



Innovate
UK

Rare Earth Exploration, Extraction, Beneficiation and Concentration

Innovation Landscape Report





University
of Exeter



British
Geological
Survey

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1. Executive Summary

This Innovation Landscape Report on Rare Earth Exploration, Extraction, Beneficiation and Concentration forms part of a series of reports into the UK Rare Earth Elements (REE) Value Chain, commissioned by Innovate UK as part of the Circular Critical Materials Supply Chains (CLIMATES) Programme which was established to develop and support critical materials supply chains within the UK, beginning with REE.

Other reports in the series include Rare Earth Processing, Rare Earth Circular Economy, Rare Earth Permanent Magnet Manufacturing and Rare Earth Permanent Magnet Alternatives.

The transition to Net Zero emissions is a mineral intensive process, increasing demand for raw materials. The rare earth elements (REE) are an essential component of many low carbon technologies, such as high strength permanent magnets in wind turbines and electric cars. China currently dominates global REE supply chains which poses a significant risk to future supply. This situation has led to REE being classified as a critical raw material for the UK.

A thorough evaluation of the recent technological advances that have occurred in the global REE supply chain ranging from exploration stage through extraction, beneficiation and concentration processes has been undertaken. Domestic expertise exists predominantly in the exploration stage of the supply chain, with large collaborative consortium projects aimed at developing geological models for REE deposits and improving exploration techniques. UK-led innovations have also been developed for deep-sea deposits, some beneficiation processes, and the mitigation of extraction-related impacts through life cycle assessment.

The UK lacks suitable geology for domestic REE extraction, however, the UK does have REE exploration companies operating in other countries who are international trade partners, consultants working on REE deposits worldwide, equipment manufacturers and has strong domestic academic expertise. Innovation is therefore important in mineral exploration and in the mineral processing required to produce REE using economically viable and sustainable methods. The mineralogy of REE deposits is diverse and sometimes complex, and

mineral processing is key to the successful development of a mine. However, this report highlights that many developing technological innovations are not adopted by industry, hindering further development and demonstration in an operational environment. Chinese dominance of the REE market and influence over competitor ventures is also a disincentive for financial investment in the diversification of the international REE supply chain.

The challenges of growing the UK REE supply chain, and key stakeholders are identified in this report. The capability gaps highlighted in this report provide opportunities for the UK to innovate and provide global expertise, including development of deposit fertility indicators, unconventional deposit types and mineralogy, extracting REE from waste streams and deep-sea deposits, and utilising artificial intelligence (AI) and machine learning. These capability gaps have been compared with UK expertise to provide a series of recommendations surrounding the delivery of the UK Critical Minerals Strategy and improving the diversification and resilience of the global REE supply chain.

This report therefore recommends that the UK should:

- Invest in domestic research and development to close capability gaps
- Enhance awareness of UK expertise to allow collaboration with international partners
- Facilitate and fund technology readiness progression of existing innovations
- Incentivise REE processing in the UK.

2. Background context



The rare earth elements (REE) consist of the 15 lanthanoids plus scandium and yttrium, which can be sub-categorised into light REE (lanthanum to samarium) and the rarer and more valuable heavy REE (europium to lutetium, plus yttrium) (European Commission, 2014). REE do not occur individually, with a deposit hosting a mix of REE in varying proportions. Geological processes cause natural fractionation, such that deposits usually contain far higher concentrations of the light REE than the heavy REE. Therefore, deposits containing only neodymium or praseodymium do not exist, instead deposits typically contain a mix of the light REE. Similarly, deposits containing only dysprosium or terbium are not found in nature, rather they are a mix of the heavy and light REE. The heavy REE have much lower crustal abundance than the light REE. The most abundant light REE (cerium) has a

similar crustal abundance to copper and can be present at weight per cent concentrations in nature, whereas the heavy REE are usually only present at concentrations of hundreds of parts per million.

REE are key constituents in many modern technologies, including portable, medical and defence technologies, owing to their luminescent, phosphorescent and magnetic properties. Importantly, they are used in technologies for reducing carbon emissions, such as permanent magnets in electric cars and wind turbines (Haque et al., 2014; Wall, 2014). Growth in the demand for these technologies means that the transition to net zero energy will be a mineral intensive process. As such, mineral demand is expected to quadruple by 2040 to meet the goals outlined in the Paris Agreement (Ali et al., 2017; Depraeter and Goutte, 2023).

China dominates the global supply of REE, accounting for approximately 68 % of global mine production in 2023 and undertaking 90% of global REE processing and smelting (Andrews-Speed and Hove, 2023; USGS, 2024). Owing to the high economic importance of the REE and the elevated supply risk associated with extraction and processing being dominated by a single country, the UK Government define the REE

as a critical raw material (Figure 1; DBT, 2022; Mudd et al., 2024). Current REE supply chains, especially for heavy REE, are a barrier to achieving our energy transition goals (Wang et al., 2024a). Implementing new innovations and strategies, as well as developing new REE supply chains, through national and international cooperation, is therefore necessary to achieve Net Zero.

