusts record a history of accretion of over 75 Myr. By constructing a multi-proxy age model and coupling that with high-resolution, stratigraphic, textural and geochemical investigation of 20 cm-long core, we are able to reconstruct the prevailing oceanographic conditions during formation. Surprisingly, we find textural stratigraphic coherence between Tropic Seamount and Pacific Fe-Mn crusts, formed since the Late Cretaceous, highlighting that global oceanic and climatic phenomena exert first order controls on crust development. The dominant controls include major oceanographic events, mineral textures, orbital forcing, and micro-topography. In addition, our results demonstrate the importance of phosphatised samples as an underexplored resource for critical metals such as Pt and Te.

In conclusion, we recognize both long-term global oceanographic controls on FeMn crust formation coupled with local-scale hydrographic and substrate geomorphological conditions that affect the thickness and composition of FeMn crusts. Together, these results help us predict the resource potential of FeMn crusts elsewhere.

Speaker biographies

Dr Pierre Josso is a geochemist in the Ore Deposits and Commodities Team of the British Geological Survey with 6 years' experience working on deep-oceanic mineral deposits and their genetic relationship to seafloor environment and water column chemistry. His work in the Marine e-tech project focused on the high-resolution geochemical and morphological 4D evolution of Fe-Mn crusts deposits to explore how local and global scale oceanographic and environmental phenomena affect the composition of crust deposits trough time. His research interests include mineral resources, fluid-rock interactions, isotopic geochemistry and geochemical modelling.

Dr Isobel Yeo is a postdoctoral researcher in Marine Geoscience at the National Oceanography Centre and a lecturer in Earth Resources at Kingston University London. Isobel has been researching mineralisation and volcanic processes in the oceans for 11 years, including projects on finding inactive hydrothermal deposits, mapping and assessing ferromanganese crusts and mineralisation and volcanic activity in oceanic fracture zones. Within SoS Minerals she has worked on the Marine e-tech project, mapping ferromanganese crustal exposure, analysing ferromanganese crust growth patterns and micro textures and examining the relationship between crustal growth and hydrographic processes.

The geology of future cobalt supply – feeding the demand for battery metals

Richard Herrington, Agnieszka Dybowska, Steve Roberts, Paul Schofield with others on the CoG³ research team

Abstract

Cobalt is a metal associated with modern technologies with the Li-ion rechargeable battery industry underpinning electric vehicle development using around 42 percent of global cobalt production. Of the battery metals, Co appears to have the tightest supply and demand fundamentals. Over 95 percent of the world's primary cobalt comes as a by-product of nickel or copper mining. Furthermore, 55% of that by-product production is located in the Democratic Republic of Congo, some of which supply has been linked to unethical mining practices.

The recent price hike for cobalt suggests that we are already witnessing an increased scarcity of cobalt supply. Mines producing complex arsenide ores in Morocco are the only primary cobalt producers. This means that a major added pressure to supply can be linked to the price of copper and nickel which have been dropping to their current six-year lows, making some of the mines

traditionally supplying by-product cobalt uneconomic. In the short term at least, with a growing cobalt market, new resources are needed to secure the shortfall supply.

In absolute terms, the planet's cobalt resources are more than adequate, for example the deep ocean manganese nodules are estimated to contain more than 120 million tonnes of cobalt, yet an imminent supply from these sources is unlikely due to the challenges of seabed mining. As a result, industry has been turning to seeking terrestrial cobalt in a range of neglected deposit types.

This talk will highlight the geological aspects of the research project CoG^3, funded through the UK's NERC SoS Minerals programme, that is specifically focused on the geology and mineralogy of cobalt in a range of styles and settings with the aim of identifying new future resources from a diversity of natural deposits http://www.nhm.ac.uk/our-science/our-work/sustainability/cog3-cobalt-project.html. This talk will assess results from the CoG^3 research to confirm that there are existing deposits where changes to processing methods could extract cobalt currently left in the ground or reporting to waste. We also highlight potential new sources where the implementation of innovative technology, also under development as part of CoG^3, could lead to a wider diversity of supply options for the primary cobalt needed for the growing green economy.

Speaker biographies

Richard Herrington is currently acting Head of the Science Directorate at the Natural History Museum and Principal Investigator of the SoS Minerals CoG3 project - The geology, geometallurgy and geomicrobiology of cobalt resources leading to new product streams. As a researcher, Richard investigates the behaviour of metals critical for our modern economy in earth systems. He specifically focuses on those metals concentrated by deep weathering processes in surface systems and have projects focused on looking at cobalt and rare earth metals in particular. Other interests include investigating the links between mineral deposit formation and the earth's geodynamic history and the association of mineral deposit formation and biota in the deep ocean. Richard's work involves collaboration with industry and the results of his research provide them with new information enabling better and more sustainable mining techniques to be considered.

Paul Schofield is a mineralogist who studies the crystal-chemistry and atomic-structure of minerals in order to constrain the conditions of geochemical and geological processes. In addition to studying the atomic structure and stability of minerals, his research focuses on the properties and behaviour of minerals within

complex, heterogeneous, multi-phase aggregates and rocks. Such systems include the matrix mineralogy of carbonaceous chondrite meteorites, oxidised lateritic ore deposits and deforming polycrystalline rocks. To study mineral properties at the atomic-scale in these complex systems his research group uses diffraction, spectroscopy and spectromicroscopy methods, particularly those available at international synchrotron and neutron facilities.

Steve Roberts is Professor of Geology and Head of the School of Ocean and Earth Science based at the National Oceanography Centre, University of Southampton. His primary research interest is seeking to understand the processes that result in the development of ore deposits, particularly of copper, zinc and gold. Recent research activity has focussed on the origin of the world class copper-cobalt deposits of the Zambia Copperbelt and the formation and evolution of hydrothermal vent sites on the Ocean Floor, in particular within the Mid-Cayman Trough in the Caribbean and the Brothers Volcano on the Kermadec Arc.

Session 2 speakers

Environmental and social perspectives

Tellurium & selenium: supply, demand and waste

John Parnell

Understanding how selenium and tellurium behave at low to moderate temperatures helps us to suggest how these elements can be recovered using less energy than at present. For example, their association with iron oxides show how they may be extracted from solution, and thus prevented from unwanted dispersion in the environment, and potentially concentrated as a resource. It also shows how iron-rich metal and coal mine waste water can become a toxic contaminant and requires control. Education about selenium in particular can take advantage of its role in the evolution of animals, and how our biology is ultimately linked with geological cycling of the element.

