3\textsuperscript{rd} International
Critical Metals Meeting

PROGRAMME
AND ABSTRACTS

Surgeons’ Hall, Edinburgh
30 April–2\textsuperscript{nd} May 2019
Dear Delegate,

On behalf the organizing committee, I am delighted to welcome you to the 3rd International Critical Metals meeting in Edinburgh. We have an exciting programme of talks and posters and plenty of time in the schedule for networking. We really hope to facilitate discussion across the supply chain of critical metals.

This conference has met its aim to bring together researchers, both academic and industrial, who are working at different stages along the life cycle of critical metals.

Session themes include:

- Critical metals for low carbon transport
- Responsible sourcing of critical metals
- Geology and resources of critical metals

We are very grateful to our academic, industrial and private sponsors and the community for supporting this meeting.

Eimear Deady
Chair, Organizing Committee
### PROGRAMME

**Tuesday 30th April**

**Critical metals for low carbon transport**

**Session chairs: Evi Petavratzi and Gus Gunn**

<table>
<thead>
<tr>
<th>Time</th>
<th>Activity</th>
</tr>
</thead>
<tbody>
<tr>
<td>08:30 – 09:00</td>
<td>Registration and coffee</td>
</tr>
<tr>
<td>09:00–09:10</td>
<td>Intro by Eimear Deady, Gus Gunn and Evi Petavratzi</td>
</tr>
<tr>
<td>09:10–09:40</td>
<td>David Merriman (keynote) 7</td>
</tr>
<tr>
<td>09:40–10:00</td>
<td>Michaux 8</td>
</tr>
<tr>
<td>10:00–10:20</td>
<td>Rietveld 9</td>
</tr>
<tr>
<td>10:20–10:40</td>
<td>Butcher 11</td>
</tr>
<tr>
<td>10:40–11:10</td>
<td>Morning coffee</td>
</tr>
<tr>
<td>11:10–11:30</td>
<td>Lundhaug* 12</td>
</tr>
<tr>
<td>11:30–11:50</td>
<td>Horn* 13</td>
</tr>
<tr>
<td>11:50–12:10</td>
<td>Danino-Perraud* 14</td>
</tr>
<tr>
<td>12:10–12:30</td>
<td>Pell* 15</td>
</tr>
<tr>
<td>12:30–13:30</td>
<td>Lunch</td>
</tr>
<tr>
<td>13:30–14:00</td>
<td>Jacqui Murray (keynote) 16</td>
</tr>
<tr>
<td>14:00–14:20</td>
<td>Mikkola 17</td>
</tr>
<tr>
<td>14:20–14:40</td>
<td>Schmid 18</td>
</tr>
<tr>
<td>14:40–15:00</td>
<td>White 19</td>
</tr>
<tr>
<td>15:00–15:20</td>
<td>Ganev 20</td>
</tr>
<tr>
<td>15:20–15:50</td>
<td>Afternoon coffee</td>
</tr>
<tr>
<td>15:50–16:10</td>
<td>Lottermoser 21</td>
</tr>
<tr>
<td>16:10–16:30</td>
<td>Barnett 22</td>
</tr>
<tr>
<td>16:30–16:50</td>
<td>Jha 23</td>
</tr>
<tr>
<td>17:00–19:00</td>
<td>Poster session</td>
</tr>
</tbody>
</table>

* student presentation
### Wednesday 1st May

**Responsible sourcing of critical metals**

Session chairs: Megan Barnett and Rob Pell

<table>
<thead>
<tr>
<th>Time</th>
<th>Speaker</th>
<th>Title</th>
</tr>
</thead>
<tbody>
<tr>
<td>09:00–09:30</td>
<td>James McQuilkan (keynote)</td>
<td>Critical metals from small-scale mining for development: The importance of the African Great Lakes Region and Delve Data Collaboration</td>
</tr>
<tr>
<td>09:30–09:50</td>
<td>Moore 25</td>
<td>Conflict and critical raw materials production: a tale of antimony production in the Balkans</td>
</tr>
<tr>
<td>09:50–10:10</td>
<td>Paneri 26</td>
<td>Renewable Energy Systems for Sustainable Mining</td>
</tr>
<tr>
<td>10:10–10:30</td>
<td>Doyle* 27</td>
<td>Environmental &amp; Social Maturity as a new concept for self-assessment of best practice in a mining context</td>
</tr>
<tr>
<td>10:30–10:50</td>
<td>Caven 28</td>
<td>Building an ecosystem for change in the responsible sourcing of critical metals – The Impact Facility for Sustainable Mining Communities</td>
</tr>
<tr>
<td>10:50–11:30</td>
<td>Morning coffee</td>
<td></td>
</tr>
<tr>
<td>11:30–11:50</td>
<td>Bilham* 29</td>
<td>A possible framework for responsible sourcing schemes, standards and mechanisms across mineral supply chains</td>
</tr>
<tr>
<td>11:50–12:10</td>
<td>Patton 30</td>
<td>Issues in securing access to critical minerals; experience from Northern Ireland</td>
</tr>
<tr>
<td>12:10–12:30</td>
<td>Lusty 31</td>
<td>Deep-sea mining: A responsible source of critical metals or a step beyond the environmental limits of our planet?</td>
</tr>
<tr>
<td>12:30–13:30</td>
<td>Lunch</td>
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</tbody>
</table>

### Geology and resources of critical metals I

Session chairs: David Kaeter and Cristina Villanova-De-Benavent

<table>
<thead>
<tr>
<th>Time</th>
<th>Speaker</th>
<th>Title</th>
</tr>
</thead>
<tbody>
<tr>
<td>13:30–14:00</td>
<td>Kathryn Goodenough (keynote)</td>
<td>The geology of decarbonization</td>
</tr>
<tr>
<td>14:00–14:20</td>
<td>Grant 33</td>
<td>Are some Critical Metals a potential secondary resource in modern seafloor massive sulphide deposits?</td>
</tr>
<tr>
<td>14:20–14:40</td>
<td>Lehrmann 34</td>
<td>Trace element systematics of sulphides and associated alteration phases from inactive hydrothermal vents at TAG, Mid-Atlantic Ridge</td>
</tr>
<tr>
<td>14:40–15:00</td>
<td>Josso 35</td>
<td>The critical metal potential of ferromanganese crusts: New insight from the north-east Atlantic</td>
</tr>
<tr>
<td>15:00–15:30</td>
<td>Afternoon coffee</td>
<td></td>
</tr>
<tr>
<td>15:30–15:50</td>
<td>Lehtonen 36</td>
<td>Advanced indicator mineral research concept for the critical mineral exploration in glaciated terrain</td>
</tr>
<tr>
<td>15:50–16:10</td>
<td>Armitage 37</td>
<td>The Songwe Hill rare earths project, Malawi – geological observations on the recently announced mineral resource upgrade</td>
</tr>
<tr>
<td>16:10–16:30</td>
<td>Elliott 38</td>
<td>Fenite exploration criteria surrounding carbonatite-hosted critical metal deposits</td>
</tr>
<tr>
<td>16:30–16:50</td>
<td>Beard 39</td>
<td>Deposit-scale geomodels for REE and HFSE exploration in carbonatite and alkaline-silicate magmatic systems</td>
</tr>
<tr>
<td>16:50–17:10</td>
<td>Jenkin 40</td>
<td>Critical and precious element recovery with environmentally benign deep eutectic solvents</td>
</tr>
<tr>
<td>17:10–17:30</td>
<td>Horsburgh* 41</td>
<td>Smart Sorting of minerals</td>
</tr>
<tr>
<td>19:45 until late</td>
<td>Conference dinner</td>
<td></td>
</tr>
<tr>
<td>Time</td>
<td>Speaker/Title</td>
<td>Presentation</td>
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<tr>
<td>09:00–09:30</td>
<td>Paul Nex (keynote)</td>
<td>Have the Wheels Fallen off your “Hype Cycle”? A retrospective look at criticality: tantalum, rare earth elements and lithium</td>
</tr>
<tr>
<td>09:30–09:50</td>
<td>Siegfried*</td>
<td>Scandium as an important critical metal in the quest for reducing carbon dioxide emissions in the 21st century</td>
</tr>
<tr>
<td>09:50–10:10</td>
<td>Nwoko*</td>
<td>Elemental Se and Te nanoparticles biosynthesised by Aerobasidium pullulans: Characterization, separation and detection with DLS, AF4-UV-MALS-ICP-MS/MS, spICP-MS and TEM</td>
</tr>
<tr>
<td>10:10–10:30</td>
<td>Lima</td>
<td>A new vision for the genesis of Santa Helena breccia, Borralha W deposit NW of Portugal</td>
</tr>
<tr>
<td>10:30–10:50</td>
<td>Solferino</td>
<td>Energy Critical Elements (ECE) in the English Lake District - Scar Crags, Dale Head North</td>
</tr>
<tr>
<td>10:50–11:00</td>
<td>Morning coffee</td>
<td></td>
</tr>
<tr>
<td>11:20–11:40</td>
<td>Gloaguen</td>
<td>Overview and assessment of the European lithium resources</td>
</tr>
<tr>
<td>11:40–12:00</td>
<td>Knoll</td>
<td>Exploring the feasibility of an anatetic model for albite spodumene pegmatites from the Austroalpine Unit (Eastern Alps)</td>
</tr>
<tr>
<td>12:00–12:20</td>
<td>Kaeter*</td>
<td>Two generations of cassiterite in albite–spodumene pegmatites from Leinster, SE Ireland: Implications for tin mineralisation in lithium pegmatites</td>
</tr>
<tr>
<td>12:20–13:30</td>
<td>Lunch</td>
<td></td>
</tr>
<tr>
<td>13:30–13:50</td>
<td>Finch</td>
<td>Critical Metal Mineralisation Associated with Magmatic Roof Zones</td>
</tr>
<tr>
<td>13:50–14:10</td>
<td>Broom-Fendley</td>
<td>Sulphate-bearing monazite-(Ce) from silicified dolomite carbonatite, Eureka, Namibia: substitution mechanisms, redox state and HREE enrichment</td>
</tr>
<tr>
<td>14:10–14:30</td>
<td>Kynicky</td>
<td>The role of carbonate-fluoride melt immiscibility in shallow REE deposits evolution: New evidence from Mongolia</td>
</tr>
<tr>
<td>14:30–14:50</td>
<td>Smith</td>
<td>Ion Adsorption Deposits: A comparison of deposits in Madagascar and China</td>
</tr>
<tr>
<td>14:50–15:10</td>
<td>Villanova-De-Benavent</td>
<td>Adsorption experiments of REE onto kaolinite in low pH water and NaCl solutions</td>
</tr>
<tr>
<td>15:10–15:40</td>
<td>Anouk Borst (ECR keynote)</td>
<td>Peralkaline-hosted Critical Metal Deposits: From magmatic enrichment to hydrothermal mobilisation</td>
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<tr>
<td>15:40–15:45</td>
<td>Conference close - brief address by organisers; Student prizes sponsored by Cornish Lithium and Zeiss</td>
<td></td>
</tr>
</tbody>
</table>

**Geology and resources of critical metals III**

Session chairs: Charlie Beard and Nicky Horsburgh

<table>
<thead>
<tr>
<th>Time</th>
<th>Speaker/Title</th>
<th>Presentation</th>
</tr>
</thead>
<tbody>
<tr>
<td>13:30–13:50</td>
<td>Finch</td>
<td>Critical Metal Mineralisation Associated with Magmatic Roof Zones</td>
</tr>
<tr>
<td>13:50–14:10</td>
<td>Broom-Fendley</td>
<td>Sulphate-bearing monazite-(Ce) from silicified dolomite carbonatite, Eureka, Namibia: substitution mechanisms, redox state and HREE enrichment</td>
</tr>
<tr>
<td>14:10–14:30</td>
<td>Kynicky</td>
<td>The role of carbonate-fluoride melt immiscibility in shallow REE deposits evolution: New evidence from Mongolia</td>
</tr>
<tr>
<td>14:30–14:50</td>
<td>Smith</td>
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</tr>
<tr>
<td>15:40–15:45</td>
<td>Conference close - brief address by organisers; Student prizes sponsored by Cornish Lithium and Zeiss</td>
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<tr>
<td>Authors</td>
<td>Number</td>
<td></td>
</tr>
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<td></td>
</tr>
<tr>
<td>Alfonso</td>
<td>58</td>
<td>Mineral chemistry of In-rich minerals from the San José ore deposit, Central Andean Tin Belt, Bolivia</td>
</tr>
<tr>
<td>Beard</td>
<td>59</td>
<td>Geomodels for REE and HFSE exploration in carbonatite and alkaline-silicate magmatic systems</td>
</tr>
<tr>
<td>Deady</td>
<td>60</td>
<td>Volcanic-Derived Placers as a Potential Resource of Rare Earth Elements: The Aksu Diamas Case Study, Turkey</td>
</tr>
<tr>
<td>Lacinska</td>
<td>61</td>
<td>The effect of X-ray energy overlaps on the results of chevkinite ((\text{Ce, La, Ca, Th})_4(\text{Fe}^{2+}, \text{Mg})_2(\text{Ti, Fe}^{3+})_3\text{Si}<em>4\text{O}</em>{22}) microanalysis using SEM EDS-WDS</td>
</tr>
<tr>
<td>Li*</td>
<td>62</td>
<td>Genesis of the Zudong regolith-hosted HREE deposit in South China</td>
</tr>
<tr>
<td>Liang</td>
<td>63</td>
<td>Formation of selenium- and tellurium-containing nanoparticles during the growth of filamentous fungi</td>
</tr>
<tr>
<td>Price*</td>
<td>64</td>
<td>Crystallisation Pathways of Mixed La and Nd Carbonates</td>
</tr>
<tr>
<td>Zhou</td>
<td>65</td>
<td>Rare earth element deposits in China</td>
</tr>
</tbody>
</table>
The EV Revolution: Impacts on critical raw material supply chains
Merriman, D.
Roskill Information Services, 54 Russell Road, London, SW19 1QL, UK

The electrification of the global vehicle fleet, both passenger and commercial, is gathering pace, as major automotive OEMs in Europe, the USA, Japan and China continue to release new hybrid and electric vehicle (xEV) models. Sales of xEVs are forecast to increase at a CAGR of 20.5% in the years to 2030, with total sales of hybrid and electric vehicles approaching 40M units.

The demand for vehicle components, most predominantly for Li-ion batteries, though also for permanent magnet motors, copper harnessing and light weight alloys, is placing huge strain on raw materials, such as lithium, cobalt, nickel, rare earths, copper and graphite.

Demand growth for lithium from battery applications alone is forecast to increase by 22.9%py through to 2028, whilst cobalt demand is forecast to increase by 10.6%py over the same period. To provide enough raw materials to meet this growth, lithium supply needs to increase more than 6-fold over the coming decade, with cobalt supply is needed to more than double. Additional supply is in the pipeline however, with multiple new producers, expansions at existing operations and greater recycling of batteries and other vehicle components. Though there have been some successes, there are several barriers to entry for additional supply to overcome. Access to finance, availability of technical and metallurgical expertise, resource nationalism, unstable political jurisdictions and regionalised consumer bases all poses potential risks to additional supply. Securing enough supply of these materials however will prove critical to realising unrestricted growth in the xEV industry, as there are often few alternatives and insufficient time to develop new technologies for commercial use.

The design of vehicle batteries, motors and electronics are key to determining demand growth for xEV raw materials, with market balance often being sensitive to changes in battery chemistries, magnet materials and conductive materials used in mainstream automotive models. Changes in the cathode chemistry of Li-ion batteries used in automotive applications have dictated cobalt, nickel and manganese requirements in recent years, as producers looked to maximise energy density. A shift in emphasis focussing more on safety, life-cycle or cost, either from market pressure, government support or changing consumer appetites, would cause significant changes to battery raw material requirements in the future however.
Projected battery minerals and metals global shortage

Michaux, S.P.¹

¹Mineral intelligence, Geological Survey of Finland. Espoo Finland

Europe plans to develop and manufacture an energy transition program towards an Electric Vehicle (EV) dominated mobility system. This includes a European Commission objective to have 200 million EV’s registered in the European Union by 2030, and to have 30 Gigafactories commissioned by 2025. To do this, unprecedented quantities of raw materials will be required to be sourced, mined, processed and then refined, to produce the needed materials for battery manufacture. This is hoped to be a European critical industry that will support long term economic security. All future projections of the capability to do this are based on market demand only, without any real situation awareness of the quantity of stated global mineral reserves.

This paper will review the status of cobalt, lithium, graphite, copper and nickel global reserves global refining capability. All of these minerals and metals are critical for battery manufacture. The historical consumption compared to projected applications and market demands suggests that there are not nearly enough mineral reserves to meet demands. This projected shortfall is of significant concern. The concept of peak mineral production will be introduced. Recommendations for the way forward will be discussed.
Exploration of worldwide metal demand of low carbon transport and impact of circular economy strategies [1]

Rietveld, E.1, Bastein, T.1

1 Netherlands Organisation of Applied Scientific Research, elmer.rietveld@tno.nl

Climate action requires significant electricity production and low-carbon transport. To achieve the Paris Agreement, the vast majority of this production capacity needs to be realized in the period up to 2050. This production capacity requires a significant amount of critical metals to, amongst others, build wind turbines, Photo Voltaic (PV) panels, grid storage systems and vehicle storage systems (i.e. batteries and fuel cells).