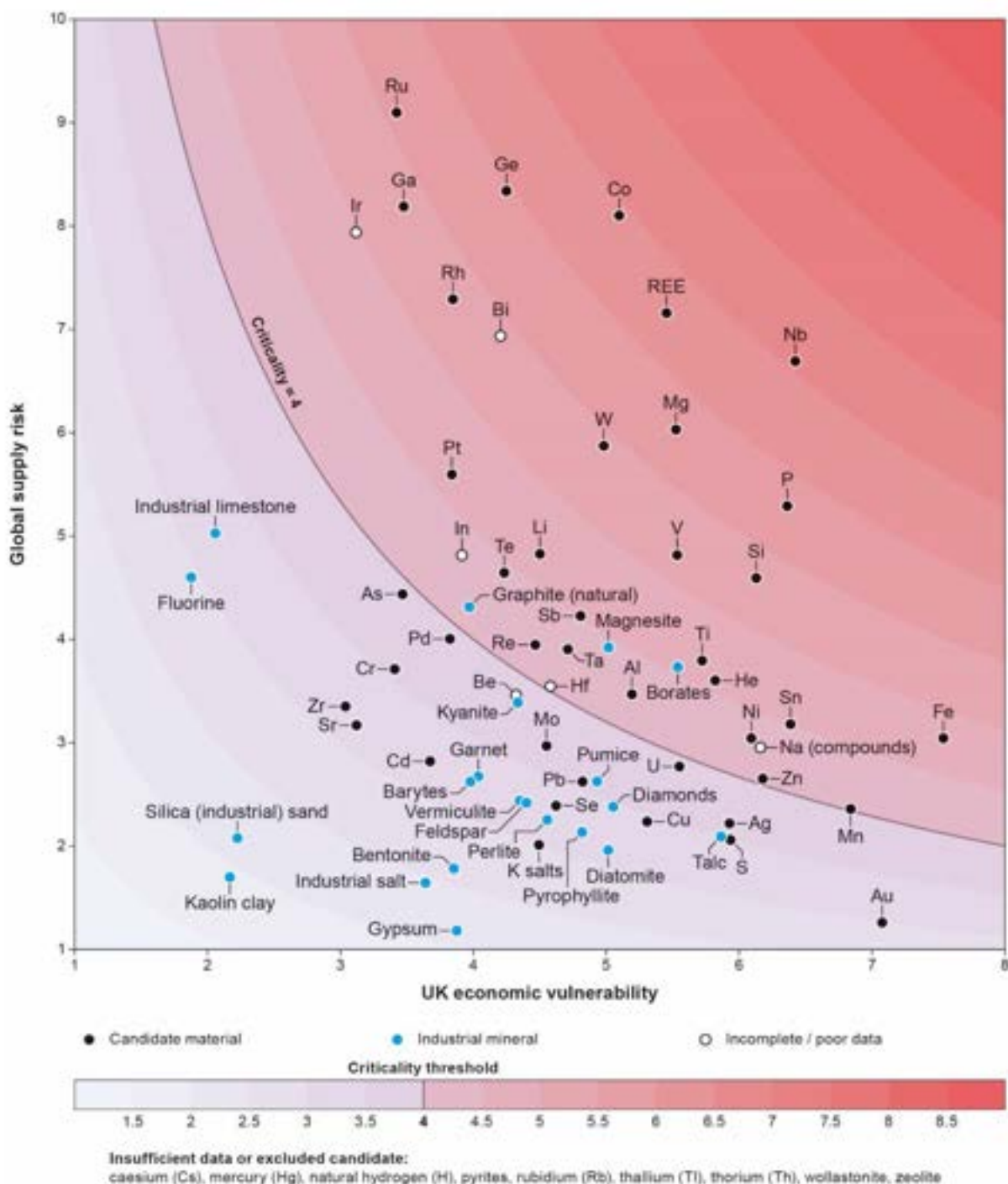


Figure 1: UK criticality assessment utilising global supply risk and economic vulnerability as assessment factors.
Source: Mudd et al., 2024 BGS © UKRI 2021

3. Technology overview

Innovations discussed in this report have been attributed a technology readiness level (e.g. TRL 6) in line with UKRI definitions (UKRI, 2022) which should be considered a minimum development level based on information available.

3.1 REE deposits

Economic sources of REE occur globally in a diverse range of deposit types (Figure 2), reflecting the different geological environments and processes that led to their formation. Different deposit types have varying proportions of light and heavy REE ratios, mineralogical variety and complexity, and abundance of other beneficial and/or deleterious elements.

The majority of global REE supply comes from the exploitation of just four deposit types: carbonatites, alkaline-silicate rocks, ion adsorption deposits, and placer mineral sands. As such, these are termed conventional deposits, from which extraction and beneficiation processes are either wide-spread or well-established.