Speaker biography

John Parnell is Professor of Geology and Petroleum Geology at the University of Aberdeen. He has extensive experience of hydrocarbon exploration, and adapts techniques from the oil and gas industry to study organic compounds in mineral deposits, and metal accumulation associated with organic matter. His research is focussed on understanding the geochemical and habitat controls on life on Earth, and the potential extrapolation to other planets.

The geomicrobiology of cobalt

Laura Newsome

Cobalt is essential for the modern technology that underpins the decarbonisation of our economies, but its supply is limited leading to its designation as a critical metal. Cobalt biogeochemistry is poorly understood, yet knowledge of how biogeochemical cycling impacts cobalt behaviour in the environment could assist the development of new techniques to recover cobalt from ores, and so improve the security of supply.

In the CoG^3 project we examined a range of Co-rich geological materials, characterised their microbial communities, and investigated how biogeochemical cycling can control the mobility of cobalt in the environment. As well as this we also considered how established and novel bioprocessing technologies can be used to recover Co from ore materials.

Our results showed that the environmental behaviour of Co in laterites is likely to be controlled by manganese biogeochemical cycling by microorganisms. Both bacteria and fungi were able to solubilise Co from laterites, and the possibility of using waste carbon substrates to stimulate this beneficial microbial activity was identified. Bioprocessing experiments demonstrated that acidophilic

microorganisms could be used to successfully recover up to 99% Co from a range of deposits, including sulfides and laterites over a period of around 30 days.

Several biomineralisation approaches proved effective for cobalt recovery from solution, including oxalate and phosphate precipitation mediated by microbial activity.

In summary, through the CoG^3 project we now have a better understanding of the geomicrobiological factors that control cobalt behaviour in the environment, and have applied this knowledge to develop bioprocessing and biorecovery technologies that could improve the security of supply for this critical metal.

Speaker biographies

Dr Laura Newsome is a Lecturer in Applied Geomicrobiology at the University of Exeter, Camborne School of Mines. Laura is a geomicrobiologist interested in understanding the behaviour of contaminants and metals in the environment, and how microorganisms can be used for bioremediation and bioprocessing applications. Her research is interdisciplinary and incorporates microbiology, mineralogy and geochemistry to develop new insights into biogeochemical metal cycling in natural and engineered environments. Laura's research interests range from the nanoscale to the field scale. She uses cutting-edge microscopy and spectroscopy techniques to investigate the mechanisms by which microorganisms interact with metals and minerals. Laura works with samples that are naturally rich in metals and samples from metal-impacted environments, characterising their microbial communities and investigating how microbial processes can mobilise, redistribute and sequester metals. She is also interested in exploring how we can use microorganisms to help recover metals from ore deposits.

Geoff Gadd is the Boyd Baxter Chair of Biology at the University of Dundee. His research interests concern the geoactive properties of microorganisms in order to understand their importance in key biosphere processes and their applied potential. The research group that he leads is particularly interested in understanding physiological and morphological responses to toxic metals and mineral substrates, mechanisms of mineral dissolution, and the formation of novel mycogenic biominerals, especially carbonates, phosphates, oxides and oxalates. Research of applied significance that builds on fundamental research includes the application of metal-mineral-microbe transformations for bioremediation of metals, metalloids and radionuclides, nuclear decommissioning, biofertilizers (phosphate release), and the production of mineral-based biomaterials. We are also interested in the biodeterioration of rock and mineral-based structural materials including concrete and cultural artefacts, as well as biocorrosion of metals. He has published over 270 refereed articles, is an elected Fellow of several scientific societies and has received national and international awards for his research.

Modelling the impact of seafloor mining

Jez Spearman, Lea-Anne Henry and Mike Zubkov

The exploitation deep sea floor mineral resources by mining is likely to result in adverse effects to local ecology ranging from the direct removal of the substrate to the formation of sediment plumes on the seafloor and sea surface. While the former is inevitable, the impact and disturbance from plumes is one of the most pressing questions facing deep-sea mineral exploitation. There are several areas of concern: plumes could result in deposition of fine sediment on sensitive species at the seafloor; or toxicity from plumes releasing natural chemical agents and nutrients into overlying waters can disrupt ecosystems. Identifying the behaviour of these deep-sea sediment plumes is an important prerequisite towards the goal of designing mining operations which are both economical and ecologically acceptable. In addressing these questions, Marine e-tech conducted novel plume experiments on the seafloor and combined this with numerical modeling, ecological observations and sensitivity modeling to assess the potential impact on benthic fauna. Surface experiments were conducted with slurries of FeMn material to test for toxicity impacts on phytoplankton from across the north and south Atlantic. Together, these represent the first comprehensive studies of their kind on the impacts of deep-sea mining plumes, from seafloor to ocean surface.

During the Marine e-tech cruise to Tropic Seamount, we were able to generate and explore the behavior of controlled plumes on the seafloor for the first time. The results, which are supported by detailed numerical modelling, show that sediment plumes, resulting from Fe-Mn crust mining operations, are likely to be limited to a few kilometres, beyond which the plume concentation is less than the natural background. This result is unexpected and contrary to previous studies that are based on numerical models and assumed particle size distribution alone. The differences appear to arise from the effect of flocculation and rapid settling of the plume particles caused in part by naturally-occurring substances, including polysaccharides.

Mapping the result of the plume experiment onto benthic species maps generated by observations over Tropic Seamount from ROV and AUV shows how future mining operations might be designed to minimize the impact on benthic ecosystems, whilst recognizing that the impact in the mining zone will be catastrophic for sessile individuals. This work forms the basis of a standardized methodology that should be included in pre-mining baseline surveys, operational monitoring and post-mining recovery.

Meanwhile, on the sea surface, waters might be affected by plumes released by dewatering of the ore or by spillage. Many elements (e.g. Cu, Cd, Ni) found in FeMn crusts, and which can leached, are potentially toxic to phytoplankton. By

doping surface seawater, collected across the Atlantic Ocean, with FeMn crust slurry we have assessed the impact of these materials on the pivotal biological process of CO_2 fixation by phytoplankton. Surprisingly, our results revealed a strong resilience of the phytoplankton to the leachate. While this is evidence that the environmental impact on surface water phytoplankton of spillage of ferromanganese polymetallic crust material could be minimal, it also establishes a relationship between ecological damage and pollution, and thus helps inform future policy of contamination limits and thresholds.