The growth of global metal production since 1998, if continued, will not be enough for supply to meet demand of 17 metals (in scope of this study) towards 2030 and 2050. For these 17 metals, an unprecedented growth of mining activity is required. Some examples of our findings are shown in the table below.

<table>
<thead>
<tr>
<th>Metal</th>
<th>Observed Mine production growth 1998-2016</th>
<th>Required annual growth rate with renewables &amp; batteries 2014-2050</th>
<th>Speed-up production compared 1998-2016 time period?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silver (Ag)</td>
<td>2.86%</td>
<td>3.0%</td>
<td>uncertain</td>
</tr>
<tr>
<td>Aluminium (Al)</td>
<td>5.37%</td>
<td>2.8%</td>
<td>safe space</td>
</tr>
<tr>
<td>Cerium/Lanthanum (Ce/La)</td>
<td>0.00%</td>
<td>3.2%</td>
<td>speed-up</td>
</tr>
<tr>
<td>Copper (Cu)</td>
<td>2.92%</td>
<td>3.4%</td>
<td>speed-up</td>
</tr>
<tr>
<td>Iron (Fe)</td>
<td>6.55%</td>
<td>3.0%</td>
<td>safe space</td>
</tr>
<tr>
<td>Indium (In)</td>
<td>5.41%</td>
<td>3.6%</td>
<td>safe space</td>
</tr>
<tr>
<td>Lithium (Li)</td>
<td>4.61%</td>
<td>6.2%</td>
<td>speed-up</td>
</tr>
<tr>
<td>Neodymium (Nd)</td>
<td>0.00%</td>
<td>4.5%</td>
<td>speed-up</td>
</tr>
<tr>
<td>Platinum/Palladium (Pt/Pd)</td>
<td>0.02%</td>
<td>2.8%</td>
<td>speed-up</td>
</tr>
<tr>
<td>Selenium (Se)</td>
<td>3.30%</td>
<td>3.0%</td>
<td>safe space</td>
</tr>
<tr>
<td>Silicium (Si)</td>
<td>5.66%</td>
<td>3.3%</td>
<td>safe space</td>
</tr>
<tr>
<td>Tin (Sn)</td>
<td>2.05%</td>
<td>3.1%</td>
<td>speed-up</td>
</tr>
<tr>
<td>Tellurium (Te)</td>
<td>4.54%</td>
<td>6.9%</td>
<td>speed-up</td>
</tr>
</tbody>
</table>

The required metals for renewable electricity capital stock apparently needs to be met by primary extraction. Recycling is found to be insignificant given the expected annual secondary metals extracted from the so-called urban mine. However, we find that three other circular strategies could have a significant impact, if systemic changes are pursued in the coming five years:

- Substitution of critical metals in renewable electricity stock: critical metal use should be diversified to remain agility to absorb needed metal demand of low carbon transport. The challenge here is to express robustness of supply chains for the private sector.

- Circular design strategies for PV panels, batteries and wind turbines: modular design to better enable future remanufacturing. The challenge here is to create acceptable legislation that effectively influence technical design decisions.

- Improved economic end-of-life criteria to enable higher re-use for applications with lower technical requirements, for instance used Electric Vehicle batteries as grid storage modules. The challenge here is to anticipate performance criteria for this cascading use in order to prevent unwanted incentives.
The evaluation and development of lithium brine prospects: examples from the Altiplano Puna, South America

Butcher, A.S.1, Petavratzi, E.2 Ford, J.2 Hughes, A.R.2 and Smith M.3

1British Geological Survey, Wallingford, Oxfordshire UK. a.butcher@bgs.ac.uk.
2British Geological Survey, Keyworth, Nottinghamshire, UK.
3British Geological Survey, Lyell Centre, Edinburgh, UK.

Recent developments in the automotive and mobile telecoms industry have led to a boom in lithium exploration and development for the new generation of batteries that are powering the increasing number of electric and hybrid cars and the smartphone revolution.

One of the cheapest sources of lithium is in the brines that contain the metal in solution. The Altiplano-Puna is the second largest high-altitude plateau in the world and is the location of numerous brine bodies containing elevated concentrations of Lithium among several other metals of economic interest. Two main closed basin host aquifers in the region are mature halite salars (e.g. Atacama) and immature clastic salars (e.g. Uyuni, Olaroz-Cauchari) (Houston J et al) [1].

There are no standard methodologies for evaluating brine resources. Unlike for codes created for solid phase minerals [2], [3], [4] these brine resources move and change within a mining project lifetime. Here we describe requirements for brine resource and reserve evaluation and development. We draw on several examples from our recent experience in the Central Andes, in Argentina, Bolivia and Chile.

References:
How much do we know about material cycles? An application of the MinFuture framework

Lundhaug, M.1*, Tschora, H.L.1, Müller, D.1

1Norwegian University of Science and Technology, Høgskoleringen 1, 7034 Trondheim, Norway, maren.c.lundhaug@ntnu.no

The complexity and the size of global material flows has over the last decades drastically increased. Which puts an emphasis on the need for monitoring of the socioeconomic metabolism or the physical economy.

During the MinFuture project a framework for monitoring of the physical economy was developed. The framework includes seven essential MFA components used in the monitoring of physical flows and stocks of materials. These include: systems, data, uncertainty, models and scenarios, visualization, indicators, and strategy support. These components are organized as a pyramid and are hierarchically linked, meaning that the robustness of the components on the higher levels are dependent on the robustness of the components on the lower levels.

The aim of this paper is to establish the MFA knowledge base for a selected set of raw materials using the developed framework through the development of a methodology for testing materials based on the MinFuture framework. As MFAs can be used as a policy and strategy development tool it is of high importance that policy makers and strategists are aware of the status MFA for the materials of interest. This way efforts can be spent more efficiently and directly relate this to the materials that are of high importance for the EU.

Preliminary results has shown us that more work is needed on systems and data. This is especially the case for critical metals in which we have a limited system understanding and large data gaps.
Europe’s cobalt resource potential for supply to low-carbon vehicles

Horn, S.¹, Petavratzi E.¹, Wall, F.², Gunn G.¹ and Shaw R.¹

¹British Geological Survey, Nicker Hill, Keyworth, Nottingham NG12 5GG, Email: shorn@bgs.ac.uk
²Camborne School of Mines, University of Exeter, Penryn Campus, Penryn TR10 9FE

Transport is the second largest contributor of greenhouse gas emissions in the European Union [1]. Electric vehicles (EVs) play a major role in decarbonising the transport sector and their deployment has increased rapidly over the past few years. More than 3 million electric cars are currently in stock globally and an EV year-on-year sale increase of 54% was recorded in 2017 [2]. Consequently, there is increasing demand for raw materials used in EV batteries, including cobalt, which is classified as a critical metal [2, 3]. More than 50% of world mine production is from the Democratic Republic of Congo (DRC), some of which is linked to human rights abuses [4, 5]. Europe however, accounts for less than 1% of global mine production of cobalt and is thus highly dependent on imports [4].

In order to facilitate future cobalt supply for the battery sector and support responsible sourcing, new research by the British Geological Survey (BGS) aims to analyse the supply chain in Europe and identify the future global demand for cobalt with a focus on the EU battery sector.

The first objective of the project is to assess Europe’s potential for primary cobalt resources and assemble information about known cobalt resources and occurrences. Globally, cobalt is mainly extracted as a by-product and is chiefly produced from three deposit types: stratiform sediment-hosted Cu-Co deposits, magmatic Ni-Cu sulfide deposits and Ni-laterite deposits [6]. In Europe, deposits of these types are worked at several locations, but only three mines in Finland currently produce cobalt: at Kevitsa cobalt is extracted from magmatic sulfide ores; at Talvivaara the cobalt is in a black shale-hosted deposit; while at Kylylahti volcanogenic massive sulfide ores are the host of cobalt [6]. The stratiform sediment-hosted deposits in Poland and Germany comprise the largest copper resources in Europe and contain an average cobalt grade of 10–1000 ppm in the Polish deposits [7]. Other potential sites of interest are cobaltiferous laterite deposits in Albania, Greece, Kosovo, Macedonia, Serbia and Turkey, which contain up to 0.08% Co [8]. In these countries, ferronickel is produced by smelting these ores. Any cobalt is enriched in the ferronickel and is therefore, effectively lost for use in other applications [8, 9].

Recent improvements in extraction and recovery technologies have the potential to reveal important sources of cobalt in secondary materials such as copper slags [10, 11]. Therefore, it is important to understand the concentration and distribution of cobalt in these secondary materials. Those mines mentioned above that currently do not extract cobalt, and other similar deposits, may increase the potential of Europe’s cobalt resource base, whilst providing environmental benefits.

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References
A Material Flow Analysis of cobalt: observation on the evolution of the cobalt flows in the European Union from 2008 to 2017

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In response to the growing tensions on raw materials, the European Commission implemented the Raw Material Initiative (RMI) in November 2008 based on three pillars: the fair and sustainable supply of raw materials from global markets, the sustainable supply of raw materials within the EU and the resource efficiency and supply of secondary raw materials through recycling [1]. The publication of a list of critical raw materials for the European Union (EU), which is regularly updated, is also part of this strategy. Cobalt is one of the 27 critical raw materials identified in the last revision (2017) [2].

Cobalt is mostly used in batteries (53%), superalloys (16%), carbides and cutting tools (11%), catalysts (6%) and permanent magnets (3%) [3] Its consumption more than doubled between 2005 and 2017 (52 000 tons to 110 000 tons) [4]. The Democratic Republic of Congo (DRC) produces 67% of cobalt minerals while China holds 60% of the refined production [3]. The geographical concentration of the production, the political instability of the DRC and the threefold price increase between 2016 and 2018 brought attention on this metal and the necessity of a better knowledge of it.

The Material Flow Analysis (MFA) methodology has been primary implemented by the Padua doctor Santoro Santoro during the 17th century in order to measure the human metabolism [5]. In 1969 Ayres and Kneese, carried out the first MFA to measure the environmental consequences of economy [6]. A MFA is characterized by two main principles, the mass balance and the necessary boundaries (geographic, temporal and between the economical and natural system). It has been used to analyse the anthropogenic life cycle (Production, processing and manufacturing, use, waste management and recycling) of a substance or a good at each stage of it [7].

A MFA can be used to calculate in use stock in order to estimate future waste streams, highlight the metal stocks and highlight the losses throughout the life cycle [8]. By giving a geographical representation of the flows (their origin, their destination...) it also allows to understand better the vulnerabilities of the supplies of a material along the chain of production.


This communication presents an update and new elements in particular with regard to recycling data. The geographic location (European Union) and the period covered by the MFA (2008-2017) will allow us to make an analyse over several years and consequently observe the evolution of the cobalt flows in and out the European Union.

Integrating life cycle assessment into the planning stages of critical metal projects

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The transition to a low-carbon economy and the technologies embraced to achieve this is driving demand for a new range of metals (Grandell et al, 2016). For example moving from a fossil fuel to an electrified transport system requires increased levels of cobalt and lithium, which are used in batteries; and rare earth elements (REE) such as Nd, which are used in magnets within the vehicle motors. Extracting these metals from the earth’s crust and processing them into a useable form comes at an environmental cost. This cost can vary depending on the geographic location, mineralogy, and processes employed. It is possible to quantify these impacts by applying a life cycle assessment (LCA). LCA enables the estimation of the cumulative environmental impacts, often including impacts that go beyond the boundaries of traditional analyses.

LCA is primarily used in the mining industry as a measuring tool for operating projects, but there is an opportunity to apply LCA in a proactive way during the exploration stage of critical metal projects, with the aim of improving the design whilst recognising environmental impacts. For example recent work has developed a framework to incorporate LCA into long-term mine-planning (Pell et al, 2018), and there has been the development of incorporating LCA into mineral processing simulations (Scheidema et al, 2015).

Once a pre-feasibility study is complete there is adequate data to perform a LCA, and through sensitivity analysis, different environmental impacts based on changing processes techniques or mineralogy can be explored. This approach is useful alongside an EIA, which is more focused on environmental risks. Incorporating the LCA into this stage of development ensures that both direct and indirect impacts of process choices are taken into account in a life cycle context. For example direct emissions of the plant can be measured, but also indirect emissions from the purchased electricity or during the production of fuels and materials or handling of the waste. By incorporating LCA into the project development process we can ensure that the low-carbon economy is fed from raw materials that have the lowest possible environmental cost.


Electric vehicle batteries: the UK government perspective

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Innovate UK

The UK Government announced in July 2017, the £246 Million Faraday Battery Challenge and it remains the largest of the missions announced in the Industrial Strategy Challenge Fund. The vision of this challenge was to make the UK the go-to place for electric vehicle batteries. The £246 Million was designed to go into early research in universities, funding of collaborative research and development projects and a scale up and prototyping facility that will enable the commercialisation of this technology in the UK. This funding fits synergistically with the UK Government’s ambition to attract a large scale manufacturing facility in the UK and the on-shoring of the supply chain here.

The challenge was also tasked with identifying and enabling all opportunities that will support this goal and make the UK a more attractive place to manufacture EV batteries. This has included several themes such as enabling the investor community, understanding the standards and regulation landscape and the supply chain in the UK, with and without a major battery manufacturing plant here.

Jacqui Murray will describe the Battery Challenge and Adam Chase from E4tech will introduce the study fresh from its launch on the 29 April 2019 of the Chemical Supply Chain for Battery Manufacture Report, commissioned by Innovate UK and UK Advanced Propulsion Centre and its wide ranging implications for UK manufacturing. It has specific relevance for metals and chemicals.
Battery mineral project of Geological Survey of Finland, government organisation reacting to rising demand

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The growing demand of minerals required for e.g. low carbon transport and economic possibilities associated with them have been recognised by economic and political decision makers in Finland. Significant interest and investment is currently put into evaluating the potential for establishing full battery value chain from responsibly sourced raw materials into production of battery cells. As part of these activities Geological Survey of Finland (GTK) has commenced a four year Battery mineral project (2019–2022). The project aims to update the understanding of deposit types associated with Co, Li and flake graphite in Finland and to evaluate the respective potential.

First year of the project includes significant amounts of resources allocated to revisiting the existing material. This material includes databases, both geophysical and geological, the latter comprising analyses, field observations, drill-core loggings, mineral deposits and ore showings. But effort will also be put into e.g. relogging of old drill cores from historical exploration targets regarded on geological bases as potential for battery minerals but with limited analytical data for these elements. Synthesis of work done in this part of the project aims at identifying new or underexplored areas for GTK’s further investigations.

Already in 2019 field work will be carried out in three larger areas regarded as poorly understood, but potential in respect to Cobalt. Work done in the field will include geophysical measurements, bedrock mapping and drilling. Instead of ore exploration sensu stricto the focus of the field studies is in creating better understanding of each area’s rock types, geological structure and development to demonstrate their ore potential.

Results of the project should encourage private sector investments in further work on the areas proven most promising and ultimately lead to development of new mines. In addition to exploration work the updated knowledge will also be useful for example in land use planning where competing interests can be better coordinated in the future to avoid future conflicts and to improve the social licence to operate of exploration and mining activities.
Why the European automotive industry struggles to secure its need for critical raw materials

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A stable supply with critical raw materials (CRM) is crucial for the transformation towards low carbon mobility [1]. In recent years, rare earth elements (REE) that are used in neodymium-iron-boron (NdFeB) permanent magnets for electric drives have been considered as some of the most critical raw materials that are required for the future of mobility [2, 3]. Their production is highly concentrated in China. Supply restrictions and price risks as a result of the high dependence on China’s production and willingness to export REE have provoked reactions worldwide in order to reduce this dependence.

Exemplified by the case of REE, this contribution provides a vital understanding of the markets for CRMs, discusses fundamental market characteristics, and identifies key challenges of matching supply and demand. Assessment of specifics of markets for CRMs underline, that bottlenecks and supply dependences do not only exist in mining, but also further downstream of the supply chain. Insufficiently established alternative supply chains remain a structural problem, especially with regard to processing and magnet production.

These findings are then discussed with regard the specific challenges for the automotive industry. Based on in-depth interviews with corporate executives from European companies along the supply chain of the automotive industry, this contribution shows challenges for the industry to cope with the changing landscape and the specifics of the markets for REE.

Results emphasize, that affected companies struggle to pursue long-term oriented strategies to secure their need for REE. Companies avoid the involvement in mine production and there seems to be a lack of willingness to commit to long-term investments. In the western world, only few noteworthy players are actively seeking access to REE production. Findings raise the question if a new mindset in the industry is required and if a more active political role of the European Union would be favorable.

As market characteristics and supplier concentration are comparable among many CRMs that are required for e-mobility, experiences with rare earths in the last years can be seen as a blueprint for fundamental issues that come along with a shift to e-mobility. Lessons learned for the future need for CRMs in general can be derived.

Low carbon transport and the Sustainable Development Goals: what role should geologists play?

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The UN Sustainable Development Goals (SDGs) aim to eradicate poverty, ensure universal access to basic services, tackle inequality, end unsustainable consumption patterns, and facilitate inclusive economic growth, social development and environmental protection.