Carbonatites are relatively rare igneous rocks comprising more than 50 % carbonate minerals (Heinrich, 1966; Le Bas, 1981; Woolley and Kempe, 1989). REE deposits associated with carbonatites are typically high grade but low tonnage deposits (Smith et al., 2016), such as Mountain Pass, USA (Castor, 2008) and Bayan Obo, China (Smith,

2007). Alkaline-silicate rocks are igneous rocks with higher abundances of alkali elements (sodium and potassium) relative to silica and aluminium and often associated with carbonatites (Leelanandam, 1989; Mitchell, 1996). Large UK-led collaborative research projects, such as HiTech AlkCarb, EURARE and SoSRare, have considerably improved our understanding of carbonatite and alkaline igneous rocks, leading to a high level of expertise and capability within the UK and the development of geomodels and exploration indicators for the exploration of REE deposits associated with these systems (e.g. Elliott et al., 2018a; Beard et al., 2023).

Ion adsorption deposits are the most important source of yttrium and other heavy REE, forming where REE-rich rocks are exposed and weathered under sub-tropical to tropical conditions. Mobilised REE become adsorbed to clay minerals or incorporated into secondary minerals (Jowitt et al., 2017; Borst et al., 2020) from which the REE can be easily leached by exchange with other cations, such as ammonia, magnesium



or calcium (Wu et al., 2023). Heavy REE supplies are predominantly sourced from ion adsorption deposits that sit above granitic rocks in China (Borst et al., 2020) but the UK has capability and expertise regarding formation of and extraction from these deposits developed during the SoSRare project. Placer deposits, also known as heavy mineral sands, are also an important source of REE where weathering and sedimentary transport processes accumulate REE minerals, such as the REE and thorium-rich beach sands of Kerala on the Indian coast (Sengupta and Van Gosen, 2016).

As the demand for REE increases and uncertainty surrounding supply risk heightens, many countries are seeking to expand domestic supplies. Where conventional sources are lacking, exploration has widened to include more unconventional sources of REE, such as highly fractionated rhyolites, iron-bearing deposits, and nodular black shales. These unconventional deposits may be poorly understood, not

yet subject to commercial extraction, or newly recognised sources of REE. As such, a better understanding of the exploration for, extraction from, and processing of unconventional deposits is a high priority for innovation.

Deep-sea deposits of REE are seeing a rise in international interest and controversy with global viewpoints and public perception varying considerably. There are four types of deep-sea deposits that are of economic interest for REE, including polymetallic nodules, ferromanganese crust, deep-sea sediments, and phosphorites. These deposits contain a wide range of critical metals, such as cobalt, tellurium, nickel, copper, gallium, and lithium (Hein et al., 2013), therefore it is likely that REE could be extracted as a by-product. Alongside the technological difficulties of exploring for and extracting from deep-sea deposits, there are still many unknowns concerning the potential environmental impacts.



Figure 2: Global REE deposits categorised by deposit type and extraction stage.
Source: Deady (2021) BGS © UKRI 2021.



3.2 REE deposit exploration

Exploration for mineral deposits that are not exposed at the surface, concealed, or have been extensively altered requires the use of geophysical and/or geochemical surveys to identify areas of potential interest. A summary of the different geophysical survey methods used to explore for REE deposit types can be found in Table 1. These methods can ‘image’ below the surface, providing valuable information (Dentith and

Mudge, 2014) that allows an understanding of the 3D structure of a deposit (e.g. Arzamastsev et al., 2000; Brauch et al., 2018), aiding in the positioning of exploration boreholes and planning of mining activities. Although, it should be noted that there are currently no recognised geophysical methods that can be employed for ion adsorption deposit exploration.

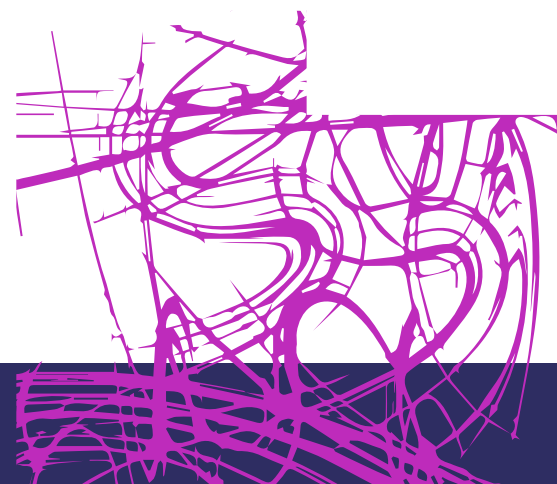
Deposit Type	Potential Geophysical Exploration Methods
Carbonatites and alkaline rocks	Gravity, magnetic, radiometric, resistivity and IP, magnetotellurics, borehole logging instruments
Iron oxide-bearing deposits	Magnetic, radiometric, gravity
Heavy mineral sands	Radiometric
Deep-sea deposits	Sonar, seismic reflection, electromagnetic, self-potential

Table 1: Summary of geophysical techniques used to explore for different REE deposit types compiled from Sengupta and Van Gosen (2016), Blue Mining (2018), Brauch et al. (2018), Shah et al. (2021) and He et al. (2024).