Speaker biographies

Dr Jeremy Spearman is a Technical Director at HR Wallingford who specialises in the development and application of dispersion models for dredging, mining and disposal and in the sediment transport and morphology of estuarine waters. He is a research partner on the SoS Minerals project — Marine e-tech. Jeremy has been a key research partner in long term projects to develop better representation of dredging processes for modelling tools for the dredging industry. The TASS model has been developed over many years in collaboration with the Dutch dredging industry (most recently the Building with Nature Project) to improve knowledge of the effects of dredging and to disseminate this knowledge so that the environmental impact assessment of dredging operations is made more rigorous. Jeremy has also been instrumental in research into the physical effects of offshore mining for aggregate in UK waters and has used this expertise in studies to evaluate the potential impacts of deep sea mining on the Pacific Shelf and New Zealand.

Lea-Anne Henry is a Chancellor's Fellow in Sustainable Management of Marine Ecosystems in the School of GeoSciences at the University of Edinburgh. The core of her research applies ecological modelling to understand the roles that climate change and human activities have on deep-sea marine ecosystems in order to inform decision-making regarding exploitation of ocean resources at the local, regional and international policy levels. Her recent collaborations on seamount ecology integrates data collected from a variety of sensors and platforms including multibeam echosounder, sidescan sonar, CTD profiling and biological sampling including ROV and camera surveys, and geochemistry to map, characterise and understand the spatial and temporal distribution of vulnerable marine ecosystems as well as the occurrence of deep-sea nursery grounds for sharks and skates.
In the past, she was a Marie Curie postdoctoral fellow during Europe's FP6 programme, and worked on the FP6 HERMES and FP7 HERMIONE programmes, as well as the H2020 project ATLAS and as workpackage leader under another H2020 project called iAtlantic. She was PI on the ANChor project under the

INSITE programme, and currently sits on the ICES Deep Water Ecology WG and the DOSI-INDEEP WG on Oil and Gas, as well as the MASTS Steering Group on Oil and Gas and is joint Co-I on the MASTS SIORC community project.

Dr Mike Zubkov has over 20 years of research experience and has over 110 refereed research publications. His research interests are in linking microbial (prokaryotes and protists) identity and diversity with the biogeochemical cycles. His research has particular emphasis on microbial mechanisms for high efficiency of inorganic and organic nutrient acquisition at ultra low (e.g. pico-Molar) concentrations using radio-isotope tracers, molecular techniques and cytometric sorting as the pivotal method for cell separation after radiotracer pulse-labelling. He is currently a Principal Investigator in one NERC grant. Mike brings microbial expertise to the SoS Minerals project – Marine e-tech.

Responsible sourcing of raw materials used in the low carbon economy

Frances Wall

The magnetic and luminescent properties of Rare Earth Elements (REE) make them essential constituents of almost all our low carbon technologies. The SoS RARE project has contributed a variety of results towards improving the responsible sourcing of these elements. We have concentrated on 'getting it right from the start', with consideration of formation of ore deposits that match industry needs, comparing how ore deposit geology influences the environmental and social performance of a mine and how to use life cycle assessment (LCA) with these deposits. A PhD by Rob Pell has developed an LCA method that can be applied early during exploration and project development, from 'pre-feasibility' stage. A spin off company, Minviro, is now being launched to apply this technique to REE and other ore deposits.

Speaker biography

Professor Frances Wall (Chair) is Professor of Applied Mineralogy — Camborne School of Mines, University of Exeter She is the Principal Investigator of the SoS Minerals project — SoS RARE — and leads the EU project HiTechAlkCarb (www.carbonatites.eu) making new exploration models for REE and other critical raw materials. Frances is a world renowned expert on carbonatites and associated commodities, including REE, niobium, tantalum and phosphate deposits and is interested in responsible mining including ethical sourcing of metals, and public perception of mining. Frances was previously Head of Camborne School of Mines 2008–2014 and was recently awarded the Geological Society of London's William Smith Medal for applied geology for 2019.

Session 3 speakers

Industry and stake-holder engagement

Geometallurgy for industrial solutions

Hylke Glass & Barrie Johnson

Research into geometallurgy was initiated as part of the COG^3 project when it was observed that cobalt recovery as a by-product of copper production was either non-existent or sub-optimal. Geometallurgy seeks to systematically integrate planning practices to add value to proposed and existing mining operations. From a strategic perspective, geometallurgy informs planning by combining insight into the natural distribution of relevant orebody properties with the spatial clustering of properties according to their metallurgical response. In a tactical sense, geometallurgy links material movement and flows to processing options and requires the availability of near real-time data. Through a series of COG^3 industry case studies, it is demonstrated how geometallurgy can enhance cobalt recovery through integrated planning of resource estimation, extraction sequence, and processing routes. Bio-processing of cobalt-containing sulfidic mineral tailings was operated as a successful full-scale enterprise at Kasese, Uganda in the early 2000s. Work in the COG^3 project has confirmed that this approach (oxidative bio-processing) can be applied not only for sulfidic ores but also those where cobalt is deported chiefly as an arsenide phase. Lateritic ores also frequently contain significant amounts of cobalt (though less than nickel) and an alternative approach (reductive bio-processing) has been developed to extract and recover target metals from these oxidised ores. While most research has been laboratory-based, a spin-off project has involved a pilot-scale study of this technology in Piaui, Brazil.

Speaker biographies

Prof Hylke J Glass is the Rio Tinto Professor of Mining and Minerals Engineering at Camborne School of Mines (CSM) since October 2001. His research focusses on integrated mining and minerals extraction, including specific interest in methods for cobalt and copper geometallurgy, block cave sequencing, sensor-based preconcentration, selective reprocessing of tailings, and post-mining revegetation dynamics. The research has attracted significant support from the mining industry, UK research councils, and EU funding programmes. Prof Glass is currently the Exeter Principal Investigator of the NERC projects 'Cobalt: the roles of Geology, Geomicrobiology and Geometallurgy in its mineral formation and recovery' (COG^3) and Beyond Biorecovery: environmental win-win by biorefining of metallic wastes into new functional materials' (B3). Prof. Glass lectures MSc and BEng students on geometallurgy, process mineralogy, sampling statistics, geostatistics, and data analysis. He supervises PhD and MSc dissertation projects that are often related to industrial applications.