This talk will give an overview of the international targets surrounding low carbon transport and assess the opportunities and challenges of low carbon transport in relation to the SDGs. Developing low carbon transport options is a key component of the international shift towards a low carbon future. Geologists have the knowledge and skill-set to advise on the future of low carbon transport and have a responsibility to contribute to the global discourse in order for this sector to develop in a sustainable way.

Organisations such as Geology for Global Development are an important facilitator to ensure that the voices of geologists are heard in the international and UK policy arena. For example, we reflect on recent engagement at the UN Forum on Science, Technology and Innovation for the SDGs, where as the primary (if not only) geoscience organisation in attendance we advocated for the importance of geoscience in global multi-stakeholder dialogue around SDGs on energy, cities, and responsible consumption and production.
Impact of EU climate and energy policy on Silicon production

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Silicon is today classified as a Critical Raw Material for the EU. In the future, the strategic role of this metalloid is bound to increase in low-carbon value chains, such as photovoltaics, clean transport, electronics and batteries.

Europe-based silicon producers are subject to EU climate and energy policy aiming at the reduction of greenhouse gas emissions. The cornerstone of this policy is the EU Emissions Trading Scheme covering the period up to 2030, which has recently been updated. The paper explores the observed and projected impact on silicon production in Europe, especially focusing on cost effects and global competitiveness.

In November 2018, the European Commission also published its Strategic Long-Term Vision for EU’s decarbonisation by 2050 [1]. This vision will shape the future of silicon in Europe. On one hand, silicon is a key enabler of decarbonisation technologies. On the other hand, it will have to be produced in even stricter conditions than today, with consequences not only on CO₂ abatement technologies but also on electricity supply. The paper presents the various possible pathways facing this industry and its value chains, and warns about potential risks.

References:
Recovery of critical metals through waste valorisation: Cerro Colorado copper deposit, Rio Tinto, Spain

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The consumption of critical metals (CRM) for high-technology applications is exponentially increasing, and scenarios predict that future demands exceed current annual worldwide production [1]. This contribution documents the content and mineralogical siting of selected critical metals (Co, Bi, In, Sb) in mined copper ores of the Cerro Colorado deposit, Iberian Pyrite Belt (IPB), Rio Tinto, Spain. A knowledge of the mineralogical hosts of CRM and their concentrations in distinct sulfide minerals will help to evaluate base metal ores of the IPB as potential CRM resources that may be economically and strategically important for the European economy [2].

The Rio Tinto mining district hosts one of the world’s largest volcanogenic massive sulfide (VMS) systems with one of the main orebodies being Cerro Colorado, 65 km north-west of Seville. Bulk composites of ore were collected from active in-pit ore stockpiles for run-of-mill operations. Concentrations of selected trace elements were determined using inductively coupled plasma-mass spectrometry (ICP–MS). Mineral identification of sulfidic ores was done using powder X-ray diffraction (XRD). Mineral identification, quantification of modal distribution and intergrowth were carried out using the QEMSCAN® method. The main ore minerals chalcopyrite, pyrite and sphalerite were analyzed for selected trace elements, using an electron microprobe analyzer (EMPA). Concentrations of selected critical metals were also determined within chalcopyrite, pyrite and sphalerite using laser ablation-inductively coupled plasma mass spectrometry (LA-ICPMS).

The above documented analyses reveal elevated mean contents of Bi (46 g/t), Co (249 g/t), In (9 g/t) and Sb (96 g/t) within the sampled ores. CRM are largely hosted by chalcopyrite (In > Sb > Co > Bi), sphalerite (Co > In > Bi > Sb) and pyrite (Co > Bi > Sb > In). Mine production data and chemical analyses of bulk ore samples indicate that current mining activities extract approximately 2200 t Co, 850 t Sb, 400 t Bi and 80 t In, annually. At present, the chalcopyrite concentrate is enriched in In (In > Sb, Co > Bi), and hence this existing industrial product should be valorized for its In content. By contrast, Co-rich pyrite (Co > Bi > Sb > In) is currently discarded to the waste stream.

The management of mine waste, in particularly acid-forming pyritic waste, is a significant challenge for the mining sector. At the Cerro Colorado mine, pyrite is an under-exploited residue from which a variety of valuable CRM could be derived. Successful recovery of CRM from the Cerro Colorado waste stream would require adjustments to the existing mineral flowsheet that would allow production of a Co-bearing pyrite concentrate. The additional benefit of such waste valorisation practices through CRM recovery would be the prevention of acid rock drainage (ARD) development in the tailings storage facility in the long term.

References:
The role of a biobased circular economy approach in sustainable critical metal extraction: the rare earth elements

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The increasing demand for rare earth elements (REE) is fuelled by their importance in a green energy future, with the demand for dysprosium predicted to increase by 5% annually by 2026. Bioleaching approaches are being intensively researched for the recovery of REE and other critical metals from waste materials, however even 100% recovery will not be able to meet increasing demand. Therefore, extraction from primary sources will be required. REE do not form high concentration ores, so their extraction can require processing large volumes of material, however REE are frequently associated with other raw materials and REE are sold as by-products of iron mining from Chinese deposits. Bioleaching offers the potential to produce valuable by-products from existing mining operations or to remediate historical mine waste. The diverse nature of REE-bearing minerals means that a variety of established and emerging bioleaching approaches could be applied: organic acid leaching, oxidative leaching of sulphidic ores, and reductive leaching of oxidised ores. We have applied these processes to three bauxites, demonstrating varied responses to bioleaching with each bauxite. The combination of low concentration ores and varied mineralogy provide a challenge to recovery: however, it is one that microbes could take on.
Analysis of Sustainable Manufacturing Approaches for Cobalt and Lithium Titanates as battery materials

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Cobalt and lithium are essential metallic constituents for lithium cobalt batteries, widely used for powering consumer electronic devices and transport vehicles. The research topic analyses on wider availability of lithium and cobalt as materials for energy storage and investigates sustainability issues, by comparing carbon footprint analysis, which includes mining, processing and transportation costs. The research investigation examines the alternative materials, such as the lithium titanates as an alternative matrix for engineering Li+−ion conducting medium for battery materials. The crystal structures of ilmenite (FeTiO3), lithium titanates (Li4Ti5O12, Li3Ti2O12 and Li6Ti6O12), lithium-cobalt oxide (LiCoO2) and alkali ferrite (MFeO2) are compared in Figures 1a to 1d,[1,2] in which the intrinsic alkali sites are shown between the octahedral co-ordinated oxide (e.g. Co2+, Ti4+) cages, through which the monovalent ionic diffusion occurs, which are essential for charging and discharging process in a battery. Such anodic materials with monovalent ion corridor might be more easily possible to manufacture from titaniferous resources than using cobalt oxide.

![Image](https://example.com/image.png)

**Figure 1:** A comparison of octahedral metal (TiO₆ or CoO₆) cages in solid-state ion diffusing media: a) ilmenite (FeTiO₃) structure; b) lithium titanates; c) LiCoO₂ structures; and sodium titanate structures [1,2].

The example of synthesis and characterisation of cobalt metal and alkali titanate extraction are discussed, by utilising the cobalt-copper metallurgical slag and titaniferous and titanio-vanadiferous resources, respectively, of the world. For the extraction of cobalt from discarded metallurgical slag, the reduction methodology using calcium sulphate (CaSO₄) is discussed for making high-grade cobalt metal. In this presentation, the method of selective separation of cobalt metals from complex copper sulphide minerals is also explained, which allows us to process the 99% pure powders of metallic cobalt at much lower temperatures (<1050°C) than during the conventional cobalt making (1300-1550°C). The carbon footprints of the conventional process with the novel low temperature reduction and magnetic separation technique are also compared.

For the synthesis of lithium titanate, the process of synthesis is based on the reaction of ilmenite minerals with lithium carbonate and separating the resulting water insoluble-titanate from the water-soluble ferrite. A clear advantage of saving energy in such a synthesis process is also explained. By comparison, the reaction conditions for the extraction of alkali titanates are also discussed, using the alkali-roasting roasting condition. The results for Li+ ion effective diffusivity in alkali titanate materials were compared with Fe3+-ions in the ilmenite like lattice.

Critical Metals from Small-Scale Mining for Development: The importance of the African Great Lakes Region and Delve Data Collaboration

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This presentation highlights some of Pact’s work supporting the livelihoods of small-scale miners exploiting critical metals in sub-Saharan Africa. Specifically, it presents two case case studies from the African Great Lakes region and one global project: 1) DRC cobalt ‘inside and outside the fence’; 2) 3Ts Rwanda ‘Sustainable Development for Mining’; 3) Delve Data initiative. In doing so, the importance of artisanal and small-scale mining (ASM) to the global supply of critical metals is outlined along with the challenges along production networks from mine to market. This includes the need to meet international due diligence and conflict-free legislation, and for improved data collection and collaboration among all stakeholders. It concludes with some practical suggestions of how the global community can support the formalisation of ASM while also helping to meet the demand for critical metals.
Conflict and critical raw materials production: a tale of antimony production in the Balkans
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A pattern of decreasing antimony production in Yugoslavia, which mirrored that of increasing production in China, terminated abruptly at the outset of the Yugoslav Wars (1991). The global geopolitical economic climate of critical raw materials production was not amenable to the re-establishment of antimony production immediately after the wars. In contrast, production of coal and bulk metals continued, though at a lower production rate. Current initiatives to improve the security of supply of critical raw materials, patterns of global production relative to manufacturing bases, and market price mean that antimony is once again a commodity of interest for exploration and development in the Balkans.

The ethnic war resulted in destruction of tailing facilities at multiple mines (all commodities), the occurrence of unexploded landmines in surrounding landscapes, an end to state-subsidised industries such as forestry, and a loss of industry-related jobs in rural landscapes. The partial or total post-conflict cessation of industries in rural locations created an internal migration trend of working populations to urban centres that, superimposed on ethnic displacement during the conflict, created a new demographic in post-mining and post-forestry landscapes.

Mining operator Mineco has taken on former, and subsequently conflict-damaged, mine sites. The company employs best practice in corporate social responsibility and engages in effective communication with local communities. Moreover, their early on-site industrial activities (for example, at a lead mine in Olovo) required the removal of landmines (completed in conjunction with the forestry commission) and reinstatement of facilities for mine waste. These are inherently ethical activities since they rejuvenate the landscape, and increase the ability of individuals to live and thrive in their environment. The early realisation of benefit to both community and mining company was reaffirmed by subsequent employment policies that are sympathetic to ethnic diversity and that partly reverse internal migration patterns. Trust has been created by the transparency of business-oriented and ethical actions of the mining company, rather than externalised CSR approaches which are sometimes perceived as purchasing of public acceptance.

Political, social and industrial legacies have created an acceptance of mining, of either long- or short-duration, that would support critical raw material (i.e. antimony) production, but that might have limited positive impacts on the economic sustainability of communities. The development of convergent solutions as the basis of ethical mining practice is considered in the context of landscapes and the energy requirements for mining in the IMP@CT project. Specifically, the predisposition of communities towards acceptance of short-duration mining, the role of champions with individual value systems, and the potential for the onset of mining to catalyse new forestry industries are discussed in the context of whether critical raw materials production can provide long term economic security for local communities.
Renewable Energy Systems for Sustainable Mining

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The mining sector is one of the largest energy consumers, accounting for 1.25-11% of the world’s total energy consumption. The industry’s energy demand is almost entirely met by fossil fuels, with only 0.001% of the final energy consumption in 2014 sourced from renewable energy technologies installed on site [1]. Similarly, the extractive industry’s output is dominated by fossil fuels. In 2014, 85.6% of the 17.4 billion metric tons of raw material extracted was in the form of oil, gas and coal [2]. The reliance on fossil fuels to generate energy for mining brings economic instability due to fluctuations in market prices. Furthermore, the mining industry has very high CO2 emissions and it is one of the hardest industries in which to decrease these emissions. A report by CDP [3] states that fossil fuel extraction companies are one of the major contributors to greenhouse gas (GHG) emissions. To comply with the Paris agreement and limit global warming, the mining industry has to follow a decarbonisation path and reduce emissions, e.g., by upgrading to new technologies, improving mining processes and adapting renewable energy technologies for energy supply.

To reduce GHG emissions from the mining industry it is essential to understand their energy usage. Energy in the form of electricity is used in stationary mining processes while fossil fuels are primarily used in diesel engine powered mobile equipment. Nowadays, almost all mining processes can be electrified, including some types of transport. Goldcorp’s Borden Lake gold mine in Canada has already taken a step to be an all-electric mine, saving 7,000 tons of CO2, 2 million litres of diesel, and 1 million litres of propane annually with the electrification [4]. Therefore, electrification and decarbonising the electricity supply can be a major step towards sustainable mining. Advancement in renewable energy technologies has also led to significant reductions in the cost of renewable electricity, making renewables cost-effective compared with fossil fuels [2]. Given the high electricity demand at mining sites, volatilities in fossil fuel prices and the need for decarbonisation of the mining industry, on-site renewables for mining have become an increasingly attractive solution. Globally 1 GW of renewable energy plants have already been installed on mines and another 1 GW is in the pipeline to be installed at existing mining projects [2].

The current mine financing paradigm promotes extraction from large ‘world-class’ deposits and sustainable mining initiatives generally assume an extended life-of-mine. The IMP@CT project proposes a new switch on-switch off (SOSO) mining paradigm to improve the viability of many critical metals and other small complex deposits. The work programme aims to develop the proof-of-concept of total and sustainable mining and processing solutions using case studies in the West Balkans. In order to ensure the sustainability of this new approach, a feasibility study on the use of renewable energy systems is being undertaken in the project. Given the focus on small complex deposits, the renewable energy systems have to be mobile and modular providing flexibility in terms of movement and generation capacity. A survey was performed to characterise mobile and modular renewable energy systems, including solar PV, bioenergy and wind turbine systems, which are readily available on the market. Containerised bioenergy systems were found to have the highest electrical power density in comparison to other renewables. In the Balkans, where the IMP@CT project is performing the case studies, these containerised bioenergy systems can be very beneficial in reviving the forestry industry and generating local business activities.

Environmental & Social Maturity as a new concept for self-assessment of best practice in a mining context

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Several significant industrial and mining accidents over the years have generated widespread studies into safety culture as a major leading indicator of workplace-related accidents. Safety culture is defined as the prevalent attitudes and perceptions of safety by management and employees. Hence, the concept of safety culture maturity has since been established as a tool that enables organisations to assess their own level of maturity based on factors such as management commitment to safety, quality of risk assessments, and the approach to incident investigations. In modern day mining operations however, environmental and social (E&S) aspects are becoming increasingly important, to ensure that companies maintain & improve the local environment and integrate community requests into the mine plans and impact assessments. As such, using the principles of safety maturity, a novel approach to E&S culture maturity is presented that aims to allow companies to self-scrutinise and improve their operational practices from an environmental and societal perspective. The E&S models each comprise 5 levels that progressively increase in maturity, with the goal being to move up the culture ladder by implementing the suggested criteria given for each stage. These E&S criteria include community involvement, employment opportunities, energy use, air quality management, etc. Using Bosnia and Herzegovina as a case study, which has recently recommenced mining operations following past conflict in the region, the model will be further developed to consider the specific, complex challenges that are most influential in earning a social licence to operate. Ultimately, the success or failure of a mining project can often be dictated by the level of trust between the company and the local communities & authorities. Therefore, it is in a company’s best interests to ensure: (1) regular collaboration with local representatives in decision making, (2) openness and transparency in public dissemination, and (3) periodic monitoring takes place to maintain overall compliance.
Building an ecosystem for change in the responsible sourcing of critical metals – The Impact Facility for Sustainable Mining Communities

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Artisanal and small scale mining (ASM) is a significant global supplier of critical metals producing an estimated 20% of gold, 26% of tantalum, and 25% of tin¹ for example. Over 40 million people are thought to be directly employed in the sector with a further 150 million dependant on the sector for their livelihoods². While of course the ASM sector faces many environmental, social and governance challenges it is downstream demand that fuels upstream supply. A variety of factors compound challenges to mining communities such as a lack of viable alternate livelihoods, failure to access to finance and markets on fair terms, and technology and knowledge gaps. These gaps drive many of the continuing issues in ASM. Ultimately ASM communities fail to form the economic linkages necessary to draw wealth into the local economy from the depletion of its community’s finite mineral resources and often net value is eroded rather than created and captured.

What is the role of various actors along the supply chain in creating opportunities for change at the mine level, to ensure the emergence of more responsible and sustainable mining practices of the commodities upon which we so heavily depend?

The Impact Facility for Sustainable Mining Communities² acts as a global grant and impact investment vehicle established specially to enable downstream supply-chain businesses, social-development foundations, and impact investors to participate in the development of high impact raw material value chains and the sustainable development of mining communities by strengthening small and medium sized mining community enterprises. The Facility manages grants and social loans to realize its development goals.

The Impact Facility is building an ecosystem to enable lasting change in ASM communities. By working with artisanal mining communities and local implementing partners the Impact Facility develops site specific improvement plans based on its “Impact Escalator” model. This requires a stepped approach, aligned with globally accepted due diligence mechanisms, to transfer knowledge and technology unlocking access to capital and markets on fair terms through demonstrated continuous improvement. The facility generates access to capital on fair terms by working with impact led funders willing to work in a frontier impact investing space to unlock development potential of mining communities through market led solutions. Access to markets is established by working with mid and downstream partners to bring responsibly mined critical metals to market. To ensure lasting change, interventions in ASM must be connected to market drivers from the mid and downstream industries, a sustainable flow of impact capital with the eventual graduation of the ASM sector to mainstream financing options and an awareness of evolving policy, resource governance and trends in consumer behaviour and downstream demand.