The UK has a high level of geophysical exploration expertise, with several UK-based companies (e.g. Metatek and TerraDat) skilled in targeting mineral deposits. The UK-led HiTech AlkCarb research project developed best practices for the geophysical exploration of carbonatites and alkaline igneous rocks (Brauch et al., 2018). The alteration patterns surrounding these systems has also been developed as an exploration vectoring tool and REE fertility indicator (Elliott et al., 2018a; Elliott et al., 2018b). Drone-based hyperspectral mapping of neodymium as a REE deposit indicator, has been developed by several research groups and tested on deposits in Namibia, Finland, and Iran with a high level of accuracy (TRL 6) (Booyesen et al., 2020; Karimzadeh and Tangestani, 2022).

The use of machine learning as a prospectivity tool (TRL 3) has significantly increased over the last decade (Shirmard et al., 2022), having been used successfully to determine element predictors of REE concentrations (e.g. Bishop and Robbins, 2024) and analyse geophysical maps to predict REE prospective areas on land and in the deep sea (e.g. Josso et al., 2023; Wang et al., 2024b). The use of machine learning and artificial intelligence within mineral exploration is still in the early stages of development and many further applications could be developed, including data mining and knowledge extraction, interpretation of geophysical data, regional to prospect-scale exploration and mineral prospectivity mapping, automated core logging, and even potentially grade tonnage estimation (Woodhead and Landry, 2021).

Exploration for deep-sea REE deposits utilises many of the well-established technologies developed for existing offshore industries, such as oil and gas (TRL 9). Autonomous underwater vehicles (AUV) or remote operated vehicles (ROV) are used to scope sites for manganese nodule density by collecting near seabed side scan sonar, high resolution images, and collecting samples (Lusty et al., 2021; Bramley Murton, NOC Southampton, per comms, 04/07/2024). Machine learning has been utilised to identify and count nodules from these images (TRL 6) and acoustic sub bottom seafloor imaging can be used to determine sediment nodule density (TRL 3) (Bramley Murton, NOC Southampton, per comms, 04/07/2024). Surveying iron-manganese crusts is more challenging, and Neettiyath et al. (2024) and subsequently the China Ocean Mineral Resources Research and Development Association have created an acoustic sub-bottom probe that allows continuous in situ measurements. The European Commission-funded Blue Mining Project developed new technologies for assessing and extracting deep-sea deposits, such as a self-potential exploration tool, electromagnetic survey, predictive mapping, and automated image analysis system for faster and more accurate resource assessment (Blue Mining, 2018).