Barrie Johnson is a research professor, based at Bangor University (UK) with >30 years experience with using specialised microorganisms to extract and recover metals. He is an elected member of the Learned Society of Wales, an Industrial Research Fellow of the Royal Society, has held honorary professorships at Exeter University and Central South University (China) and research fellowships awarded by the US Department of Energy and Bureau of Mines. He has worked with many of the leading global mining companies (Rio Tinto, BHP Billiton, Newmont Mining, Vale etc.) and collaborates with many research groups throughout the world on fundamental and applied aspects of biohydrometallurgy. He has published over 350 articles in journals, books and conference proceedings, and has worked on over 70 funded (research council, EU and industry) research projects. His research was highlighted by Scientific American highlighted as one of '10 world changing ideas' in their December 2011 edition.

Industrial applications of deep eutectic liquids in metal extraction

Gawen Jenkin and Andy Abbott

Traditional ore processing by pyro- or hydro-metallurgy is energy intensive and produces large quantities of waste that require treatment. The use of cyanide or mercury for gold processing has low public acceptability and large open-pit mines are increasingly being meeting public opposition. Deep Eutectic Solvents (DES) are one possible more environmentally-benign approach that can be used for mineral processing. These are water-free solvents that are environmentally-benign, relatively cheap, and show a high selectivity for different metals in both the dissolution and recovery steps. The application of these solvents to mineral processing has been investigated during the course of the TeaSe project. We have demonstrated rapid dissolution of gold as well as e-tech element (Te, Se, Bi, Sb) bearing minerals, offering the opportunity to recover these elements as by-products during gold processing, we have shown that metals such as lead and copper can be extracted directly from sulfide minerals by electrolytic reduction in DES, and we have demonstrated the potential for remediation of mercury from artisanal gold tailings, as well as recovering gold. Looking forward, DES have potential applications as a safe alternative to mercury for artisanal gold extraction, for in situ leaching deep underground, and for metal extraction in frontier environments — the poles, the marine environment and even the extra-terrestrial environment. Building on the fundamental work funded by SoS, the University of Leicester is now working with a startup company, Argo Natural Resources, who are aiming to commercialise the application of DES in mineral processing for large scale and artisanal mining, tailings retreatment and e-waste recycling.

Speaker biographies

Gawen Jenkin is Professor of Applied Geology at the University of Leicester. Gawen has taught Mineral Deposit Geology and Genesis and in 2009 was awarded a Distinguished University Teaching Fellowship 'In recognition of his inspiring and imaginative teaching and his involvement in national initiatives which promote student learning in Geology.' He has been Schools Liaison and Student Recruitment Tutor for Geology since 2003 and estimates he has given more than 300 talks on Open Days and school visits. Recently he has been an adviser to the exam boards for the new Geology A/AS and GCSE qualifications. His research in geochemistry has continued on areas as diverse as arsenic in human toenails (and in earthworms), the 'Snowball Earth' in Ethiopia, and natural CO_2 sequestration, as well as gold mineralisation in Scotland and the Solomon Islands and copper in Cyprus. Recently he has developed a new field of mineral processing in collaboration with Leicester Chemistry, which forms the topic of this talk. Gawen is a researcher on the SoS Minerals project — TeASe investigating mineral processing techniques using eutectic liquids in metal extraction.

Andy Abbott is Professor of Physical Chemistry at the University of Leicester. His research interests have been primarily in the area of green solvents. He has carried out extensive research into the characterisation of supercritical fluids and ionic liquids. The research has encompassed diverse applications including electrochemistry, synthesis, novel materials and biocatalysis. In 1999 his work on the formation of ionic liquids based on choline chloride led to the formation of a joint venture company, Scionix Ltd, which was formed between the University of Leicester and Whyte Chemicals Ltd. Andy is currently the research director of this company.

Stakeholder engagement, outreach and input to the policy and regulatory framework for deep-sea mining

Paul Lusty

Growing demand for mineral raw materials, coupled with the increasing challenges of land-based mining and geopolitics will motivate the search for alternative sources of mineral supply, pushing resource development into frontier environments. A resource frontier currently attracting significant attention is the ocean floor, which covers more than two-thirds of the planet's surface, and is expected to host a proportionate amount of the world's mineral resources. Extracting these resources will present something of a societal conundrum. Deep-sea mining (DSM) will inevitably impact the natural environment, yet many of the metals these resources contain are vital to technologies that are integral to a low-

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Industry and stake-holder engagement

carbon future and meeting global sustainable development goals. The Marine e-tech project has actively sought to inform this debate through engagement with industry, policymakers, regulators, inter-governmental organisations, scientists, research funding agencies, non-governmental organisations and the media. Highlights include contributing to the development of the International Seabed Authority (ISA) draft mining regulations, via a workshop hosted by the Royal Society and Foreign & Commonwealth Office. PIs Murton and Lusty were invited to join the 'Cross Government Deep Seabed Mining Environmental Working Group,' which was established to help the UK Government build its environmental policy on DSM and contribute to environmental regulations being developed by the ISA. We were consulted on a 'POSTnote' on 'Deep-Sea Mining'. Lusty was a member of the Royal Society Working Group that published 'Future Ocean Resources: Metal-rich Minerals and Genetics'. This was one of the Society's 'policy projects', which aimed to inform the 'Foresight Future of the Sea' project undertaken by the UK Government Office for Science. Lusty and Murton acted as Guest Editors on a thematic issue of 'Elements' devoted to 'Deep-Ocean Mineral Deposits', which involved 13 international authors, with varied backgrounds (from biologists to lawyers and spanning industry to regulators) to ensure balanced coverage of the subject.

We have engaged with and presented on DSM to relevant EU-funded projects and organisations e.g. EIT Raw Materials and the MIN-GUIDE (Mineral Policy Guide) project. We have disseminated the project results at a number of international meetings and workshops, including the Irish Association of Economic Geology Annual Conference, Goldschmidt Conference, Underwater Mining Conference, Geological Society William Smith Meeting, and the 3rd International Critical Metals Conference. In addition to publishing the project results in the peer-review literature (e.g. in Minerals, Chemical Geology), the project team have responded to growing media interest in DSM, providing interviews to The Guardian, BBC, The Economist and Ocean News & Technology. Brazilian project partners from the University of São Paulo, who have received funding support from the São Paulo Research Foundation (FAPESP) have helped to expand our international reach. This collaboration will culminate in a four day end of project workshop, which will be held in Ubatuba, Brazil in late 2019.