This presentation will draw on case study material from the Impact Facility’s pilot project in East Africa in ASM gold mining. This project operates in partnership with Fairtrade and is funded by Comic Relief, RVO, RVO, EPRM and Genesis Foundation, and supported by Fairphone.

A possible framework for responsible sourcing schemes, standards and mechanisms across mineral supply chains

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There are numerous schemes to address aspects of the social and environmental impacts of mining, including those of the International Council on Mining and Metals, the Initiative for Responsible Mining Assurance and the Responsible Mining Index, among many others. But the viability and effectiveness of such schemes is often contested, and their impact is likely to depend on their having demonstrable value to and engagement from multiple actors across complex interacting supply chains and value chains, including mining companies, manufacturers, investors, retailers, and end-point consumers.

Responsible sourcing schemes vary in terms of the social, environmental and economic impacts they address, where in the value chain they focus, what mineral resources they refer to and geographical scope, among other factors. There may be trade-offs between breadth of scope and level of uptake, and different supply chain actors will respond differently to the various characteristics of responsible sourcing schemes. The sheer number and variety of schemes may hinder rather than help development and implementation of good practice as companies across the value chain struggle to decide which of these schemes they should engage with, and what technologies, management methods and standards to apply. Improving our understanding of these considerations is essential if such schemes are to be taken up across value chains, and to make a positive practical difference to people and places affected by mining.

To date, there has been little research on responsible sourcing schemes, their characteristics and their actual or potential impact. Reports produced by the University of Queensland’s Centre for Social Responsibility in Mining in 2015 and the BGR (the German Federal Institute for Geosciences and Natural Resources) in 2017 have categorised and compared a selection of these schemes across various dimensions and characteristics such as geographic and supply chain scope, commodities and social/environmental factors addressed, rigour of assurance and enforcement, and so on. Such simple typologies based only on schemes’ characteristics are likely to be of limited value in appraising schemes and their efficacy, or in developing improved models and mechanisms to stimulate responsible mining and responsible sourcing. They neglect a wider interconnected ecosystem of components, tools, existing and potential technologies, management measures, standards and alternative governance mechanisms (including legislation and regulation) relevant to responsible sourcing and certification across supply chains, of which such schemes are a part. Nor do they engage with ‘circular economy’ concepts such as recycling and reuse. By the same token, circular economy thinking all too often ignores the continuing need for primary production of raw materials through mining, or at least treats it as an inconvenient externality.

I will present work underway to develop a more holistic framework for responsible sourcing and sustainable resource management. This framework will underpin my PhD research project to explore how different actors across the minerals value chain might assess the viability and value of responsible sourcing schemes and other mechanisms, so as to optimise their design, uptake and impact.
Issues in securing access to critical minerals; experience from Northern Ireland

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Northern Ireland is arguably the most actively prospected region of the UK with approximately 25% of the country under licence (either active or in application) for base metals (vested in the local government department responsible for economic development) and precious metals (vested in the Crown Estate). The region is certainly the most prospective for gold, with one active mine, a second, ranked 7th globally by grade, making its way through the planning system, and bedrock occurrences identified at other locations.

Recent exploration carried out in 2018 involving a helicopter SkyTEM survey has identified potential for Volcanogenic Hosted Massive Sulphide. Prospecting has identified anomalous cobalt occurrences in the same licence area. The results of this exploration activity have led to areas of interest for follow up.

The Northern Ireland government recognised the need to establish a more secure and sustainable energy system in 2010 when it published the Strategic Energy Framework. Targets set in 2010 for decarbonising electricity generation have been met, largely with turbines.

The 2017 consultation on an Industrial Strategy for Northern Ireland set out proposals for economic priorities up to 2030. It recognised the need for a sustainable approach to energy policy and a requirement to balance the three sustainability pillars of environmental, economic and social concerns to achieve (among other things) affordable decarbonisation.

This balance of sustainability considerations is were Northern Ireland is gaining experience with respect to mineral development. Regardless of whether the minerals being targeted are precious, base metals or one that is specified on the EU critical list, the extraction process is largely the same – some sort of mining operation will be required, either surface or underground. Local opposition to any sort of mineral development in Northern Ireland is growing, driven by direct opposition to proposed gold mining in a designated Area of Outstanding Natural Beauty. Despite the potential economic benefits, environmental protection is regarded as a greater concern. Even grass roots exploration is seen as merely a stepping-stone to a mine.

Education around the need to mine minerals that are required by the technologies that contribute to decarbonisation is vital. Social issues are not confined to overseas jurisdictions. If general opposition to mining is not to become an additional hurdle to sourcing critical minerals, regardless of what targets governments have set, there needs to be a broader understanding of the role that these minerals play and the processes used to acquire them sustainably.
Deep-sea mining: A responsible source of critical metals or a step beyond the environmental limits of our planet?

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Growing demand for mineral raw materials, coupled with the increasing challenges of land-based mining and geopolitics [1] 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 [2]. Seafloor massive sulfide (SMS) deposits, although compositionally variable, are notable for their relatively high concentrations of base and precious metals. For example, the ‘Solwara 1’ SMS deposit (off Papua New Guinea) contains a mineral resource with a grade of ~8% Cu [3]; very attractive, considering that the average Cu-ore grade being mined globally is now ~0.6% [4]. Polymetallic nodules and cobalt-rich crusts are strongly enriched in critical metals (e.g. Co, Te, REE) considered essential for the transition to a low-carbon economy. The most prospective area in the Pacific for cobalt-rich crusts is thought to contain a Co resource of ~50 million tonnes [5], compared with ‘Identified’ world terrestrial cobalt resources of ~25 million tonnes [6]. Tellurium, one of the least common elements on Earth, reaches concentrations (max. ~200 ppm) in cobalt-rich crusts rarely encountered elsewhere in nature [5].

In addition to the contribution deep-ocean mineral resources could make to future raw material supply, there are indications that these deposits could offer a more environmentally and socially acceptable source of metal supply. Mining is one of the most energy intensive industrial sectors. In contrast to many mineral deposits on land, the deep-ocean deposits currently being considered for extraction are generally exposed on the seabed, which means there is little or no requirement for energy intensive overburden removal. The higher grade of many seafloor mineral deposits means less ore has to be handled and processed relative to lower grade resources on land, to produce the same amount of metal, with associated energy savings and reduced carbon emissions. Crusts and nodules can be easily dissolved, releasing their metals into solution [5]; and there is potential for using low energy, chemical and biochemical processes for selective metal recovery. Social licence to operate is a growing issue for the global mining sector. However, in the deep-ocean there are no human populations to disturb and no permanent mining infrastructure is envisaged.

Despite these apparent advantages the environmental impacts of deep-sea mining are a major concern; with greatest uncertainty resulting from a lack of fundamental knowledge about the deep-ocean ecosystems that may be affected. There are many other unknowns, for example, the types of mining technology that will be used and their potential impacts, the scale of suspended sediment plumes that may be generated, and the timescales involved for deep-ocean ecosystem recovery. Furthermore, each deposit type has different metal compositions, morphology, spatial extent, and ecosystem functions, resulting in different disturbance risks [7]. This uncertainty and a lack of quantitative data, because no commercial-scale deep-sea mining has yet taken place, means that making direct comparisons of the ‘environmental performance’ of the production of critical metals from deep-ocean and land-based mineral deposits is not currently feasible.

The Geology of Decarbonisation

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Decarbonisation of energy and transport, through a shift towards renewable energy and electric vehicles, is expected to be a vital part of the global economy in the 2020s and beyond. These low-carbon technologies typically make use of a wide range of metals, many of which are considered to be ‘critical’. Demand for these metals is forecast to grow rapidly in coming years, and the consequent pressure on the supply chain necessitates development of new mines and efficient processing technologies. As part of this, broader coordination of geological data for exploration is essential [1].

In the case of major and precious metals, such as copper and gold, their global distribution and tectonic settings are well understood and have been the basis of extensive research over many years [e.g. 2, 3]. Critical metals required for new technologies have historically enjoyed less attention, and so the link between their mineralisation and the wider geodynamic context is typically less well-known. For example, deposits of the rare earth elements (REE) and niobium are known to be associated with alkaline rocks and carbonatites, which most commonly form in intracontinental rifts. However, many strongly mineralised alkaline igneous suites worldwide are found in post-collisional settings [4]. Similarly, large deposits of tantalum and lithium are associated with pegmatites, which are generally considered to be related to large granitic bodies emplaced in collisional to post-collisional settings. However, rare-metal pegmatites have formed since Archaean times and some examples lack any clear association with parental granitoids; understanding their genesis is vital for developing exploration models [5].

This talk will provide an overview of the broader tectonomagmatic settings in which deposits of some critical metals are formed, and look at the potential for recognition of new metallogenetic belts that deserve further exploration.


The work described here draws on research funded by the European Commission through the EURARE (FP7 grant no 309373) and HiTech AlkCarb (H2020 grant 689909) projects, and by NERC through SoS RARE (NE/M01116X/1) and the Geoscience for Sustainable Futures ODA programme at BGS.
Are some critical metals a potential secondary resource in modern seafloor massive sulphide deposits?

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Actively-forming modern seafloor massive sulphide (SMS) deposits are analogous to ancient volcanogenic-hosted massive sulphide (VMS) deposits. Among other metals, VMS deposits are known to be significant sources for Co, Sn, Mn, In, Bi, Te, Ga, and Ge [1], metals deemed as critical by the EU or USGS [2,3]. Growing interest in the mining potential of SMS deposits has not previously taken into account high-resolution sub-seafloor mineralogical characterisation which is crucial to assessment of overall metal resources, as historically samples have primarily been collected from the surface of deposits only, and often not analysed for the majority of the critical trace metals [4].

Critical metal distributions were documented in detail using high-resolution laser-ablation ICP-MS (LA-ICP-MS) across the sub-seafloor profile of the pyrite-dominated actively-forming 3.9 million tonne TAG deposit on the Mid-Atlantic Ridge (MAR) [4]. Pyrite is the dominant (>50%) host for Mo, Mn, Sb, U, V, Bi, W and Ge, primarily as mineral inclusions or surface absorption fixing processes, and above 95% of the Co and As as direct lattice substitution. Sphalerite is the primary host of Ga and 24% of the Ge. Chalcopyrite is the primary host for Sn, In and significant Ga (40%) and Ge (28%). Comparison of TAG data to a compilation of LA-ICP-MS data for global SMS and VMS deposits reveal significant concentrations of some critical metals are consistently present in one or more sulphide phases: as substitutions in the lattice of pyrite (e.g. Co), Zn- or Cu-bearing sulphides (e.g. In, Sn, Ge, Ga), micro- to nano-scale sulphide and sulphosalt inclusions in pyrite (e.g. Bi, Ga, Ge, In, Sn, W), or a combination (e.g. As, Sb, Mo). Incorporation mechanisms and the trace element fingerprint of sulphides correspond closely to the conditions of mineralisation in all deposits analysed, reflecting distinctive high- and low- temperature suites, even after zone-refining and metamorphism [4].

Some of these critical metals may be found in abundance in actively-forming seafloor massive sulphide systems. Estimations of the total metal budget across an entire seafloor hydrothermal system was made using sulphide-rich scales deposited directly from primary end-member metal-rich upwelling hydrothermal fluids in closed production pipes from the high-temperature basalt-hosted Reykjanes geothermal system on the subaerial MAR in southwest Iceland [5]. Geochemical profiles to 2.7 km depth reveal that the distribution and behaviour of critical metals are comparable to micro-analytical observations in both SMS and VMS deposits. Mass accumulation calculations show that 988 tonnes (t) of Mn, 86 t of As, 70 t of Cr, 64 t of Co, 50 t of V, 16 t of Te, 11 t of Mo and between 2 and 7 t each of Sb, Sn, Ga, Ge, W, Bi, and total REEs have accumulated over the ~20,000 year lifetime of the Reykjanes system. Calculated tonnages precipitated from primary hydrothermal fluids sourced at depth in the Reykjanes system represent the full sub-seafloor metal budget of an actively-forming basalt-hosted seafloor hydrothermal system, and indicates that at least a third of the total metal budget may be deposited well below the seafloor in analogous actively-forming SMS deposits [5].

Some SMS deposits may have the potential to become resources in the future, and this data shows that detailed analysis of the mineralogical residence and distribution of the critical metals will be of particular importance when assessing potential metallurgical performance and extraction methods.

Trace element systematics of sulphides and associated alteration phases from inactive hydrothermal vents at TAG, Mid-Atlantic Ridge

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Strategic metals are crucial for a growing demand in high-tech and green energy applications, but the security of supply of the metals is at risk. With land-based mining activities refocusing on more remote and technically challenging environments, seafloor massive sulphides (SMS) which form through hydrothermal venting in today’s oceans, may contribute to the strategic metal budget in the future [1]. While recent estimates of the resource potential for base and precious metals of modern SMS account for 600 Mt [1], the inventory of strategic metals associated with SMS and their fate during alteration processes are poorly understood.

During this study 32 surface and subsurface samples were investigated which originate from 6 extinct SMS mounds at the TAG hydrothermal field at 26°09’N on the Mid-Atlantic Ridge. The trace element budget of SMS in primary pyrite, marcasite, chalcopyrite and alteration phases such as goethite, jarosite and atacamite was analysed for 25 elements by laser ablation-inductively coupled plasma-mass spectrometry (LA-ICP-MS). Here, we present the concentrations of the strategic metals indium (In) and cobalt (Co) from two samples, as an example of: a) fresh chimney fragment (SS-6A) comprising of pyrite, marcasite, chalcopyrite and goethite; and b) weathered massive sulphide block (55-10A) comprising of pyrite, chalcopyrite, goethite, jarosite and atacamite.

![Graph showing In and Co concentrations](image)

**Figure 1:** Indium versus cobalt concentrations in primary sulphides and alteration phases from a fresh chimney fragment (SS-6A) and a weathered massive sulphide block (SS-10A).

Concentrations of In and Co in the primary sulphides differ by several orders of magnitude (Figure 1), reflecting the nature of the samples and their different paragenetic stages which is also represented by distinctive sulphide mineral textures, especially in the pyrite. LA-ICP-MS analyses of atacamite show that the strategic metals do not get incorporated into the mineral whereas jarosite and goethite act as a sink for indium, but also selenium, germanium, gallium and many other elements. This suggests that the alteration phases (e.g. goethite, jarosite) should be included in any future assessment of the economic potential, especially as they may be easier to process than sulphides.

The critical metal potential of ferromanganese crusts: New insight from the north-east Atlantic

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Effective resource management and improving the security of supply of minerals requires an understanding of all potential resources in the geosphere. Currently, nearly all primary metal production is derived from mineral deposits on the continents, neglecting the mineral potential of more than 70\% of the planet’s surface.

Deep-sea hydrogenetic (precipitated directly from ambient seawater) ferromanganese (Fe-Mn) or cobalt-rich crusts are strongly enriched relative to the Earth’s crust in many metals (e.g. Mn, Co, Te, REE, Pt, Ni and Cu) \cite{1} of growing economic importance, due to their use in renewable energy technologies. This enrichment, in the case of tellurium up to nearly nine orders of magnitude compared to its average lithospheric concentration, is a direct function of the physio-chemical properties of the primary component of these crusts, Fe and Mn oxyhydroxides; and their extremely slow growth rates \cite{2,3}, which result in continuous metal enrichment over millions of year via scavenging of dissolved species from ambient seawater.

Our general understanding of the geological and oceanographic processes controlling Fe–Mn crust formation are well known. As a result we also have a good appreciation of the global distribution of these deposits, which principally form on sediment-free topographic highs in the open ocean, such as ridges, plateaus and seamounts, at water depths between 400–7000 meters below sea level. However, accurate assessment of their future mineral resource potential is hindered by a lack of understanding of their precise spatial distribution on individual edifices, and grade consistency over areas considered sufficient to sustain potential mining activities \cite{4,5}. These knowledge gaps also have implications for understanding the environmental impacts of extracting these resources and ensuring responsible development. This is something we have been studying in the north-east Atlantic, through combined resource and biological habitat mapping studies.

During this presentation we will describe the results of a comprehensive geochemical study of Fe-Mn crust samples from Tropic Seamount, in the north-east Atlantic, which forms part of the NERC-funded ‘MarineE-Tech’ project. This data indicates that the Fe-Mn crusts at Tropic Seamount contain an average of 0.5 \pm 0.4 wt.\% Co (avg. \pm 2\%), 50 \pm 30 ppm Te and 176 \pm 97 ppb Pt. Interpretation of the geochemical data in the context of geological mapping, hydrographic reconstructions, and water depth has been used to identify the most prospective resource areas on Tropic Seamount. This resource information can be combined with habitat mapping data to assess the potential conflicts with ecosystem protection.

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Advanced indicator mineral research concept for the critical mineral exploration in glaciated terrain

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Increasing self-sufficiency in terms of critical minerals is in the focus of the mineral strategy of the EU and Finland. The aim is to decrease dependency on imports from outside the EU and to ensure own production of raw materials for high-technology industries. Metals defined as critical include, for example, rare earth elements (REE), antimony, cobalt, magnesium, niobium and platinum group metals (PGM), that are used in the electronics industry, smart products, catalytic converters and batteries.