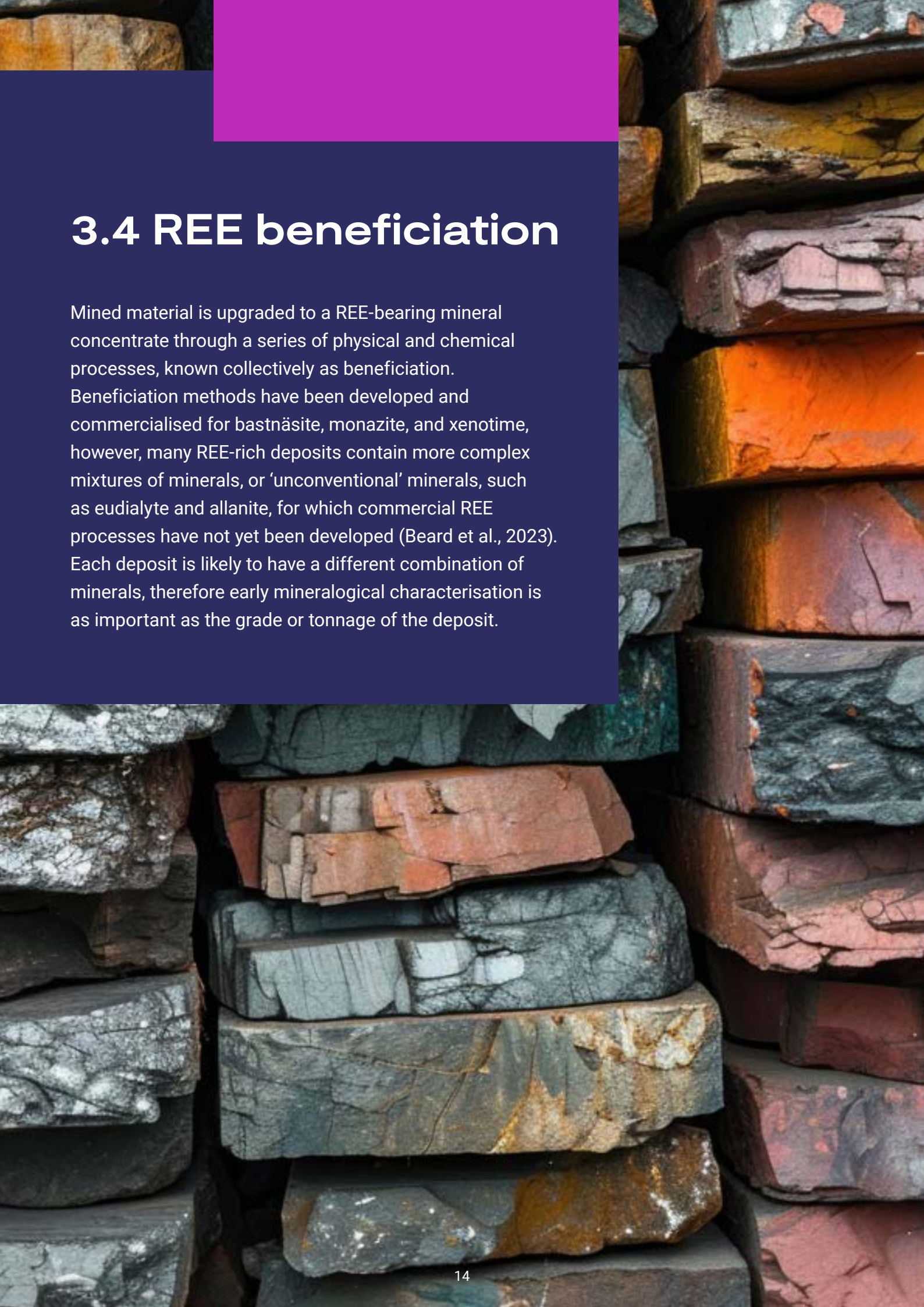
3.3 REE extraction

Despite the 250 known REE minerals, only bastnäsite, monazite, and xenotime are currently mined commercially for the extraction of REE (Wall, 2018), plus direct extraction of heavy REE from ion adsorption clays. Carbonatite-related deposits and ion adsorption clay deposits are now the primary source of REE, having replaced mineral sands that historically provided REE in the 1960s (Sengupta and Van Gosen, 2016). Whilst REE from alkaline-silicate rocks have been limited to by-products extracted during processing of apatite and loparite (Chakhmouradian and Wall, 2012; Kogarko, 2018).

Ion adsorption deposits from weathered granites are the most important source of heavy REE (Jowitt et al., 2017). The predominant salt reagent used to exchange REE from the clays in situ or in tanks is ammonium sulphate, a cheap and easily available fertiliser reagent. The in situ leaching employed at Chinese and Myanmar ion adsorption deposits has caused considerable environmental damage, including landslides and contamination in some locations. Many of the operations in Myanmar are small-scale and, in some cases, illegal. Ion adsorption deposits are also being explored, and in some cases mined, outside of China and Myanmar. Most have opted for mining and tank leaching operations. It is recognised that innovations are needed to make in situ leaching feasible without the associated environmental impacts, and to improve remediation techniques where materials are removed. Electro-sorption, a common seawater desalination method, is a potential alternative for leaching (TRL 4-9) involving the application of voltage to an electrode causing migration and adsorption of REE to the electrode (Wang et al., 2022).



There is much that is still unknown regarding the extraction of deep-sea deposits and both the EU and UK are committed to a moratorium on deep-sea mining until more evidence of the impacts of extraction are known (DEFRA, 2023; Delivorias, 2024). In contrast, Norway opened an area of their exclusive economic zone in January 2024 for companies to apply for exploration licenses (Stallard, 2024). The Japan Agency for Marine-Earth Science have developed deep-sea mud pumping technology that has been successfully tested at 2,470 m depth (JAMSTEC, 2022). The Apollo II nodule harvesting and in situ processing vehicle (TRL 6) has been developed by Blue Nodules (2020), and the Eureka II autonomous underwater vehicles have both been designed to selectively harvest polymetallic nodules (TRL 6) and reduce environmental disturbance (Impossible Metals 2024a; 2024b). However, the biggest challenge for progressing this industry is public perception and the social license to operate, which can only be addressed by greater transparency over the impacts of deep-sea mining and monitoring (Bramley Murton, NOC Southampton, per comms, 19/07/2024). In situ and observable experiments are able to monitor impacts and influence technology design, such as designing collectors that create turbidity currents to promote local deposition of disturbed sediments (Muñoz-Royo et al., 2022).



3.4 REE beneficiation

Mined material is upgraded to a REE-bearing mineral concentrate through a series of physical and chemical processes, known collectively as beneficiation. Beneficiation methods have been developed and commercialised for bastnäsite, monazite, and xenotime, however, many REE-rich deposits contain more complex mixtures of minerals, or ‘unconventional’ minerals, such as eudialyte and allanite, for which commercial REE processes have not yet been developed (Beard et al., 2023). Each deposit is likely to have a different combination of minerals, therefore early mineralogical characterisation is as important as the grade or tonnage of the deposit.