Speaker biography

Paul Lusty is a Principal Economic Geologist at the British Geological Survey, where he leads the Ore Deposits and Commodities research team. He is Chartered Geologist with many years of commercial and research experience in the natural resources sector in the UK and overseas. His research interests have

evolved from land-based mineral exploration and prospectivity analysis, focussed on orogenic gold deposits and volcanogenic massive sulfide mineralization, to modern seafloor hydrothermal systems and understanding the preservation potential of extinct seafloor massive sulfide deposits. Recently he has been working on the formation of deep-ocean ferromanganese crusts and their potential as critical metal resources. He is also working on by-product metal recovery from enhanced geothermal systems. He was a member of a Royal Society Working Group that produced an evidence pack on marine resources and acted as a Guest Editor for an issue of 'Elements' on this topic.

Targeting near-term critical metal deposits after speculative bubbles: An example from Namibia

Ed Loye

The rare earth elements (REE) play a vital function in low-carbon transportation and generation of renewable energy, notably the light rare earth element (LREE) magnet metals neodymium (Nd), praseodymium (Pr), and the heavy rare earth element (HREE) dysprosium (Dy), in EV and HEV motors, and wind turbine generators. The 'REE boom' of 2010–2012 was in response to a combination of Chinese policy changes, political events, resultant increased REE prices, government interventions, and expanded media coverage that impacted a relatively small REE industry. As many as 400 junior companies had entered the space by the early 2010s but most have since stalled or disappeared completely. Mine to market requires years of planning, permitting, delineation, and engineering and metallurgical hurdles; all dependent on substantial and sustained funding. The four principal components to a successful REE project today can be summarized as (1) deposit composition, (2) logistics, (3) mining mechanics and ore beneficiation, (4) off-take agreement (in reality likely to be to China in the near term). With these four criteria in mind, e-tech Metals are exploring the Eureka REE-Nd-Pr deposit in Namibia. Eureka is notable for its exceptionally large crystals (up to 7 cm) of conventional REE-ore (monazite), with consistent low radioactivity content (normally a restrictive penalty element). Mineral processing test-work at Eureka has demonstrated that a high-grade marketable monazite concentrate is easily recovered from a coarse grind and simple gravity and magnetic separation only. Thus, although relatively small, the Eureka deposit might be the 'right size' to provide Nd and Pr for magnet manufacturing in the near term.

Speaker biography

Edward Loye is the Project Administrator for the SoS Minerals project: SoS RARE at Camborne School of Mines, University of Exeter. The project aims to improve

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understanding of how the rare earth elements (REE) are concentrated in natural systems, and use this information to investigate more efficient and environmentally friendly ways to extract and recover the REE. Ed's research areas include REE mineralisation in and around carbonatite complexes in Namibia. He is also the Managing Director of e-tech Metals Ltd., a junior mining company assessing the Eureka REE deposit in Namibia.

Panel discussion

Professor Frances Wall (Chair) is Professor of Applied Mineralogy — Camborne School of Mines, University of Exeter She is the Principal Investigator of the SoS Minerals project — SoS RARE — and leads the EU project HiTechAlkCarb (www.carbonatites.eu) making new exploration models for REE and other critical raw materials. Frances is a world renowned expert on carbonatites and associated commodities, including REE, niobium, tantalum and phosphate deposits and is interested in responsible mining including ethical sourcing of metals, and public perception of mining. Frances was previously Head of Camborne School of Mines 2008–2014 and was recently awarded the Geological Society of London's William Smith Medal for applied geology for 2019.

Richard Herrington is currently acting Head of the Science Directorate at the Natural History Museum and Principal Investigator of the SoS Minerals CoG^3 project — The geology, geometallurgy and geomicrobiology of cobalt resources leading to new product streams. As a researcher, Richard investigates the behaviour of metals critical for our modern economy in earth systems. He specifically focuses on those metals concentrated by deep weathering processes in surface systems and have projects focused on looking at cobalt and rare earth metals in particular. Other interests include investigating the links between mineral deposit formation and the earth's geodynamic history and the association of mineral deposit formation and biota in the deep ocean. Richard's work involves collaboration with industry and the results of his research provide them with new information enabling better and more sustainable mining techniques to be considered.

Dr Dan Smith is an Associate Professor in Applied & Environmental Geoscience at the University of Leicester. Dan's research tackles ore formation, and the crustal magmatic processes that underpin mineralisation. His particular areas of interest are in those deposits where magmas and fluids combine to form metal-rich ores (particularly copper, gold and the critical elements that accompany them). Dan currently leads the SoS Minerals project TeaSe — a consortium of researchers studying tellurium and selenium resources, to support the growth of clean energy (Te & Se being vital ingredients in modern solar panels). In 2018, Dan was one of the Mineralogical Society's Distinguished Lecturers, and toured the UK to talk about his research into ore formation, reducing the environmental impact of resources, and ensuring security of supply of raw materials.

Dr Bram Murton is Associate Head of Marine Geosciences and leads at the National Oceanography Centre's Marine Mineral Research team. Bram's expertise is in oceanic crust and the formation of mineral deposits including volcanic and tectonic processes, hydrothermal circulation and metalliferous mineralisation.

I use and develop a combination of technologies including remote and autonomous underwater vehicles, seafloor geophysics, geology, petrology and geochemistry to investigate sub-oceanic mantle melting, volcanic activity and the formation and fate of seafloor mineral deposits. Bram is the Principal Investigator of the SoS Minerals project — Marine e-tech investigating the formation of seafloor Fe-Mn crusts. He is also the principal investigator on the EU funded project on the prospectivity of seafloor massive sulphide deposits as metal-rich resources (Blue Mining).

Adrian Boyce is Professor of Applied Geology, Scottish Universities Environmental Research Centre (SUERC) at the University of Glasgow. He is a Fellow of the Society of Economic Geologists (SEG) and Geology Applied to Mineral Deposits (SGA) and a leader of applied stable isotope Geoscience research in the UK and beyond. Adrian has co-published over 300 peer-reviewed papers, many focused on the application of stable isotope geochemistry to hydrothermal processes. He has run the NERC Isotope Community Support Facility at SUERC for over 20 years, set in one of Europe's leading stable isotope laboratories, through which he has been responsible for the isotopic aspects of over 120 peer-reviewed NERC projects, including over 75 PhD students. He has demonstrated the utility of underpinning stable isotope techniques on research from km- to sub-millimetre scale fundamental hydrothermal processes from crustal fluid flow mechanisms to ocean vents to major ore deposits to geothermal energy. Adrian was Chair of Expert Group for the SoS Minerals Programme and is a member of the associated Programme Executive Board.