In Finland, like in other Nordic countries, there is a significant potential for undiscovered critical mineral deposits. However, the exploration is challenging in the recently glaciated terrains with continuous till cover and only sparse bedrock outcrops. An ERDF (European Regional Development Fund) sponsored project, Automated identification of indicator minerals in the exploration of critical minerals (2016–2019) INDIKA, investigated new advanced exploration methodologies in till-covered terrains. One of the aims of the INDIKA project was also to improve digital data collection and management. Research partners of the project, Geological Survey of Finland, University of Oulu and Lapland University of Applied Sciences, worked together with a number of companies operating in the mining industry.

Indicator minerals are specific and distinct for certain deposit types. Usually, the indicator minerals exist in higher concentrations and more wide spread in glacial sediments than the actual ore minerals, thus providing an excellent tool for mineral exploration. Particularly, glacigenic sediments, such as till and clays, provide good sample media for indicator mineral based exploration targeting critical minerals.

During the INDIKA project a new exploration concept for critical minerals was developed, based on a combination of on-site and laboratory methods. The on-site studies covered sample processing and mobile analysis techniques, such as pXRF and pXRD, for elemental analysis and mineral identification. The laboratory experiments included testing of various types and combinations of sample concentration and preparation methods, followed by automated electron optical analysis (FE-SEM-EDS) of heavy mineral concentrates.

The results demonstrate that the presence of critical minerals and their indicators can be often identified already during the field work. However, detailed laboratory and analytical work is needed to confirm the discoveries, to quantify the concentrations of indicator minerals, and to provide applicable information for mineral exploration. The results from digital data acquisition and management were encouraging. Case studies in northern Finland have proven that the resulting concept is effective for finding new sources of critical minerals.
The Songwe Hill rare earths project, Malawi – geological observations on the recently announced mineral resource upgrade

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Songwe Hill in the Chilwa Alkaline Province of Malawi hosts an Early Cretaceous carbonatite intrusion in an apparently coeval syenite-phonolite complex, with potassic alteration of the silicate rocks to fenite. 17,745m of resource drilling has been carried out in three stages (2011, 2011-2012, and 2018) by Lancaster Exploration Ltd, a subsidiary of Mkango Resources Ltd. A pre-feasibility study was published in 2015. With the announcement of a new mineral resource estimate on 4th February 2019, work has begun on the Bankable Feasibility Study, to be funded by Mkango’s joint-venture partner Talaxis Ltd, and is expected to conclude in the first half of 2020.

The mineral resource estimate in 2015, above a cut-off grade of 1% total rare earth oxides (TREO), consisted of 13.2 Mt at 1.62% TREO in the Indicated category and 18.6 Mt at 1.38% TREO in the Inferred category.

Following the 2018 drilling programme, Mkango recently announced a Measured Resource of 8.8 Mt at 1.5% total rare earth oxide (TREO), an Indicated Resource of 12.2 Mt at 1.35% TREO, and an Inferred Resource of 27.5 Mt at 1.33% TREO. A geological loss of 4% was applied to account for voids. The updated resource represents a 60% increase in total Measured and Indicated Resources to 21 Mt, including the first Measured Resource estimate. The majority of the previously delineated near-surface Inferred Resource was upgraded to either the Measured or Indicated categories.

Approximately 95% of the Measured and Indicated Mineral Resource blocks are less than 160 m below surface, indicating that the majority will be accessible by open pit mining. Two zones within the Measured category that carry relatively high grades are the anticipated locations of starter pits.

Mine planning and metallurgical optimisation are evaluating opportunities to improve all aspects of mining and processing. For these purposes, a 60 t bulk ore sample was collected from locations mainly in the Measured Resource zones.

The updated and enlarged resource underpins Mkango’s strategy to be a long-term, sustainable producer of neodymium, praseodymium, dysprosium and terbium used in permanent magnet motors for electric vehicles, wind turbines and other clean technologies. The resource is open at depth and observations during the 2018 field campaign suggest there is potential for extensions of the Songwe carbonatite and for other REE deposits in the licence area.
Fenite exploration criteria surrounding carbonatite-hosted critical metal deposits

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Carbonate and alkaline-silicate rocks are the most important source of critical metals such as rare earth elements (REE) and niobium (Nb). Future neodymium-iron-boron magnet production is forecast to increase dramatically due to their use in wind turbines and electric cars, which the UK government had fully committed to by 2050. Whilst China currently produces >95% of the world’s REE supply [1], pressure is mounting to develop new geomodels and exploration criteria to better understand critical metal enrichments in carbonatite complexes.

Carbonatic magmas release alkali-rich fluids as they cool and crystallise, metasomatising the country rock during a process called fenitisation [2]. Fenite alteration patterns consist of an inner potassic aureole surrounded by a sodic aureole that can extend >1km from the source intrusion. Alteration patterns have previously been used as successful exploration tools (e.g. porphyry copper), and fenite aureoles have great potential to be used as such.

Anions such as fluoride and chloride complex with REE and Nb in fenitising fluids, mobilising them in to the fenite, where they precipitate as enriched ‘micro-mineral assemblages’ [3]. REE-enriched carbonatite intrusions are typically late-stage and more evolved. Strong correlations exist between the complexity of fenite textures, brecciation, mineral zoning and REE-enriched intrusions.

Fenite apatite crystals typically exhibit zoning under cathodoluminescence and SEM, recording metasomatic activity and changing chemistry of fenitising fluid pulses. REE-enriched complexes show systematic increases in Na, Sr and TREE fromapatite core to rim, reflecting fluid and therefore melt chemical evolution. Apatite at these enriched complexes display either late-stage REE-rich purple luminescing rims or blue-purple luminescing crystals.

Zoning within fenite apatite crystals from the Sokli carbonatite complex, Finland provide insights into fluid flow in the country rock. Imaging of fenite apatite associated with multiple intrusive stages, indicates a relationship between intrusion size and the distance fenitising fluids travel. Comparisons between fenite apatite and their carbonatite counterparts, also indicate that there is no preferential mobilisation of particular REE, and that the entire distribution are mobilised into the associated fenite.

Results indicate that fenite aureoles have great potential to be used as exploration indicators. Alteration patterns are spatially extensive and can be observed at a variety of erosion levels, acting as vectors toward source intrusions. The composition and zoning of fenite minerals also indicate whether these intrusions have the potential to be enriched in critical metals.

Deposit-scale geomodels for REE and HFSE exploration in carbonatite and alkaline-silicate magmatic systems

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Rapid growth in the demand for critical metals, including the rare earth elements (REE) and high field strength elements (HFSE), is driving expansion and diversification in their supply chains. Although alternative sources are being explored, the majority of the world’s resources of these elements are found in alkaline igneous rocks and carbonatites. These small magmatic centres represent highly-fractionated residua of low-degree mantle melts, with the majority occurring in failed continental rifts. Approximately ten percent of the > 500 catalogued global occurrences contain mineralisation. However, the mineral exploration industry has traditionally focussed on major- and precious metals, such as iron and gold, therefore exploration models for alkaline rocks and carbonatites are less well developed.

We have compiled geological, exploration targeting, and environmental factors pertinent for the development of critical metal resources hosted by carbonatite and alkaline-silicate magmatic systems. For these two interrelated suites of igneous rocks we are building interactive digital geomodels, for a target audience of economic geologists from industry and from academia. The schematic models will be presented at deposit-scale (ca. 1–5 km lateral) and will indicate the key lithological units that typically host mineralisation, placing these within a depth and horizontal reference frame within these fossil magma bodies.

Our model will show the processes that mobilise, concentrate and trap the metals within magmatic layering and roof zones, and during hydrothermal alteration (fenitisation) of wall rocks. Typical geophysical signatures derived from induced polarisation, gamma radiometric, gravitational and magnetic techniques will be shown on an overlay. This, in concert with information on indicator mineral chemistry, both within float and within alteration haloes surrounding these intrusions will facilitate vectoring toward critical metal mineralisations.

The diversity of metalliferous minerals within these deposits is much greater than that of traditionally mined major or precious metal deposits, with some phases currently being processed more easily than others. Recovery rates and energy usage are improving at a rapid rate as the pertinent metallurgical techniques mature. The models also take into account environmental considerations specific to alkaline rocks and carbonatites, such as radioactivity of certain minerals.

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Critical and precious element recovery with environmentally-benign Deep Eutectic Solvents

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Gold and copper concentrates often contain high enrichments of scarce or critical elements such as Te, Bi and Sb, but there are few financial incentives for recovery of these elements as by-products. Deep eutectic solvents (DES) may provide novel processing opportunities – these are a form of ionic liquid that are mixtures of salts such as choline chloride with hydrogen-bond donors such as urea. DESs are environmentally benign, yet chemically stable and, furthermore, the components are already produced in large quantities at low cost.

We have demonstrated that gold is rapidly dissolved in DES by iodine oxidation [1,2], whereas many base metal sulfides are unreactive or react only slowly. However, most trace minerals that host the majority of Te, Bi and Sb in a concentrate, such as native Te and Bi, tellurides, or Bi- or Sb-bearing sulfosalts, are rapidly dissolved at similar rates to gold, suggesting routes to recovering gold and critical elements.

Systematic patterns are observed in the leaching rate in homologous mineral series, for example Ag₂Te leaches more rapidly than Ag₂S and in turn that leaches more rapidly than Ag₂Se. Sometimes sulfides leach most rapidly, e.g. Bi₂S₃ > Bi₂Te₃ > Bi₂Se₃. In all cases investigated so far the selenide leaches the slowest suggesting lower solvation energy. These observations are enabling us to predict and quantitatively model the bulk leaching behavior of various ore concentrates and design bulk leaching tests. An example will be presented where Se and Bi leaching from gold ore is demonstrated.

Smart sorting of minerals

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The introduction of luminescence spectroscopy to the beneficiation of ore has the potential to increase productivity and decrease the environmental impact. Optimisation of the run-of-mine (ROM) material at the sorting stage reduces energy consumption, water use and processing time. Luminescence can be used to target key minerals, increasing the grade or alternatively to remove deleterious materials that can poison the line.

In the present study, we focus on Rare Earth Ore minerals as an example of the technique. Many Rare Earth Element (REE) minerals display distinctive emission lines related to f-f energy cascades of trivalent lanthanide ions (Ln³⁺). Natural REE mineral systems have been incompletely studied, with much work concentrated on synthetic analogues. However synthetic materials are poor indicators of the behaviour of natural systems, due to the complex interaction of multiple REE, local defects (including chemical substitution) and lattice damage in natural systems. These all dramatically affect how energy is transferred though the structure, modifying the spectrum and the quantum efficiency.

We study here the spectra of natural REE-bearing ore minerals, including catapleiite, eudialyte, fluorite and monazite, from multiple localities. Common features include; discrete REE emission, REE energy transfer, thermoluminescence (TL) on heating and thermal hysteresis of luminescent properties. We find luminescence spectra of some these minerals shows a strong provenance dependence, with the same mineral from different localities producing different spectra.

Current sorting technologies utilise X-rays and lasers as excitation methods. Light is emitted during X-Ray fluorescence (XRF) and X-Ray transmission (XRT); and by using this light (or even exciting the samples with lasers), the coupling of luminescence technology to existing systems become viable. Our work demonstrates that, in principle, luminescence smart sorting of REE minerals can be successfully applied, so long as the target minerals are characterised for the locality of interest.
Have the Wheels Fallen off your “Hype Cycle”? A retrospective look at criticality: tantalum, rare earth elements and lithium

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Critical or strategic metals / minerals / materials are not a new phenomenon; it is possible that a motivating factor for the invasion of Britain by the Romans was to obtain metals and the oil crisis of the 1970’s highlighted modern society’s dependence on hydrocarbons. In the last 45 years technology-dependent demand, either real, forecast or imagined has resulted in exploration booms, price spikes and increased research output for specific commodities including tantalum, rare earth elements and lithium. These have typically been followed by a short-term market collapse until a period of stabilization is reached. These boom and bust cycles may mirror the overall commodity trends, or more typically they are independent.

This phenomenon is similar to the stages defined in the “the hype cycle” by Fenn (1995) [1][2] for emerging technologies which has subsequently been applied to commodities and regarded as a feedback control mechanism [3]. This path is typically illustrated graphically with time along the X-axis and expectation or visibility along the Y-axis (Fig. 1.)

![Hype Cycle Diagram](image)

Figure 1. The general hype cycle with its four stages as developed by Gartner [4]

Whereas a single emerging technology would follow a typical “hype cycle” path, commodities depending on their principle useage, may follow multiple paths, each of which would be linked to a particular demand.

In a similar way to new technology growth, perceived take-up of critical materials with new technologies is likely to be over-anticipated with an over-optimistic forecast demand and under estimated costs. This seems to be a feature of most human activities.

Scandium as an important critical metal in the quest for reducing carbon dioxide emissions in the 21st century.

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Scandium, element number 21, has a long history of being the neglected new metal. Famously considered one of the REE due to its charge, so called affinity and position in the periodic and atomic tables, it acts unlike the rest of the family, being crystallised early and being incorporated within minerals largely composed of Fe, Ti and Zr – all which have very similar cationic radii. It is this fact which sets Sc apart from the other REE as it tends not to concentrate and rarely fractionates to any degree. Scandium’s role in the low carbon industry is dependent upon two vital aspects, (1) the provisions of ever lighter but stronger aluminium alloys, and (2) the role of scandium as a catalyst in solid oxide fuel cells (SOFC). Making aerospace metals lighter, and cutting down power generation emissions, means less carbon dioxide and therefore vital for future consideration. Exploration has to date had only limited success in finding ‘economic’ deposits, largely because focus has been on the miss-considered association with other REE.

The association of scandium with some examples of alkaline rocks and carbonatites has been long known. Although there is a clear association with these complexes and REE (and sometimes Sc) there is very different mineral deportment between these elements. It is apparent that the scandium will be associated with the more mafic and even ultra mafic parts of these complexes. It can be observed to be incorporated within chiefly clinopyroxene and of these, those that are the earliest crystallised. Most examples of significant Sc enrichment recorded appear rather to be associated with the weathered saprolite above carbonatites rather the mafic alkaline rocks. As the Sc content of secondary weathering products increases during especially during lateritic weathering events, it is considered that many of these more mafic rocks have not been adequately explored.

Recent studies of Glenover pyroxenite complex in South Africa has shown that the scandium reports in zircon, Ti-Nb minerals and clinopyroxene (aegerine). Similarly, at the Bayan Obo deposit in China [1], which is mined for its REE, the waste minerals are aegerine which in this case contain significant Sc. Recent exploration research conducted at the Crater Lake deposit in Canada [2] has located anomalous amounts of Sc with recorded rock samples in excess of 1000 ppm Sc reported. Scandium in this example can be noted to largely be hosted within hedenbergite. The contained iron results in a high magnetic susceptibility and therefore this mineral can be upgraded with simple magnetic separation. Plots of the REE content as well as Sc content of the rock samples clearly note the highest results of Sc are all associated with mafic clinopyroxenites and/or mixed iron rich ‘mafic’ syenites.

In a further example studied - Karingarab carbonatite in Namibia where secondary scandium mineralisation occurs in the overlying weathered parts - it can be see that the relationship of the contained Sc into mineral species can be quickly defined and identified through the use of ‘self-organised mapping studies’ or SOMS. The relationship of Sc is best satisfied through association with iron rich secondary minerals. These have similarly been identified in the secondary laterite deposits presently being developed in Australia. SOMS is quick, cost effective and a particularly important avenue for showing the different mineral associations of scandium and REE bearing minerals in large geochemical datasets as often generated during exploration studies.

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Elemental Se and Te nanoparticles biosynthesised by Aerobasidium pullulans: Characterization, separation and detection with DLS, AF4-UV-MALS-ICP-MS/MS, spICP-MS and TEM

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Selenium (Se) and Tellurium (Te) are strategic elements required for their photoconductive and photovoltaic properties, however, there is a global supply uncertainty in view of their low crustal abundances [1] which necessitates alternative and sustainable strategies for their production. Elemental Se and Te nanoparticles (NPs) were synthesised by Aerobasidium pullulans grown for 10, 20, and 30 days on nutrient media enriched with Na₂SeO₃/Na₂TeO₃. The suspensions were filtered and total elemental concentrations were determined with ICP-MS/MS as follows Se=81.6 ± 0.40 mg L⁻¹, and Te= 21.5 ± 0.13 mg L⁻¹ (n=10). NPs were separated from solution with asymmetric flow-field flow fractionation (AF4), and coupled with UV/VIS absorption, multi-angle light scattering (MALS) and inductively-coupled plasma mass spectrometry/mass spectrometry (ICP-MS/MS) for simultaneous detection. Particle sizes in two aqueous mobile phases (Novachem surfactant [NVC], and a phosphate buffer [PB]) were compared. Particle size computed from light scattering yielded mean radii of gyration in NVC 80 ± 0.4 nm; and 93 ± 0.55 nm, and in PB 75 ± 0.31 nm and 88 ± 0.25 nm (respectively for Se and Te NPs). Transmission electron microscopy (TEM) showed spherical shapes for Se and Te (NPs) however an additional filtering of Te-enriched suspension yielded rod-shaped particles, which was remarkable considering the electrical properties of Te-nanorods [2]. The study has therefore demonstrated a sustainable method for the sequestration of Se and Te NPs by fungi from liquid salts; with various shapes and sizes which have been adequately characterised using multiple techniques.