Beneficiation typically starts with crushing and grinding (comminution) to liberate target ore minerals. Comminution innovations are not particular to REE deposits and are broadly applicable to all ores. Ore minerals are then concentrated using their physical properties (e.g. density and magnetism) to separate them from other uneconomic minerals, such as gravitational and magnetic separation methods. The UK-based company, Gravity Mining Limited, collaborated with Lindian Resources to develop Multi Gravity Separators (TRL 7) to concentrate monazite, which will be installed at the Kangankunde carbonatite project,

Malawi. Smart sorting uses a variety of sensor-based techniques to sort ore minerals from the surrounding crushed rock (TRL 4-9) and has the potential to process lower grade materials, such as waste (TOMRA, 2024). Sensors that have been developed include X-ray transmission (Robben & Wotruba, 2019), colour-based sorting (Shatwell et al., 2023), luminescence sorting (Horsburgh, 2019), and near-infrared sorting (Robben et al., 2012). Challenges involved in the industrial adoption of more recently developed spectroscopic sensors such as these, include the requirement for industrial partners to allow progression from concept to pilot plant (Adrian Finch, University of St Andrews, per comms, 17/07/2024).



Flotation is an additional beneficiation method which involves adding chemicals or reagents to the crushed ore to create a slurry. This slurry is agitated with air bubbles to which the REE-bearing minerals attach and rise to the surface, where they can be collected. Concorde Cells (TRL 6 for REE and TRL 9 for other commodities) have been developed specifically to recover fine and ultrafine particles during flotation (Yáñez et al., 2024; John Good, per comms, 04/07/2024). The majority of flotation reagents for REE minerals are currently produced in China. Development of new flotation reagents that are selective, cost-effective, and function at lower temperatures is an innovation opportunity that would improve REE mineral recovery, reduce REE supply chain risks, and reduce the energy use / carbon footprint of REE beneficiation (John Goode, per comms, 04/07/2024). Artificial intelligence, and artificial neural networks can be used to find other reagents and optimise selective reagents, as well as predicting flotation efficiencies (Labidi et al., 2007; Bendaouia et al., 2024). Research into the flotation of allanite and eudialyte is sparse. Allanite research has focused on flotation and direct leaching methods (TRL 5), whereas flotation of eudialyte has never successfully been

achieved. Unconventional mineralogy such as this can be found at many REE deposits, therefore developing a flotation method for REE silicate minerals is a capability gap where the UK could innovate and help develop international supply chains.

Mineral concentrates generated by beneficiation need to be prepared for later separation, enriching the concentrate to an intermediate mixed rare earth compound (sulphates, hydroxides, carbonates, or oxalates) through a series of chemical treatments, known as hydrometallurgy or 'cracking'. A complex global transportation network exists, shipping mined concentrates to cracking facilities followed by separation plants (Figure 3). Although hydrometallurgy processes are well established for bastnäsite, monazite, and xenotime, the methods use hot acid and alkaline leaching and precipitate thorium compounds (Jha et al., 2016; Lynas, 2024), and as such there are opportunities to look at more efficient pathways with lower environmental impacts. Successful hydrometallurgical cracking processes for other minerals, such as eudialyte and allanite, have not yet been developed at commercial scale (Beard et al., 2023), providing further opportunity for innovation.