Dr Jon Naden is the Science Coordination Team Lead of the SoS Minerals Programme. Jon is an Minerals Geoscientist at the British Geological Survey with nearly 30 years of experience in mineral deposit research. Much of this has involved collaboration with the mineral exploration/economic geology departments of European Geological Surveys, SME mining companies and universities. He is a past Chair of the Mineral Deposits Studies Group. Current research interest include copper, gold and tellurium mineralisation associated with volcanic and magmatic activity.

Poster presentations

Poster 1 – Security of Supply of Mineral Resources Programme – infographic.
Ellie Evans and Jon Naden

Poster 2 – Modelling ferromanganese crust distribution on seamounts for resource estimates.
Sarah A Howarth, Isobel A Yeo and Bramley J Murton

Poster 3 – Te and Se in mafic VMS systems.
Andrew J Martin, Manuel Keith, Daniel B Parvaz, Iain McDonald, Katie A McFall, Christopher J MacLeod and Gawen R T Jenkin

Poster 4 – Crystal chemistry of rare earth minerals from Brazilian occurrences.
Marcelo B Andrade, Daniel Atencio and Andrezza A Azzi

Poster 5 – Computational modelling for environmentally friendly processing.
John Harding, Aaron Finney, Stephen Stackhouse, Sebastian Lectez, Colin Freeman and Linghan Kong

Poster 6 – A comparison of three approaches for bio-processing a cobalt-containing limonite ore.
Sarah Smith, Barry Grail and Barrie Johnson

Poster 7 – Processing, including bioprocessing, of easily leachable deposits.
Megan Barnett, Barbara Palumbo-Roe, Simon Gregory, Anthony Stockdale, Alex Crawford, Maria Romero-Gonzalez, Joseph Hufton, Sarah Pepper and Steve Banwart

Poster 8 – Tellurium and Selenium Cycling in Sedimentary Deposits.
Joseph Armstrong, John Parnell, Liam Bullock, Magali Perez, Connor Brolly, Xueying Wang and Jorg Feldmann

Poster 9 – The role of semi-metals in precious metal transport in porphyry Cu deposits.
Katie McFall and Iain McDonald

Poster 10 – Luminescence as a Smart Sorting Tool for REE Minerals.
Nicky Horsburgh and Adrian Finch

Poster 11 – Natural biogeochemistry of cobalt, nickel and manganese in Costa Rican lateritic soils.
Agustín F Solano-Arguedas, Laura Newsome, Richard A D Pattick, Clare H Robinson and Jonathan R Lloyd

Poster 12 – The Incorporation of Cobalt into Synthetic Iron Oxyhydroxide Systems – Implications for Natural Systems.
Sandra Dressler, Caroline A Kirk, Sandie E. Dann, Paul F Schofield and Richard J Herrington

Poster 13 – The role of hydrothermal activity in upgrading REE-deposits.
Bruce Yardley, Sam Broom-Fendley Martin Smith and Delia Cangelosi

Poster 14 – Nano- to Macro- scale characteristics and genesis of REE ion adsorption deposits.
Martin Smith, Eva Marquis, Cristina Villanova de Benavent, Anouk Bourst, Adrian Finch

Poster 15 – Thermochemical, Ionometallurgical and Pyrometallurgical Aspects of Rare-Earth Oxide Extraction and Separation.
S Sanchez Segado, S Stackhouse, F Wall, E Loye, A Abbott, and Animesh Jha

Poster 16 – Microbial Reduction of Cobalt-Nickel Bearing Lateritic Mn (III/IV)-Oxide Minerals.
D S J Mulroy, V S Coker, J R Lloyd, P F Schofield, J F W Mosselmans

PhD research

SoS MinErals has been supporting 17 PhD studentships across the programme. Many of these are are now near to completion.

REE mobility in carbonatite

Project: SoS RARE, **Student name:** Delia Cangelosi, **Location:** University of Leeds, **Supervisor(s):** Dr David Banks (University of Leeds) and Prof Bruce Yardley (University of Leeds).

Research summary: The overall aim of this project is to understand the nature of processes leading to REE mineralisation and in particular what is at the origin of the unique HREE enrichment observed in some carbonatite deposits. To tackle this I have focused on identifying the role of hydrothermal fluids and alteration on carbonatites REE content.

Rare earth element mobility during the genesis and evolution of ion adsorption deposits associated with alkali granitoid complexes

Project: SoS RARE, **Student name:** Eva Marquis, **Location:** University of Brighton, **Supervisor(s):** Dr Martin Smith (University of Brighton), Dr Kathryn Goodenough (British Geological Survey), Dr Norman Moles (University of Brighton).

Research summary: Ion adsorption clays are currently the world's major source of heavy rare earth elements. The purpose of this investigation is to determine the preconditions necessary for the formation of ion adsorption clays that are strongly enriched in rare earth elements. Focusing on a series of alkaline complexes in North West Madagascar, this project will investigate the mobility of REE during the magmatic, hydrothermal and weathering evolution of the complexes. A multitude of techniques, including SEM, XRF, ICP-MS, LA-ICP-MS, and stable and radiogenic isotope analyses, will be used to understand the processes of involved in the concentration of rare earth elements in these unconventional deposits.

Controls on tellurium and selenium enrichment in organic-rich sediments

Project: TeASe, **Student name:** Joe Armstrong, **Location:** University of Aberdeen, **Supervisor(s):** Prof John Parnell (University of Aberdeen) and Dr Stephen Bowden (University of Aberdeen).

Research summary: A detailed geochemical study of organic-rich sedimentary and meta-sedimentary rocks. Specifically focussing on the mechanisms controlling the common enrichment of Tellurium, Selenium and other related trace elements in these lithologies.

Distribution and enrichment of Te and Se in VMS systems

Project: TeASe, **Student name:** Andrew Martin, **Location:** Cardiff University, **Supervisor(s):** Dr Hazel Prichard (Cardiff University) and Dr Iain McDonald (Cardiff University).