References

A new vision for the genesis of Santa Helena breccia, Borralha W deposit

NW of Portugal

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The Borralha deposit is located in Northwest of the Iberian Variscan Belt. This deposit, during 1904 to 1985 period, exploited tungsten ores with underground mining works. The mineralization occurred in vertical and sub-horizontal quartz veins with wolframite, scheelite and sulphides. In addition to the wolframite mineralized veins, Borralha has two breccia pipes where the outcropping Santa Helena breccia (SHB) is the most important. In the European Variscan Belt, the SHB is a rare example of W mineralization in breccia pipes. SHB corresponds to a sub-vertical structure, with N-S major axis, revealing at least 575 m in length, over 150 m in width and at least 200 m in depth. This body cut the contact between synorogenic Variscan granites and metasedimentary rocks (Silurian in age). The lithological composition of fragments is identical to the surrounding rocks with different sizes and angular shapes. In former times, a small exploitation of the SHB was performed in outcrops near two N-S subvertical quartz veins that limit the breccia at east and west [1]. This work made part of a bigger project, named INTERREG V-A España – Portugal (POCTEP) 2014-2020 -0284_ESMIMET_3. The aim of this research is to give a contribution for a better knowledge of the SHB, from the standpoint of its genesis and tungsten mineralization mode of occurrence. Once that, this is an outcropping pipe which gives the possibility to exploit in open pit.

The genesis of the SHB would occur in four distinct steps, the first would have been a brecciation that occurred due to hydraulic fracturing of the regional rocks and posterior collapse forming a collapse breccia (CB). The second step is characterized by “cementation” of the collapse breccia by a barren quartz that consolidates the fragments. In the step three, the previous breccia would be injected by a material constituted by quartz+ fine muscovite+ small rock fragments forming small cavities in the matrix and showing a sharp contact between an injected breccia (IB) and CB. The last step for the genesis of the SHB would be the mineralization formation, that could occur in two distinct ways. The first with impregnation of the matrix from the IB with disseminated mineralization, and the second with ore bearing fluids migrating towards the areas with greater porosity or induced porosity along the marginal sectors of the SHB or larger cavities and veinlets.

The mineralization of SHB would occur in four different stages. In the first stage were described the occurrence of oxides, phosphates and a first generation of scheelite associated to iron-manganese chlorite. The second stage would be characterized the occurrence of two types of wolframites (distinguished by its iron content) and the second generation of scheelite associated to iron-chlorite. The third stage exhibit the occurrence of niobium-tungsten oxides, cassiterite and the major sulphides. The last stage would be characterized by the third generation of wolframite, enriched in Mn, minor sulphides and sulphasalts [2]. The obtained results prove that mineralization and grades are dispersed all over WO3 arriving to 1 kg / ton of WO3, however some sector exhibit higher grades.

Energy Critical Elements (ECE) in the English Lake District - Scar Crags, Dale Head North

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The English Lake District represent an excellent natural laboratory to understand formation of vein-type ECE ores in the proximity of a large intrusive body, and hosted by a suite of different lithologies, from sedimentary (siltstone-mudstone), to (pseudo)-metasomatised sediments (bleached siltstones), and volcanics (tuffs, ignimbrites). Specifically in the localities of Scar Crags and Dale Head North, significant grades of Co-As-Bi-bearing minerals are reported in the literature ([1],[2]), not further studied since the early eighties.

The current investigations used lithological and structural data, and samples collected at the aforementioned localities coupled with reflected light microscopy, paragenetic sequencing, scanning electron microscopy, energy dispersive spectrometry, and electron micro-probe analysis to define the entire suite of ECE present in these mineralisation, assess their abundance, identify/confirm mineral phases, and finally create a tentative model for mineralising fluids chemistry and source, and methods of emplacement.

The key outcomes are: 1. Large abundance of As and Co minerals, including glaucodot, cobaltite and alloclase, but also presence of minor grades of Bi, Se, Sb, and Te minerals and, at Dale Head North occasional crystals of allanite (LREE-bearing), and some bizarre minerals tentatively identified as LREE-bearing carbo-fluoride, and Y-HREE-bearing phosphate (also observed rutile and zircon within quartz intergrown with ore minerals, and apatite). 2. Single stage, high/moderate sulphur-bearing fluids responsible for Scar Crags mineralisation. In contrast, two stages (1st oxygen-rich, sulphur-absent, 2nd stage sulphur-bearing) of diverse fluids forming Dale Head North ore. 3. Likely mixed source magmatic and connate waters involved in the transport of metals (inclusive of ECE) for both mineralisations. 4. Key role of the permeability of the host rock (siltstone vs volcanic tuffs) in terms of defining rock-mineralising fluids interaction, thus affecting ore mineral precipitation stages and type of ECE mobilized to the trap.

Overview and assessment of the European lithium resources

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Driven by a global move towards renewable energy through the last decade, lithium has become a strategic metal due to its physical and chemical properties (e.g., lightest solid element and excellent conductor of heat and electricity) making it an excellent candidate for electrification of transport and green technologies such as Li-ion batteries and other energy storage devices. In this context, European interest in lithium mining and exploration has risen sharply and many countries are currently assessing their own mineral resources and reserves in order to secure their supplies.

From this perspective, a geographically-based compilation of the European lithium hard-rock occurrences and ore deposits with their corresponding features (e.g., deposit types, Li-bearing minerals, Li concentrations) is presented. Accordingly, it appears that lithium is not particularly rare and is well represented and distributed through various deposit types related to several orogenic cycles from Precambrian to Miocene ages. Thus, about thirty hard-rock deposits have been identified mostly resulting from endogenous processes such as lithium-cesium-tantalum (LCT) pegmatites (e.g., Sepeda in Portugal; Aclare in Ireland; Läntta in Finland), rare-metal granites (RMG; Beauvoir in France; Cinovec in Czech Republic) and greisen mineralisation (Cligga Head, Tregonning-Godolphin, Meldon in UK; Montebras in France). Local exogenous processes such as hydrothermal and erosion transport may be also related to significant secondary Li-endowments including jadarite precipitation in the Jadar Basin (Serbia) but are rarely related to economic grade of lithium (e.g., Mn-(Fe) deposits, bauxite). Moreover, a systematic assessment of metallogenic processes in the Li endowment has been conducted and several relevant parameters have been identified and may offer exploration guidance for mining companies and governments. These parameters are: 1) a pre-existing Li-rich source related either to paleoenvironmental sedimentation conditions or a crustal anomaly; 2) presence of lithospheric thickening, which may reflect a favourable process to concentrate Li; 3) a regional or local extensional regime; and 4) existence of fracture sets acting as channel ways for exogenous processes.
Exploring the feasibility of an anatectic model for albite-spodumene pegmatites from the Austroalpine Unit (Eastern Alps)

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Albite-spodumene (LiAlSi2O6) pegmatites are generally considered to be the product of extreme fractionation of melts or fluids deriving from large alkaline granite intrusions. Anatectic melts deriving from partially molten metasediments are in contrast not believed to be a possible source for such pegmatites. In the Austroalpine Unit of the Eastern Alps, albite-spodumene pegmatites are associated with simple pegmatites and relatively small inhomogeneous leucogranite bodies, all Permian in age. Large parent granites were however never observed. Instead, field relations, petrography, geochronology as well as phase and whole rock major- and trace-elements geochemistry suggests that these pegmatites and leucogranites derived from anatexis in upper amphibolite facies of Al-rich metapelite. Bulk rock and LA ICPS-MS mineral geochemistry indicate that before melting, metapelites could have contained significant Li (in average 120 ppm) and that the main Li-carrier in the protholith was staurolite (with up to 800 ppm Li). The aim of this study is to test with geochemical modelling if melting of such metapelites could be the origin of the albite-spodumene pegmatites.

The modelling approach consists in three steps. (1) Thermodynamic modelling is carried out in the NaCaKFMA$SH$ system with the TheriaK-Domino software package, the tc6 thermodynamic database and the most recent set of activity models for sub- and suprasolidus metapelite. It is used for calculating the proportion of solid phases and melt for two types of scenario inspired from field observations: prograde melting of metapelite and metasomatism of metapelite by migrating melt. (2) Phase proportions and Li-partitioning coefficient are used for calculating the Li-distribution. Different melting models are considered: batch melting, fractionated melting and melting with overstepping. (3) Fractionation of Li in simple pegmatite and leucogranite of known Li-concentration is modelled with mass-balance.

Using conservative parameters and realistic hypotheses, these models show that 15 to 25 vol% melt containing more than 200 ppm Li can escape the migmatis, in case melting is associated with destabilization of staurolite. Following fractionation of the melt with 99% in mass within simple pegmatite and leucogranite containing 100 ppm Li yields high-evolved melts with 10,000 ppm Li. This value corresponds to the Li saturation in felsic melts necessary for crystallizing spodumene. Our geochemical model shows that partitioning of Li between restite and anatectic melt coeval with breakdown of staurolite, followed by fractionation is a realistic genetic process for the formation of the albite-spodumene pegmatites of the Austroalpine Unit.

Two generations of cassiterite in albite–spodumene pegmatites from Leinster, SE Ireland: Implications for tin mineralisation in lithium pegmatites

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An increasing demand for high-technology elements resulted in current exploration by Blackstairs Lithium Ltd. in a highly prospective area with anatetic [1] lithium-caesium-tantalum-enriched (LCT) pegmatites of the albite–spodumene subtype. The LCT pegmatites are restricted to the East Carlow Deformation Zone (ECDZ) at the eastern margin of the late Caledonian S-type Leinster Batholith in southeast Ireland.

Rare-element pegmatites of the LCT family are predominantly mined for lithium for Li-ion batteries, but often contain heavy alkali metals and high-field-strength elements (HFSE) such as Ta as valuable by-products. Tin, which behaves in a geochemically similar way to the HFSE, is also often enriched in LCT pegmatites worldwide, including southeast Ireland. Tin has a promising application in high energy-density anode materials for rechargeable batteries [e.g. 2] which could strongly increase its future demand. Apart from that, tin has important high-technology applications as electric soldering material and as tin indium oxide in touchscreens.

Petrography, cathodoluminescence (CL) imaging and LA-ICP-MS chemical mapping of cassiterite within metasomatic albites of the Leinster LCT pegmatites reveals complex crystallization histories. Two chemically distinct generations are observed, often within single grains. Early magmatic cassiterite shows low Ta/Nb ratios but overall high concentrations of other HFSE such as Ti, W and U, while later hydrothermal cassiterite shows high Ta/Nb with generally low concentrations of impurities apart from Ta. Both types show oscillatory zoning in trace elements, while hydrothermal rims can additionally show chemically distinct steps characterised by abrupt changes in trace element chemistry and changing CL patterns. A third type of cassiterite, replacing early magmatic zones, has abundant anhedral columbite inclusions as well as minor chloride, quartz, albite and apatite inclusions and is itself enriched in Mn, Nb and W. It formed prior to crystallisation of hydrothermal cassiterite, possibly from dissolution–precipitation of cassiterite along fluid-induced fractures combined with co-precipitation of inclusion minerals.

Multi-generation cassiterite in rare-element pegmatites was also discovered in melt and fluid inclusions of other rare-element pegmatites [3]. The authors present evidence that leucogranitic melt does not reach Sn saturation prior to unmixing into a polymerized peraluminous melt and a depolymerized water-rich melt. The polymerized endmember crystallized HFSE-rich magmatic cassiterite, while the water-rich melt carries substantial Sn without being saturated (up to 4000 ppm). A fluid unmixing from the latter could have caused precipitation of the second generation of cassiterite. This is in accordance with the observations presented here and the model for LCT pegmatite formation at Leinster proposed in [4].

The unmixing processes used to explain Sn mineralisation and transport in LCT pegmatites are also a possible mechanism for the liberation of Sn-rich fluids from late-stage granitic magmas, which subsequently form mesothermal tin-(tungsten) deposits [e.g. 5].

Critical Metal Mineralisation Associated with Magmatic Roof Zones

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The tops of magma chambers – ‘Magmatic Roof Zones’ – are exceptional geological environments often associated with mineralisation. The roof zone constitutes the products of an isolated lens of magma whose composition and physical properties are often distinct from that of the main body of the chamber. Magma compositions are modified by interaction with roof rocks and volatile contents may be exceptionally high. The temperature, viscosity and plasticity of the magma are often distinct from that in the main body of the chamber.

We describe field, geochemical and isotopic studies from the roof zones of a suite of subvolcanic magma chamber systems associated with the Mid-Proterozoic Gardar province, South Greenland [1]. Recent glaciation has provided excellent 3-dimensional exposures through the subvolcanic systems, often preserving a cross-section through the roof [e.g. 2] and there are few better field areas globally to study mineralising processes in roof zones. Xenolith-rich horizons in the Gardar plutons delineate boundary layers where convection cells in the chamber isolate a static lens of roof magma (above) from the convecting chamber (below). The roof magma penetrates and reacts with the country rocks, amplifying compositional and physical contrasts to the main body of the magma. This unique geochemical environment creates compositional, redox and temperature gradients, often associated with mineralisation, and we illustrate these processes with the Ta-Nb mineralisation at Motzfeldt and Be-Li-REE ores at Ilimaussaq. Roof zones are complex magmatic systems in which repeated sheeting produces highly variable rocks with few internal chilled contacts. Furthermore, the high volatile contents can lead to aggressive late-stage hydrothermal fluids which complex and mobilise high field strength elements after magmatic crystallisation. Different Gardar intrusions show different hydrothermal behaviour and we use S isotope data to constrain the different redox-temperature-time pathways as the intrusions and their associated fluids cool. The resulting replacement minerals and intimate intergrowths can be problematic for mineral processing [2,3].

Sulphate-bearing monazite-(Ce) from silicified dolomite carbonatite, Eureka, Namibia: substitution mechanisms, redox state and HREE enrichment

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Sulphate-bearing monazite-(Ce) occurs in silicified dolomite carbonatite at Eureka farm, about 30 km southwest of Usakos, Namibia. This monazite contains the highest $SO_4$ contents, up to 11 wt.%, presented to-date and thus is a good example for understanding S substitution in monazite and the role of S in REE-rich carbonatite systems.

Sulphate-bearing monazite occurs as a reaction rim, up to 0.5 mm thick, around primary, sulphate-free, monazite. This reaction zone is heterogeneous, and the sulphate-bearing monazite exhibits symplectic intergrowths with calcite and Fe-oxide minerals. The surrounding rock is almost completely altered to chalcedonic quartz which locally contains celestine and Fe-oxides inclusions along planes after dolomite. These features point to near-total alteration of the carbonatite, removing Ca, Mg and CO$_3$, and substantial introduction of silica.

Major element data, obtained by EPMA, show that sulphate is incorporated into monazite by anhydrite exchange $[(Sr,Ca)^{2+} + S^{4-} \leftrightarrow REE^{3+} + P^{5+}; 1]$. However, anhydrite exchange cannot be the sole mechanism for the incorporation of sulphate as it results in an excess of $M^{2+}$ cations. To compensate, previous workers speculated that an auxiliary substitution with OH$^-$ also takes place $[REE^{3+} + O^{2-} \leftrightarrow (Ca, Sr)^{2+} + OH^−; 1]$, but new Raman data from this study do not support this mechanism. Rather, our new XPS data indicate that S-bearing monazite exhibits considerable variation in the oxidation state of Ce and S, which may compensate for the $M^{3+}$ excess. Coupled substitution of Ce$^{4+}$ with Na$^+$ $[3Ce^{4+} \leftrightarrow Na^+ + 2Ce^{4+}]$ is indicated by a positive correlation between Na and Ce, lending further support to a redox controlled substitution mechanism. Moreover, sulphate-bearing monazite also has elevated contents of other redox-sensitive elements, such as U, V and Mo.

In contrast to unaltered sulphate, sulphate-bearing monazite from Eureka incorporates relatively elevated concentrations of trace elements, including elevated HREE contents. The abundance and variety of substituting elements attests to the considerable structural distortion from incorporating a proportion of sulphur into the phosphorus site, but also considerable change in crystallisation environment. Owing to its localised extent, we tentatively consider silicification and the formation of sulphate-bearing monazite to be caused by a hydrothermal process, possibly in the range of 150–385°C by comparison with other studies [2]. While the effect of other complexing anions cannot be ruled out, the change in REE distribution in the S-bearing monazite is testament that such a fluid fractionates the REE. Sulphur may play a role in this fractionation during transport or deposition.