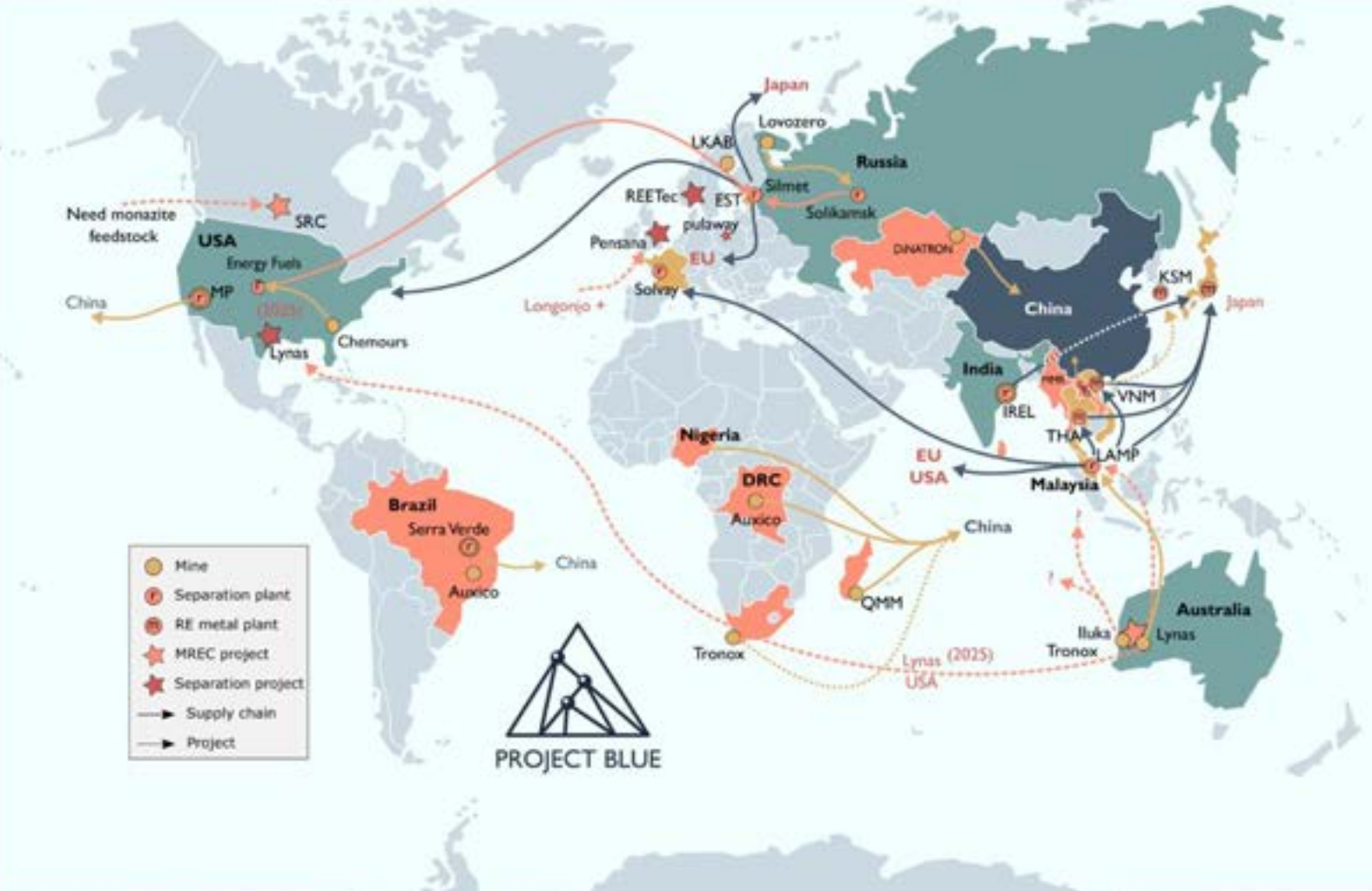


Figure 3: Worldwide shipping destinations for REE mineral concentrates, MREC, and metals.

Source: Project Blue (2024) Reproduced with permission. Copyright © 2023 Project Blue. All rights reserved

Thorium and uranium are naturally occurring radioactive elements that are often incorporated into REE minerals during geological processes (Kanazawa & Kamitani, 2006), displaying a positive correlation between REE enrichment and radioactive element concentration (Wall et al., 2017). Beneficiation processes enrich both REE and radioactive elements, producing a challenging radioactive waste stream that must be stored in tailings and requiring additional considerations during the shipping of concentrates. Any material registering as Class 7 Radioactive Materials have to

be transported according to international and national regulations outlined by the International Atomic Energy Agency (IAEA, 2018). If country regulations allow, uranium and thorium have the potential to be produced as a by-product of REE operations, an opportunity exploited by Energy Fuels in Utah, USA. Research reactors in Norway have also assessed the potential for using thorium-based fuels (Emblemsvåg, 2022). There are opportunities for innovation in the removal, handling, storage and novel uses for thorium and uranium as a by-product of REE extraction.

3.5 REE extraction from waste streams

REE can be found in low concentrations within many geological deposits and may be concentrated in the waste material during beneficiation. Therefore, they have the potential to be extracted as a by-product from an active waste stream during production or 'remined' from historic waste stored on site.

For example, the potential for REE recovery from ash produced during coal combustion has been the focus of multiple research projects over the last decade (e.g. Franus et al., 2015; Rybak and Rybak, 2021; Vilakazi et al., 2022; Liu et al., 2023). Estimated mean REE concentrations in coal ash vary between 378 - 496 ppm (Ketris and Yudovich, 2009; Zhang et al., 2020) and may be as high as 1.7 wt.% REE (Taggart et al., 2016), prompting the US Department of Energy to propose plans for a REE extraction pilot plant (DOE-NETL, 2023). REE concentrations in UK coal ash samples are similarly variable (246 - 481 ppm; Blissett et al., 2014; Thompson et al., 2018). Coal ash in the UK is already used in construction and coal fed power stations are also due to be phased out (BEIS, 2021). As such, extracting REE from coal ash is unlikely to be an economically viable option in the UK.

Tailings typically consist of wet slurries produced by processing of metal or industrial mineral ores. Historic and contemporary tailings are increasingly being assessed as mineral exploration targets due to their

potential for metals not extracted during processing. Their fine grain size and surface position lessens requirements for energy intensive mining and comminution processes, making them attractive stockpiles of metals for future extraction. The potential of tailings for REE extraction is directly related to the type of ore deposit (Figure 4). Extraction of pyrochlore (niobium) from carbonatites, phosphate mining, and bauxite processing for aluminium, all have the potential to produce REE as a by-product. Despite research projects successfully solving technical challenges associated with REE extraction from red muds during bauxite processing (e.g. EURARE) and waste from phosphate mines (e.g. Critical Materials Institute, USA), they have not resulted in REE production. Business models and incentives for producers may be required to promote recovery from these waste streams. Historic tailings facilities may come with challenges, such as heterogenous composition and uncertainty regarding ownership, making active waste streams a more attractive target. A pilot plant in South Africa is being developed by the UK-listed company Rainbow Rare Earths to allow production of REE from phosphogypsum tailings.