Research summary: The volcanogenic massive sulfide deposits in the Troodos ophiolite, Cyprus,) are ancient analogues for modern day seafloor massive sulfide mineralisation. The PhD project concerns a detailed in situ study of trace elements in sulfides from twenty VMS deposits hosted in the Troodos ophiolite to better understand factors that influence the distribution, enrichment and incorporation of trace elements in different sulfide minerals.

Isotopic constraints on the distribution of chalcophile elements in magmatic systems

Project: TeASe, **Student name:** Callum Reekie, **Location:** University of Cambridge, **Supervisor(s):** Dr Helen Williams (University of Cambridge), Prof Marian Holness (University of Cambridge), Prof Colin Macpherson (Durham University), Dr Frances Jenner (The Open University) and Dr Geoff Bromiley (University of Edinburgh).

Research summary: Ph.D. research will aim to develop quantitative models for the stable isotope fractionation of Fe, Zn, Cu, and potentially Se, and chalcophile element behaviour during the differentiation of magmatic systems. Research will initially focus on calc-alkaline rocks of the Skaergaard intrusion, Greenland, and expand to consider major alkaline hydrothermal deposits such as Cripple Creek, Colorado. Experimental petrology will further be employed to examine stable isotope fractionation between sulphide and silicate liquids.

Geological and oceanographic controls on the variation in concentration of e-tech elements (REE, cobalt and tellurium) in seafloor Fe-Mn crusts

Project: Marine e-tech, **Student name:** Sarah Howarth, **Location:** University of Southampton, **Supervisor(s):** Dr Bramley Murton (National Oceanography Centre), Dr Mark Vard (University of Southampton), Prof Tim Henstock (National Oceanography Centre), Dr Tim Le Bas (National Oceanography Centre).

Research summary: Ferromanganese crusts grow throughout the global ocean by direct precipitation from seawater and consist of thin layers (2 up to 25 cm thick) accumulated on hard substrate rocks over millions of years. Because of their extremely high specific surface area, and very slow growth rates, crusts sorb large quantities of elements from seawater, including those metals, such as REE, cobalt and tellurium, considered critical to high-technology and 'green' energy production. The environment of crust formation on seamounts is highly variable,

affecting their composition and thickness at all spatial levels: ocean basin, regional, local, and within individual crusts. Geochemical studies of crusts from different water depths and locations reveal dependence in composition on a variety of factors. For example, we can distinguish between a metal group that is controlled by Mn- and a second group of metals that is closely related to the Fe+ content of the crusts. Both metal groups behave inversely and vary with water depth. In spite of the work already done on ferromanganese crusts, there is a clear need for investigation of the processes that control the origin, distribution, and resource potential of these deposits at local and sub-regional scales. The project focuses on the differences, and their causes, between NE and SW Atlantic crusts.

Bio-reduction of cobalt bearing manganese minerals

Project: CoG^3, **Student name:** Ed Thomas, **Location:** University of Manchester, **Supervisor(s):** Prof John Lloyd (University of Manchester), Dr Burkhard Kaulich (Diamond Light Source), Dr Victoria Coker (University of Manchester).

Research summary: Global cobalt demand is expected to rise in the future as we head towards a green energy economy due to its use in wind turbines, solar fuel cell and electric vehicles. Laterites and Manganese nodules are potentially new sources of Co that can be extracted by microbial processes. Little is known about the natural biogeochemical cycling of cobalt in these environmentally dynamic systems. It is hoped that by studying a suite of microcosms containing potential ores using a range of state of the art microbial and geochemical techniques that we can elucidate information about the natural biogeochemistry of this crucial metal. In particular Scanning transmission X-ray microscopy (beamline I08, DLS) provides, at a scale of 20nm, elemental distributions, metal oxidation states and structural information to help investigate the potential for bio-mining of cobalt with a view to securing a safe, sustainable supply into the future.

Defining mineralogy and its structural evolution and reaction pathways during bio-processing of Co-bearing Fe- and Mn-Oxides

Project: CoG^3, **Student name:** Sul Mulroy, **Location:** University of Manchester, **Supervisor(s):** Prof Richard Pattrick (University of Manchester), Prof John Lloyd (University of Manchester), Dr Paul Schofield (Natural History Museum), Dr Victoria Coker (University of Manchester).

Research summary: Significant cobalt resources are held in deposits of iron and manganese oxide minerals such as terrestrial Ni-(Co)-Laterites and deep-sea Polymetallic Nodules. Metal reducing bacteria (e.g. Geobacter sulfurreducens) can reduce Fe and Mn out of oxide minerals leaving remnant Co and other metals in oxide phases. This represents a possible processing or beneficiation treatment

for ores with great importance as G.sulf operates at ambient P, T and pH. The products of bio-reduction of Co-bearing iron minerals have potential applications due to their unique magnetic properties, the nature of bio-reduced Mn-phases is yet to be determined but represent materials with potentially useful applications.

Incorporation of Co into synthetic Fe oxyhydroxide systems – Implications for natural systems

Project: CoG^3, **Student name:** Sandra Dressler, **Location:** Loughborough University, **Supervisor(s):** Dr Caroline Kirk (Loughborough University), Dr Paul Schofield (Natural History Museum), Dr Rachel Norman ((Natural History Museum), Prof. Richard Herrington (Natural History Museum).

Research summary: The project will focus on synthesising and characterising iron oxyhydroxide phases, such as goethite and ferrihydrite, and the incorporation of cobalt into these systems. The programme of research will investigate the effects of pH, time, cobalt starting reagent, concentration of base and temperature on the phase or phases produced. Additionally, real-time dynamic studies will be carried out to investigate the transformation pathways of the synthesised phases with respect to temperature as well as monitor the stability of phases during washing procedures. A multi-technique approach to characterisation of these phases and their transformations will be carried out using in-house equipment (X-ray diffraction, IR Spectroscopy, Raman Spectroscopy, Thermogravimetric Analysis and Transmission Electron Microscopy) as well as Synchrotron Spectroscopy and Diffraction on beamlines at Diamond Light Source. To complete the time resolved studies, a reaction cell will be developed for use at the X-ray diffraction laboratories housed at the NHM.

Optimisation of biomineral precipitation in chemo-organotrophic systems for metal recovery

Project: CoG^3, **Student name:** John Ferrier, **Location:** University of Dundee, **Supervisor(s):** Professor Geoffrey Gadd (University of Dundee).