The role of carbonate-fluoride melt immiscibility in shallow REE deposits evolution: New evidence from Mongolia

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The most important and economic REE deposits in Mongolia are hosted by a range of carbonatite dikes mineralized in rare-earth elements (REE). These dikes are host to a previously unreported macroscale texture involving pseudographic intergrowths of fluorite and calcite. The inclusions within calcite occur as either pure fluorite, with associated REE minerals within the surrounding calcite, or as mixed calcite-fluorite inclusions, with associated Zr minerals. Consideration of the nature of the texture, and the proportions of fluorite and calcite present (~29 and 71 mole %, respectively), indicates that these textures formed through either cotectic crystallization of the immiscible separation of carbonate and fluoride melts. Pure fluorite inclusions are depleted in REE relative to the calcite. A model is proposed, in which a carbonate-fluoride melt phase enriched in Zr and the REE, separated from a phonolitic melt, and then either unmixed or underwent cotectic crystallization to generate an REE-rich carbonate melt and an REE-poor fluorite phase. The separation of the fluorite phase (either solid or melt) may have contributed to the enrichment of the carbonate melt in REE, and ultimately its saturation with REE minerals. Previous data have suggested that dry carbonate melts separated from silicate melts are relatively depleted in the REE, and thus melt immiscibility cannot result in the formation of REE-enriched carbonatites. The observations presented here provide a mechanism by which this could occur, as under either model the textures imply initial separation of a mixed carbonate-fluoride melt from silicate magma. Multistage silicate-carbonate-fluoride melt immiscibility may be a previously unrecognized, but important process in the generation of REE-mineralized carbonatites.

Figure 1: Representative images of carbonatites and calcite-fluorite intergrowth texture at a range of scales. (A) Representative carbonatite with calcite-fluorite intergrowth texture at macro scale, (B) BSE image of synchysite-(Ce), parisite-(Ce) and bastnasite-(Ce) in carbonatite, (C) Fluorite-calcite macro-inclusion. (D) Area highlighted in (C), showing calcite-fluorite intergrowth in BSE image. Fl-fluorite; Cc – calcite; Syn – synchysite-(Ce); Par – pararange-(Ce); Bst – bastnasite-(Ce).
Ion adsorption deposits: A comparison of deposits in Madagascar and China

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The world’s primary source of the HREE is from ion adsorption deposits, in which >50% of the REE occur in easily leachable form within lateritic weathering profiles. These are currently only mined from granitoid systems in southern China. There is potential to find weathered, easily leachable deposits that are associated with more REE enriched bedrock with more specific elemental enrichments, but which formed by similar mechanisms to the Chinese deposits. The Ambohimirahavavy deposit is developed in weathering profiles over a Mesozoic alkaline complex, which exhibits REE mineralisation associated with zirconosilicates and niobates in late stage alkaline pegmatites and hydrothermal veins. In this study we compare deposits from Madagascar with those from the Zhaibei granite, China, in order to test for commonalities in genetic mechanism and host of REE mineralisation.

The overall grades of REE are comparable between deposits, and may be higher in restricted zones derived from mineralised bedrock in Madagascar. Sequential leaching using ammonium sulphate solution at pH 4 shows that there is a contrast in the leachability, with high levels (60-70%) of LREE (La-Gd) extractable at both sites, but with only 40-50% of the HREE leachable in Malagasy samples. This indicates a key role for precursor mineralogy as higher REE grades are hosted in zirconosilicate minerals at the Madagascar site. The initial control on REE distribution is bedrock heterogeneity, and secondary control comes from the topography of the area and the hydrology of the weathering environment. Topographic highs are zones of oxidation and leaching, identifiable from positive Ce anomalies, whilst slopes are areas of redeposition and adsorption. Within individual profiles highest leachable REE grades occur at pedological boundaries where there is a contrast in permeability, resulting in retardation of groundwater flow and shifts in pH leading to enhanced sorption. At the microscale XANES and XAFS scans show that the REE are adsorbed as 8 or 9 co-ordinated hydrous outer sphere complexes on the surface of kaolinite. This process is identical to the microstructural site of REE in the Chinese deposits, and confirms that the same process is sequestering the REE in weathered rocks globally. Grades in REE are comparable in laterites between sites, suggesting sorption on kaolinite may be the critical step in concentration with laterites rather than the primary bedrocks concentration of the REE.

For many exploited deposits in China the enrichment in HREE, which is one of the prime drivers for interest in the deposits, is not apparent. Where the Zhaibei granites do show HREE enrichment, petrographic analysis of precursor bedrock indicates that this occurred pre-weathering, forming secondary HREE-enriched fluorcarbonates and phosphates. Neodymium isotope analyses indicate that the REE in these phases cannot be sourced from the surrounding granite and requires addition of REE either via mixing with specialised magmas, or via metasomatism by externally derived fluids [1]. Identification of the most HREE enriched IADs therefore requires petrological investigation of precursor lithologies to detect localities permissive for HREE enrichment.

Adsorption experiments of REE onto kaolinite in low pH water and NaCl solutions

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Ion adsorption REE deposits are the main worldwide source of heavy REE (HREE: Tb-Lu) and Y [1]. They form after weathering of granitic bedrocks containing igneous and/or hydrothermal REE-bearing minerals [1]. The interaction of rainwater with the atmosphere, the vegetation cover and the rocks produce acidic solutions which contain various anions and organic compounds. These have the capacity to dissolve the primary minerals, and incorporate and transport REE downwards the weathering profile. The REE are subsequently incorporated in secondary phosphates and oxides, or are adsorbed onto clay minerals, e.g. kaolinite [1]. A series of experiments were performed in order to increase knowledge on the processes occurring in a weathering profile, that facilitate the adsorption of REE onto kaolinite in ion adsorption REE deposits.

The experiments involved introducing kaolinite powder (“China clay BP light kaolin” provided by Imerys®), with 2 μm average particle size, LOI 11.16 wt.%, and ζ-potential of -36.6 mV, in a solution with REE (multi-element calibration standard 8500-6944 from Agilent®, 10 ppm Ce, Dy, Er, Eu, Gd, Ho, La, Lu, Nd, Pr, Sc, Sm, Tb, Th, Tm, Y, Yb) following a solid/ratio of 2.5 g/L [2]. Three experiments with low (0.025 M) and high (0.5 M) ionic strength (1) NaCl solutions were carried out: a) 5-days long with one sampling per day, at pH~2, with 100 ppb REE; b) 1-day long with one sampling after 2, 6 and 24 hours, at pH~2.2, with 100 ppb REE; c) 1-day long with one sampling after 2, 6 and 24 hours, at pH~1.4, with 1 ppm REE. An additional 1-day long experiment using deionised water (milliQ®) at pH~4.2 with 100 ppb REE was performed. The samples were centrifuged at 2500 rpm for 30-40 min, the supernatant was extracted and diluted with 4% HNO₃, and analysed by ICP-MS (Inductive Coupled Plasma Mass Spectrometry). Finally, the tubes were then introduced into a desiccator at 40°C to allow the solution to evaporate and ultimately analyse the kaolinite powder.

The obtained REE composition in the solutions was constant, even after only 2 hours, with no significant increase or decrease in the REE concentration with time. Therefore, the adsorption reaction is rapid, as reported by [2]. In the low I NaCl experiments (pH~1-2), 25-40 ppb (initial 100 ppb REE) and 800-900 ppb (initial 1 ppm REE) of the individual REE were obtained, whereas in the high I no adsorption or slight desorption was observed (the concentration of REE measured exceeded the initial 100 ppb or 1 ppm, respectively). In addition, Sc and Th were always found in low concentrations in the solution (<5 ppb), and therefore retained in the kaolinite. In contrast, in the experiment with deionised water (pH~4) the REE concentrations in the solution were much lower (below 10 ppb individual REE), Sc was similar to the other REE but Th was significantly lower than the REE. With NaCl and pH~1-2, the calculated sorption coefficient [2] showed no fractionation between HREE and LREE. However, with deionised water and at pH~4, a mild fractionation was observed, where LREE contents were higher than HREE in the solution.

These experiments show that adsorption of REE onto kaolinite is more favourable in water with less acidic pH, than in NaCl solutions with highly acidic pH. In addition, sorption is more favourable in low I solutions, while high I solutions may lead to desorption [3]. Therefore, both salinity and acidity play important roles in the process. Hence, the factors controlling the adsorption of REE onto kaolinite have to be further studied. Upcoming experiments will be carried out with other conditions, including using other anions as complexing agents.

Peralkaline-hosted Critical Metal Deposits: From magmatic enrichment to hydrothermal mobilisation

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Peralkaline igneous complexes provide important deposits for critical metals. These include high field strength elements (HFSE, e.g. rare earth elements, Zr, Ti, Hf, Nb and Ta), U, Th, Li and Be, hosted in complex alkali-halogen rich silicates and oxides such as eudialyte, steenstrupine and pyrochlore. Peralkaline magmas are typically associated with extensional tectonic settings, where they form through extensive fractional crystallisation of low degree partial melts from metasomatically enriched lithospheric mantle domains [1]. Due to their extreme enrichment in alkalis and volatiles (F, Cl, OH), the magmas crystallise over extended temperature intervals and follow a near-continuous evolution from discrete silicate melts to alkaline aqueous fluids [2]. Consequently, primary mineral assemblages are often subjected to extensive late-stage hydrothermal replacement reactions to produce intimate intergrowths of secondary HFSE-phases and possibly mobilising elements of interest [3]. These processes appear to be ubiquitous to most peralkaline critical metal deposits [4], but may have variable implications on overall ore grades and required mineral processing techniques.

This talk will discuss the respective roles of primary magmatic enrichment processes and subsequent hydrothermal replacement reactions on the mineralogy and ore potential of peralkaline-hosted critical metal deposits in the metallogenic Gardar Province, South Greenland. The Gardar Province represents an area of voluminous alkaline magmatism associated with Mesoproterozoic rifting along the margin of Archaean North Atlantic Craton (1320-1160 Ma) [5]. The province hosts several world-class critical metal deposits in layered floor cumulates and roof zones of well-exposed shallow crustal magma chambers [6]. These include a eudialyte-hosted Zr-REE-Nb deposit (Kringlerne), a steenstrupine-sphalerite hosted REE-U-Zn deposit (Kvanefield), and a pyrochlore hosted Ta-Nb deposit (Motzfeldt) [7]. All deposits reside in highly evolved alkaline to peralkaline nepheline syenites, but display variable primary and secondary mineralisation styles due to differences in the physico-chemical conditions of the melts and late-stage fluids. Using mineralogical, geochemical and isotopic data, I will present new insights into the sources of HFSE enrichment across the Gardar, the nature of late-magmatic fluids and their ability to remobilise critical metals following magmatic crystallisation [8].

POSTERS
Mineral chemistry of In-rich minerals from the San José ore deposit, Central Andean Tin Belt, Bolivia

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The Central Andean Tin Belt contains deposits with high concentrations of indium (In) [1], which is catalogued as a high technology-critical element. In this study we present a mineralogical and geochemical study of the In-bearing minerals from the San José deposit, located in the Oruro town (Bolivia), and belongs to the Oruro District, in the Central Andean Tin Belt. This deposit is known for containing a wealth of minerals [1]. The San José mine is exploited by a small-scale cooperative of miners for Sn, Ag, Zn and Pb.

The San José deposit is related to a Miocene intrusive porphyry body and hosted in a meta-sedimentary sequence of Silurian age. The mineralization of this deposit occurs in two main styles: (a) a Sn-rich mineralization, represented by quartz veins with cassiterite, pyrite and monazite and (b) a Zn-Pb-Ag mineralization, in disseminations represented by sphalerite, galena and stannite group minerals. Other minerals from this stage are cylindrite, franqueite, stephanite, andorite, acanthite, zinkenite, holcartite, boulangerite, jamesonite, jarosite, zonyite, onoratoite and others.

In the San José deposit Indium occurs mainly in the stannite- kërsterite solid solution, in sphalerite and in cassiterite, as in the case of other deposits from this belt, eg. those from the Santa Fe district [2]. Two generations of sphalerite have been identified; the first generation has contents higher than 1.5 wt% In and values of 3 wt% are common, Fe reaches up to 1.0 wt% and Cd, up to 1.9 wt%. In this generation, In contents inversely correlate with the Fe content. The second generation is Fe, Cd and In-poor. The members of stannite group, including the In-rich sakuraiite, yield remarkable concentrations of In, up to 3.2 wt%, even if exceptional concentrations, as high as 24.4 wt% have been obtained. Petrurkite have also been identified. In addition, analysed cassiterite yield In contents mostly around 0.10-0.20 wt% but maximum concentrations are as high as 0.99 wt%.

The high In contents in minerals from the San José deposit should be taken into account as a potential by-product of the production of Ag and base metals, increasing the value of the produced mineral concentrates.

Deposit-scale geomodels for REE and HFSE exploration in carbonatite and alkaline-silicate magmatic systems

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Rapid growth in the demand for critical metals, including the rare earth elements (REE) and high field strength elements (HFSE), is driving expansion and diversification in their supply chains. Although alternative sources are being explored, the majority of the world’s resources of these elements are found in alkaline igneous rocks and carbonatites. These small magmatic centres represent highly-fractionated residua of low-degree mantle melts, with the majority occurring in failed continental rifts. Approximately ten percent of the > 500 catalogued global occurrences contain mineralisation. However, the mineral exploration industry has traditionally focussed on major- and precious metals, such as iron and gold, therefore exploration models for alkaline rocks and carbonatites are less well developed.

We have compiled geological, exploration targeting, and environmental factors pertinent for the development of critical metal resources hosted by carbonatite and alkaline-silicate magmatic systems. For these two interrelated suites of igneous rocks we are building interactive digital geomodels, for a target audience of economic geologists from industry and from academia. The schematic models will be presented at deposit-scale (ca. 1–5 km lateral) and will indicate the key lithological units that typically host mineralisation, placing these within a depth and horizontal reference frame within these fossil magma bodies.

Our model will show the processes that mobilise, concentrate and trap the metals within magmatic layering and roof zones, and during hydrothermal alteration (fenitisation) of wall rocks. Typical geophysical signatures derived from induced polarisation, gamma radiometric, gravitational and magnetic techniques will be shown on an overlay. This, in concert with information on indicator mineral chemistry, both within float and within alteration haloes surrounding these intrusions will facilitate vectoring toward critical metal mineralisations.

The diversity of metalliferous minerals within these deposits is much greater than that of traditionally mined major or precious metal deposits, with some phases currently being processed more easily than others. Recovery rates and energy usage are improving at a rapid rate as the pertinent metallurgical techniques mature. The models also take into account environmental considerations specific to alkaline rocks and carbonatites, such as radioactivity of certain minerals.

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Poster and Oral presentations.
Volcanic-Derived Placers as a Potential Resource of Rare Earth Elements: The Aksu Diamas Case Study, Turkey

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Rare earth elements (REE) are essential raw materials used in modern technology. Current production of REE is dominated by hard-rock mining, particularly in China, which typically requires high energy input. In order to expand the resource base of the REE, it is important to determine what alternative sources exist. REE placers have been known for many years, and require less energy than mining of hard rock, but the REE ore minerals are typically derived from eroded granitic rocks and are commonly radioactive. Other types of REE placers, such as those derived from volcanic activity, are rare.

The Aksu Diamas heavy mineral placer in Turkey has been assessed for potential REE extraction as a by-product of magnetite production, but its genesis was not previously well understood. REE at Aksu Diamas are hosted in an array of mineral phases, including apatite, chevkinite group minerals (CGM), monazite, allanite and britholite, which are concentrated in lenses and channels in unconsolidated Quaternary sands. Fingerprinting of pyroxene, CGM, magnetite and zircon have identified the source of the placer as the nearby Gölcük alkaline volcanic complex, which has a history of eruption throughout the Plio-Quaternary. Heavy minerals were eroded from tephra and reworked into basinal sediments. This type of deposit may represent a potential resource of REE in other areas of alkaline volcanism [1].

The effect of X-ray energy overlaps on the results of chevkinite (Ce, La, Ca, Th)₄(Fe²⁺, Mg)₂(Ti, Fe³⁺)₃Si₄O₂₂ microanalysis using SEM EDS-WDS

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The chevkinite mineral group (CMG) consists of Ti-bearing silicates with a high content of rare earth elements (REE), ≤50 wt% REE₂O₃. The CMG includes chevkinite (Ce, La, Ca, Th)₄(Fe²⁺, Mg)₂(Ti, Fe³⁺)₃Si₄O₂₂, perrierite and polyaevite. These can be found in igneous, volcanic and metamorphic rocks [1]. Although, commonly considered accessory phases, their high REE contents make them potential ore minerals. Further, their complex crystal chemistry can be used to fingerprint geochemical facies or act as natural analogues of crystalline matrices for radionuclide immobilisation. However, this complex chemistry is also the origin of analytical challenges and here, we present the issues associated with elemental microanalysis using scanning electron microscopy with energy and wavelength dispersive spectrometry (SEM EDS-WDS). Analysis of several crystals of chevkinite from the Aksu Diamas placer deposit in Turkey [2] was performed using an FEI Quanta 600 SEM with an Oxford Instruments X-Max 50 mm² silicon drift detector (SDD) for EDS and Wave 500 spectrometer for WDS, running with Oxford Instruments INCA (v4) software. EDS was used for major elements and WDS to resolve X-ray energy overlaps, and for selected minor and trace elements. The SEM was operated at 20 kV accelerating voltage, 10 nA beam current. EDS process time of 4 resulted in deadtimes <45%. Count times of 60s and 60/30s peak/background were used for EDS and WDS acquisition, respectively. For WDS analysis, elements were kept within 24 hr calibration. Laser ablation inductively coupled plasma mass spectrometry was performed using a New Wave Research 193UC laser ablation system equipped with a TV2 cell coupled to a Nu Instruments Attom single collector inductively coupled plasma mass spectrometer (SC-ICP-MS).