Research summary: Biologically-induced mineralization is common in microbes. Fungi are capable of precipitating minerals including oxides, carbonates, phosphates and oxalates by differing mechanisms but all dependent on chemoorganotrophic metabolism, and varying nutritional and environmental conditions. Through manipulation of growth conditions, it is possible to promote metal bioprecipitation which provides a means of biorecovery of metals. Further, biominerals can be of nanoscale dimensions in spherical, nanocrystalline, rod and tube-like forms. This provides further applied interest in view of the very high surface area to volume ratio and reactivity of such preparations. There is

a dearth of information in this area and this PhD project therefore provides an excellent opportunity to obtain fundamental data and increase understanding of biomineralization in the biogeochemistry of Co and other metals, and applied significance in bioprocessing and production of useful biomineral products.

Geochemical modelling of environmental processes in REE Mining

Project: SoS RARE, **Student name:** Alex Crawford, **Location:** University of Leeds, **Supervisor(s):** Prof Steve Banwart (University of Leeds), Dr Barbara Palumbo-Roe (British Geological Survey), Dr Simon Gregory (British Geological Survey).

Research summary: My PhD will study the geochemistry of rare earth elements and their solubilisation and mobilisation from easily leachable mining deposits. I will be developing a modelling approach of in situ leaching for industrial application that can be applied to a wide variety of mine sites and engineered leaching conditions.

Laser and X-ray luminescence of REE minerals

Project: SoS RARE, **Student name:** Nicky Horsburgh, **Location:** University of St Andrews, **Supervisor(s):** Dr Adrian Finch (University of St Andrews), Prof. Frances Wall (University of Exeter, Camborne School of Mines), Prof Animesh Jha (University of Leeds).

Research summary: In addition to understanding the fundamentals of REE luminescence, my project will enable the development of applications that exploit the luminescent properties of REE-bearing minerals. As an example to enhance grade and/or target particular REE minerals it may be possible to develop 'smart sorting' so that the luminescent properties of REE-bearing minerals are applied during ore beneficiation.

Responsible sourcing of rare earth elements

Project: SoS RARE, **Student name:** Robert Pell, **Location:** University of Exeter (Camborne School of Mines), **Supervisor(s):** Prof Frances Wall (University of Exeter, Camborne School of Mines), Dr Kathryn Goodenough (British Geological Survey).

Research summary: This project compares the environmental performance of rare earth production from different geological settings.

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PhD research

Geometallurgy of cobalt recovery at KGHM Polska Miedz S.A.

Project: CoG^3, **Student name:** Paulina Pazik, **Location:** University of Exeter (Camborne School of Mines), **Supervisor(s):** Prof. Hylke Glass (University of Exeter, Camborne School of Mines), Dr. Przemyslaw Kowalczuk (Wroclaw University of Science and Technology, Poland), Dr. Tomasz Chmielewski (Wroclaw University of Science and Technology, Poland).

Research summary: The project aims to add value to the KGHM operations by developing innovative and cost-effective methods to recover cobalt from its ores. The potential presence of cobalt in the ores is well-known, but it is currently not recovered. This project aims to understand the estimation of cobalt resources in a volumetric and mineralogical sense. In terms of mineralogy, this requires a robust characterisation of the ore in terms of the constituent minerals and the associations of cobalt minerals. Analyses will be performed with Qemscan and other advanced analytical techniques using samples selected on the basis of geology. In terms of volumetric analysis, geostatistics will be applied and, if required, developed to estimate the variability of the cobalt fed into the processing plant. Evaluation of geotechnical properties of the ore will also be undertaken — this will help inform an understanding of the downstream behaviour of the cobalt minerals and its associations. With sound understanding of the cobalt-bearing ore in place, the processing of KGHM ores will be analysed. The emphasis will lie on developing a process model which explains the passage of cobalt minerals through the KGHM process. With a firm understanding of the fate of cobalt in the process, the most promising options for recovery of cobalt will be investigated. While cobalt is not recovered with the current flotation process, it is expected that a leaching process will be necessary to extract cobalt. The research will investigate the dimensioning of a suitable leaching process in terms of process parameter. Subsequently, the sensitivity of the leaching performance to variations in the feed mineralogy and process parameters will be assessed. Finally, the project will assess the economic viability of cobalt recovery in the KGHM copper ore.

Resource efficient, low environmental impact production of rare earths from Songwe, Malawi

Project: SoS RARE, **Student name:** Milly Owens, **Location:** University of Exeter (Camborne School of Mines), **Supervisor(s):** Professor Frances Wall (University of Exeter, Camborne School of Mines), Dr Kathryn Hadler (Imperial College London) and Will Dawes.

Research summary: I am researching improvements to the recovery of rare earth bearing minerals by carrying out fundamental studies of the mineral properties and flotation process.

...Continued

PhD research

Electrochemical separation of Te and Se minerals

Project: TeASe, **Student name:** Francesca Bevan, **Location:** University of Leicester, **Supervisor(s):** Prof Andrew Abbott, Dr Gawen Jenkin, Dr Dan Smith (all University of Leicester).

Research summary: The aim of this project will be to investigate the potential for techniques using Deep Eutectic Solvents to process and purify Te and Se and recover them from otherwise unrecycled materials. I will also assess the potential to scale up to industrial scale and characterise the purity and form of the recovered Se and Te from ores.

Microbial reduction of metalloid oxyanions: significance of geochimical factors

Project: TeASe, **Student name:** Lara Codognotto, **Location:** University of Dundee, Supervisor(s): Professor Geoffrey Gadd (University of Dundee).

Research summary: The aim of this project is to examine geochemical influence on Se/Te reduction by aerobic microbes, using model systems of simple to intermediate complexity, in order to identify and understand what limitations there are to the process, and their importance. The influence of other metal and mineral components, organic components and nutrients on metalloid reductive capabilities of geoactive bacterial and fungal strains will be characterised, together with the abilities of strains to effect other metal-mineral transformations. Simple pure culture systems as well as mixed bacterial-fungal microcosms and simulated soil matrices will be used. Abiotic influence on the form and location of precipitated metalloids will also be investigated. The project will therefore produce fundamental scientific information regarding aerobic Se/Te reduction and its significance, and therefore add to our current understanding of Se/Te biogeochemistry. This project will use an interdisciplinary approach and the student will receive training in geomicrobiology and environmental mineralogy with associated analytical and preparative techniques, including growth and manipulation of experimental organisms, and techniques including atomic absorption spectrophotometry (AAS), X-ray powder diffraction (XRPD), and advanced light and electron microscopy, X-ray element analysis and mapping.

Publications

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