The review of the data highlighted a ‘problematic spectral region’ between 4.4 – 4.9 keV with the X-ray peaks of Ce, La, Ba and Ti (Ce Lα, 4.84 keV, La Lα, 4.65 keV, Ti Kα, 4.51 keV, Ti Kβ 4.931 keV and Ba Lα, 4.465 keV). The in-use spectral energy resolution of the system is 0.145 keV, imposing a limit of peak separation. The overlaps of Ti Kα and Ba Lα with only 0.045 keV separation, as well as La Lα and the Ti K series peaks, provide the greatest analytical challenges. The automatic peak determination/fitting of EDS has misidentified the presence Ba at approx. 1 wt% of BaO and at the same time underestimated the measured concentration of Ti by approx. 0.3 wt% TiO₂. This overlapping pair seem to have also affected the concentrations of La and Ce when measured by EDS, collectively leading to a significant analytical error. The concentrations of La and Ce are not affected by the misidentification of Ba, when based on WDS analysis, but appear to have been significantly overestimated by EDS. This is related to the positioning of La Lα, 4.65 keV between the Ti Kα and Kβ. It is clear that the lower spectral resolution of EDS in comparison to WDS (ca. 10 eV) makes it impractical to use EDS only for detection of La in minerals containing Ti as a major element, despite advances in peak fitting protocols. The recent advancement in EDS performance with the SDD detector enable accuracy and precision equivalent to that of the high spectral resolution wavelength-dispersive spectrometer in the electron probe microanalyser [3]. However, in analytically challenging minerals such as the CMG with severe X-ray energy overlaps in multiple major elements, the role of the operator is key in determination of the capability of the EDS detector to measure elements of interest based on the limitations of its spectral energy resolution. A combination of an experienced operator and SEM with both EDS and WDS are likely to provide most reliable results.

References:
Genesis of the Zudong regolith-hosted HREE deposit in South China
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The Zudong heavy rare earth element (HREE) deposit in South China is the largest regolith-hosted HREE deposit in the world with a resource of ~17,600 t of REO, at an average grade of ~0.1 wt. % REO [1]. Subtropical weathering of the parent A-type granite formed ore bodies hosted mainly within the lower B to upper C horizons of the resulting soil. The thickness of the ore bodies varies from a few meters to up to 10 m. Rare earth element concentrations increase from ~300 ppm in the parent rock to ~1500 ppm in the ore zone. The entire soil profile is HREE-enriched with (La/Yb)ᵣ ratios <1. Exchangeable REEs, representing REEs that are adsorbed, mainly by kaolinite and halloysite, in the deposit, constitutes ~65% of the bulk REE content; the LREEs are preferentially adsorbed. The proportions of REEs adsorbed or chemically bound by Fe-Mn oxyhydroxides and organic matter are negligible. REE is also hosted by supergene chernovite [YAsO₄], cerianite [CeO₂] and residual aeschynite/euxenite-group and fergusonite-group minerals, xenotime-(Y), zircon, and thorite.

Weathering of the HREE-enriched Zudong granite liberated the REE hosted by synchysite-(Y), yttrian fluoride, gadolinite-(Y), hingganite-(Y), and yttrialite-(Y), which are susceptible to chemical weathering, in the parent rock. Also, weathering of alkali feldspar and muscovite produced halloysite and subordinate illite and smectite. In the upper parts of the soil profile, where conditions were acidic, dissolution of REE minerals and desorption of REE from the clay minerals are promoted and the REEs tend to remain in solution. Deeper in the profile (lower part of the B horizon and upper part of the C horizon), conditions become less acidic leading to adsorption of the REEs on the surface of halloysite and precipitation of supergene chernovite-(Y). With progressive weathering, abundant halloysite, which is comparatively metastable to kaolinite but of higher adsorption capacity, would transform to kaolinite in the upper parts of the soil profile, thereby releasing the adsorbed REEs to the weathering fluids. The released REEs would be transported to greater depth, at where adsorption is much more favourable. Ongoing operation of this eluviation-illuviation process at Zudong has gradually enriched the soils in HREEs to form a resource that now supplies much of the world’s HREE.

Formation of selenium- and tellurium-containing nanoparticles during the growth of filamentous fungi

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Microbial Se or Te reduction offers a potential route to biorecovery of these elements from solution [1]. Reduction is often efficient and large amounts of these metalloids can be removed from solution, resulting in extensive precipitation around biomass. This is more effective than biomethylation, which can result in only small amounts of removal, and would necessitate a further trapping step to recover volatilized methylated derivatives [2]. In this research, the fungi Aureobasidium pullulans, Mortierella humilis, Trichoderma harzianum, and Phoma glomerata were used to investigate the formation of selenium- and tellurium-containing nanoparticles during growth on selenium- and tellurium-containing media. Most organisms were able to grow on both selenium- and tellurium-containing media at concentrations of 1 mM and has resulted in extensive precipitation of elemental selenium and tellurium on fungal surfaces observed by the bright red and black colour changes. Red or black deposits were confirmed as elemental selenium and tellurium, respectively, by X-ray powder diffraction. Apart from elemental selenium and tellurium, selenium oxide and tellurium oxide were also found after growth of Trichoderma harzianum in the presence of 1 mM selenite and tellurite together with the formation of elemental selenium and tellurium. The hyphal matrix provided nucleation sites for metalloid deposition with extracellular protein and extracellular polymeric substances serving to localize the resultant Se or Te nanoparticles. These findings are relevant to remedial treatments for selenium and tellurium contamination, and possible novel approaches for selenium and tellurium biorecovery from liquid matrices [3].

Crystallisation Pathways of Mixed La and Nd Carbonates

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Rare Earth Elements (REE) carbonates and fluoro-carbonates are often found associated with hydrothermal REE deposits in carbonate-rich rocks, such as at Banyan Obo, China - the world’s largest REE producer [1, 2]. REE are sought after due to their unique properties and are integral to modern technologies such as lasers, catalytic converters, batteries, electro-magnets etc. [3]. Chemical data and modelling endeavours suggest [1, 4] that these REE carbonate minerals form from the interaction between the hydrothermal fluid with the surrounding carbonate bearing wall-rocks.

Much of the work on REE aqueous geochemistry focuses on the behaviour of discrete REE [5, 6]. The primary objective of this project is to determine whether mixed REE solutions would influence the formation process of REE bearing carbonates. The crystallisation kinetics of REE carbonates in aqueous solutions can be observed using absorbance as a proxy for crystallisation and particle growth [7, 8, 9]. Using the same rationale and methods as previous work, absorbance was monitored during the growth of mixed La and Nd carbonates.

Results suggest that the crystallisation process begins with an amorphous phase that transitions to a crystalline phase after a lag time, which is proposed to be REE and mixture specific. Low initial absorbance of the suspension is interpreted as the amorphous phase and a subsequent sharp rise in absorbance marks the onset of the phase change between the amorphous and crystalline phases [7, 8, 9].

We find that the crystallisation times of mixed REE carbonates are altered by the relative La/Nd ratio in the system. Samples of mixed La/Nd carbonates begin their phase transition at times in-between that of the two end-members carbonate compositions. For example, La carbonate begins crystallising after 5-6 minutes, Nd carbonate at 300 minutes and a 50:50 mix begins at 60 minutes. Interestingly, this phase transition time is not proportional to the mix ratio nor is it to the mean ionic potential of the mixture, which appear to govern the kinetics of single, discrete REE carbonates [9].

Our results show that the presence of another REE in the system as well as its mixture ratio are important factors influencing the crystallisation kinetics of REE carbonates. X-Ray Diffraction, Scanning Electron Microscopy and Fourier-Transform Infrared Spectroscopy characterisation of the products throughout the crystallisation process will further elucidate kinetics of the crystallization process of mixed REE carbonates.

Rare earth element deposits in China

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China has dominated the world’s rare earth elements (REE) production since the 1980s and currently, China contributes to more than 80% of the global production. China also possesses the largest REE resources in the world. Major REE deposits include carbonatite-related deposits and regolith-hosted deposits. There are also considerable amounts of REE resources associated with hydrothermal Fe-Cu deposits.

The carbonatite-related deposits are represented by the world’s largest Bayan Obo deposit in north China, and deposits in the Mianning-Dechang belt in southwest China. There are also a few smaller deposits in central and eastern China. These deposits are significantly light REE-enriched. The major REE minerals in these deposits include bastnäsite-(Ce) and monazite, associated with synchysite-(Ce), parsite-(Ce), fluorite, barite, and sulfides. The REE mineralization is closely related to intrusion of carbonatites and alkaline complexes and the consequent hydrothermal metasomatism.

The regolith-hosted deposits are geographically restricted to south China and mainly hosted in weathering crusts of granites. These deposits are characterized by large tonnages but low grades, yet REE extraction is economically feasible by low-cost in-situ leaching with dilute electrolyte solutions. Most of the REE are weakly adsorbed on kaolinite and halloysite in these deposits, with sub-ordinate occurrence as supergene and residual REE minerals. REE enrichment is caused by continuous leaching at the shallow parts and adsorption by the kaolinite-group minerals at the lower parts of the weathering crusts.

Apart from the carbonatite-related and regolith-hosted deposits, hydrothermal Fe-Cu deposits in southwest China host significant amount of the REE resources. The REE were mobilized and concentrated during multi-stage hydrothermal alteration and mainly hosted in apatite, monazite, and allanite. REE are also produced from several placer deposits along the coastal southeast China. Recently, explorations on other potential REE sources, including sea mud from the South China Sea, phosphorites, bauxites, and coal in southwest China, have been launched to seek for more resources in facing the continuously rising global demand.
## DELEGATE INDEX

<table>
<thead>
<tr>
<th>Initial</th>
<th>Name</th>
<th>Email</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Alfonso, Pura</td>
<td><a href="mailto:maria.pura.alfonso@upc.edu">maria.pura.alfonso@upc.edu</a></td>
</tr>
<tr>
<td></td>
<td>Armitage, Paul</td>
<td><a href="mailto:paul@mkango.ca">paul@mkango.ca</a></td>
</tr>
<tr>
<td>B</td>
<td>Barnett, Megan</td>
<td><a href="mailto:megan@bgs.ac.uk">megan@bgs.ac.uk</a></td>
</tr>
<tr>
<td></td>
<td>Beard, Charles</td>
<td><a href="mailto:cbeard@bgs.ac.uk">cbeard@bgs.ac.uk</a></td>
</tr>
<tr>
<td></td>
<td>Bilham, Nic</td>
<td><a href="mailto:nb533@exeter.ac.uk">nb533@exeter.ac.uk</a></td>
</tr>
<tr>
<td></td>
<td>Bloodworth, Andrew</td>
<td><a href="mailto:ajbl@bgs.ac.uk">ajbl@bgs.ac.uk</a></td>
</tr>
<tr>
<td></td>
<td>Borst, Anouk</td>
<td><a href="mailto:amb43@st-andrews.ac.uk">amb43@st-andrews.ac.uk</a></td>
</tr>
<tr>
<td></td>
<td>Broom-Fendley, Sam</td>
<td><a href="mailto:s.l.broom-fendley@ex.ac.uk">s.l.broom-fendley@ex.ac.uk</a></td>
</tr>
<tr>
<td></td>
<td>Butcher, Alan</td>
<td><a href="mailto:alan.butcher@gtk.fi">alan.butcher@gtk.fi</a></td>
</tr>
<tr>
<td></td>
<td>Butcher, Andrew</td>
<td><a href="mailto:a.butcher@bgs.ac.uk">a.butcher@bgs.ac.uk</a></td>
</tr>
<tr>
<td>C</td>
<td>Caven, Sarah</td>
<td><a href="mailto:SCAVEN@TDISTRATEGIES.COM">SCAVEN@TDISTRATEGIES.COM</a></td>
</tr>
<tr>
<td>D</td>
<td>Danino-Perraud, Raphael</td>
<td><a href="mailto:R.Danino-Perraud@brgm.fr">R.Danino-Perraud@brgm.fr</a></td>
</tr>
<tr>
<td></td>
<td>Deady, Eimear</td>
<td><a href="mailto:eimear@bgs.ac.uk">eimear@bgs.ac.uk</a></td>
</tr>
<tr>
<td></td>
<td>Doyle, Keiran</td>
<td><a href="mailto:kd408@exeter.ac.uk">kd408@exeter.ac.uk</a></td>
</tr>
<tr>
<td>E</td>
<td>Elliott, Holly</td>
<td><a href="mailto:h.elliott@exeter.ac.uk">h.elliott@exeter.ac.uk</a></td>
</tr>
<tr>
<td>F</td>
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<tr>
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<tr>
<td>G</td>
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</tr>
</tbody>
</table>
AUTHOR LIST

A
Abbott, A.P., 40
Alfonso, P., 56
Andrade, M.B., 51
Armitage, P.E.B., 37
Atencio, D., 51

B
Badenszki, E., 49
Banks, D.A., 51
Barnett, M.J., 22
Barros, R., 49
Bastein, T., 9
Beard, C., 32, 39, 59
Bilham, N.T., 29
Bobos, I., 45
Borst A.M., 50, 53, 55
Broom-Fendley S., 38, 51
Brtnicky, M., 52
Butcher, A.S., 11
Butler, I.B., 64

C
Canet, C., 56
Carter, A.S., 28
Caven, S., 28, 59
Chen, W.T., 65
Chew, D.M., 49
Cooper, M.J., 34
Csetenyi, L., 63

D
Danino-Perraud, R., 14
Deadly E.A., 22, 32, 39, 42, 60, 61,
Doyle, K., 27

E
Egbers, P., 63
Elliott, H.A.L., 38
Estrade, G., 53

F
Feldmann, J., 44, 63
Finch, A.A., 41, 50, 53, 55
Ford, J., 11
Friis, H., 55
Fryzova, R., 52
G
Gadd, G.M., 44, 63
Ganev, I., 20
Gill, J.C., 19
Gloaguen, E., 47
Gonçalves, A., 45
Goodenough K.M., 32, 39, 53 , 60
Gourcerol, B., 47
Graham H., 40
Grant, H.L.J., 33
Gregory, S.P., 22
Gronen, L., 21
Gunn, G., 13

H
Hannington, M.D., 33
Hardardóttir, V., 33
Harris, R.C., 40
Holwell, D.A., 40
Horn, S., 13
Horsburgh, N.J., 41, 50, 55
Howarth, S., 35
Huet, B., 48
Hughes, A.R., 11
Huovinen, I., 36
Hutchison, W., 50, 55

J
Jenkin G.R.T., 40
Jha, A., 23
Jiménez-Franco, A., 56
Josso, P., 35
Joutsenvaara, J., 36

K
Kaeter, D., 49
Kale, B.B., 23
Kalliosalo, H., 36
Karinen, J., 36
Khan, R., 40
Kiefer, S., 21
Kirstein, L.A., 64
Knoll, T., 48
Koskinen, H., 36
Krupp, E., 44
Kynicky, J., 52, 53

L
Lacinska, A.M., 60, 61
Lehrmann, B., 34
Lehtonen, M., 36
Li, M.Y.H., 62, 65
Li, X.C., 65
Liang, X., 44, 63
Lima, L., 45
Lottermosser, B.G., 21
Loye, E., 51
Lukkari S., 36
Lundhaug, M., 12
Lusty P.A.J., 31, 35

M
Mali, H., 48
Marques Sá, C.S., 45
Marquis, E., 53
McQuilken, J., 24
Melletton, J., 47
Menuge, J.F., 49
Merriman, D., 7
Michaux, S.P., 8
Mikkola, P., 17
Milton, J.A., 34
Moore, K., 25, 26
Moradi, S., 26
Müller, D., 12
Murray, J., 16
Murton B.J., 34, 35

N
Nason, P., 53
Nex, P., 32, 42
Ngwenya, B.T., 64
Noronha, F., 45
Nwoko, K., 44, 63

P
Palumbo-Roe, B. 22,
Paneri, A., 25, 26
Patton, M.A.G., 30
Paulick, H., 48
Pell, R., 15
Perez, M., 44, 63
Petavratzi E., 11, 13
Petersen, S., 33
Pickles, J.R., 51

X
Xu, C., 53

Y
Price, D.L., 64

R
Ramos, V., 45
Ray, S., 51
Rietveld, E., 9
Roberts, D., 25
Roberts, N.M.R., 60
Rushton J.C., 61

S
Sarala, P., 36
Schmid, M., 18
Schuster, R., 48
Shaw, R., 13, 32, 60
Sidki-Rius, N., 56
Sidorenko, O., 25, 27
Siegfried, P.R., 43
Sindern, S., 21
Smith, D.J., 40
Smith M.P., 11, 51, 52, 53, 54
Sokól, K., 50, 55
Solferino, G.F.D., 46
Song, W., 52
Stanley, C.J., 40
Strand, K., 36

T
Taivalkoski, A., 36
Toppila, R., 36
Torró, L., 56
Trujillo, E., 56
Tschora, H.L., 12
Tuduri, J., 47

V
van de Ven, M., 55
Villanova de Benavent, C., 53, 54

W
Wall, F., 13, 15, 38, 51
Westwood N.T., 46
White, E.D., 19
Wierzbicka-Wieczorek, M., 21
Williams-Jones, A.E., 62
Yan, X., 15, 26
Yeo, I., 35

Z
Zhou, M.F., 62, 65