Acidic water at metallic and coal mine sites can also mobilise metals, with a strong correlation between REE concentration and low pH fluids (Cicek et al., 2023; Middleton

et al., 2024). There are many emerging innovative methods, such as cloud point extraction, magnetic separation, ionic liquids, molecular recognition technology, and supported liquid membranes (Mwewa et

al., 2022; Middleton et al., 2024), which can remediate acidic waters and recover metals. However, many of these methods have yet to be tested in a relevant or operational environment (Mwewa et al., 2022).

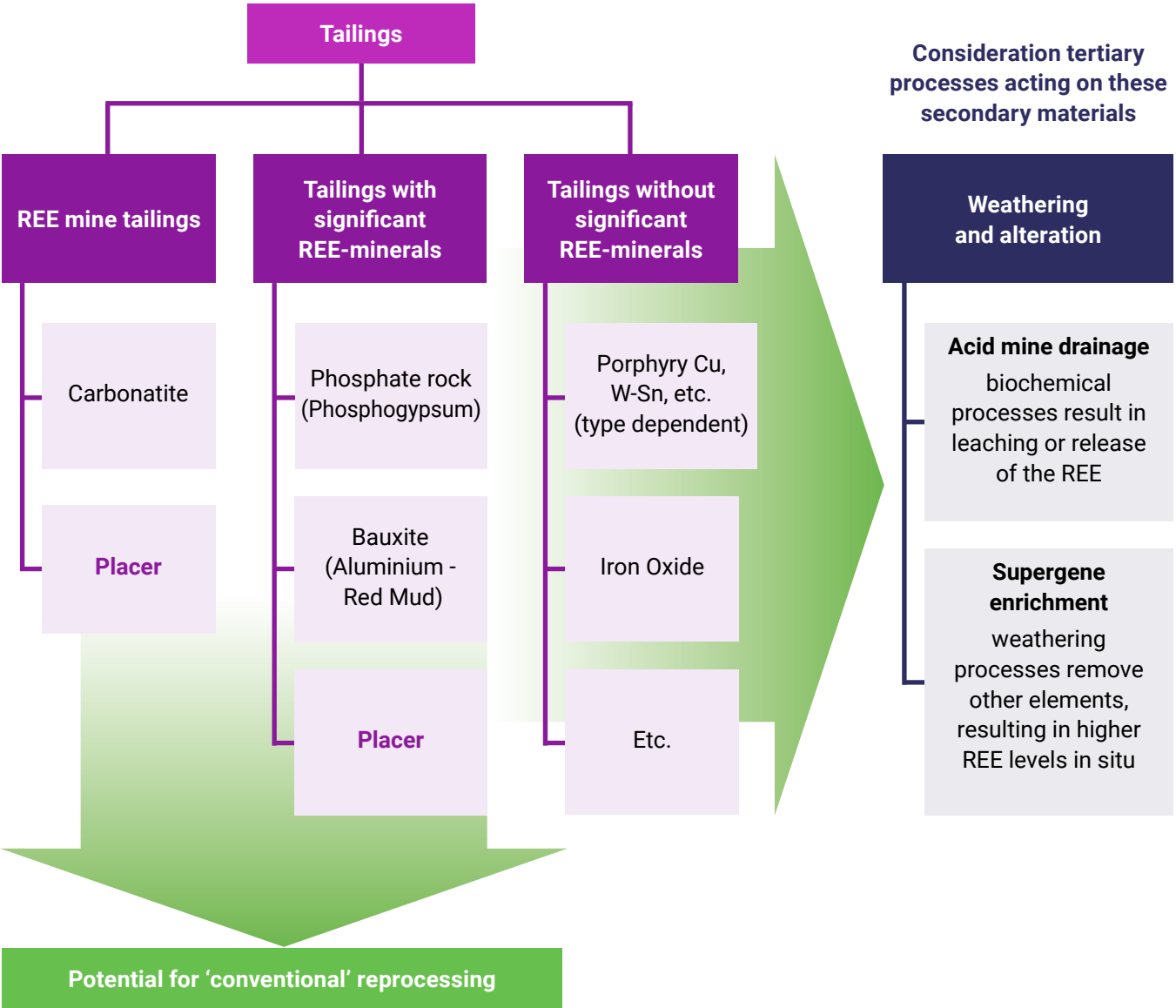


Figure 4: REE-enrichment in tailings based on type of deposit being extracted and processed (Marquis and Hudson-Edwards, in progress). Reproduced with permission. All rights reserved

Biorecovery also have potential to recover REE from tailings, acid mine drainage, and wastewater, using microbes that can liberate REE from liquid streams, allowing both remediation and metal recovery. Microbes are currently used to recover copper, nickel, uranium, and gold, but not yet REE, although the

German company BRAIN has developed a microorganism bank for testing at extraction sites (TRL 7) (BRAIN, 2014; Barnett and Gregory, BGS, per comms, 04/07/2024). The next step in developing biorecovery would be understanding the active microbial processes required to extract REE from solid minerals.



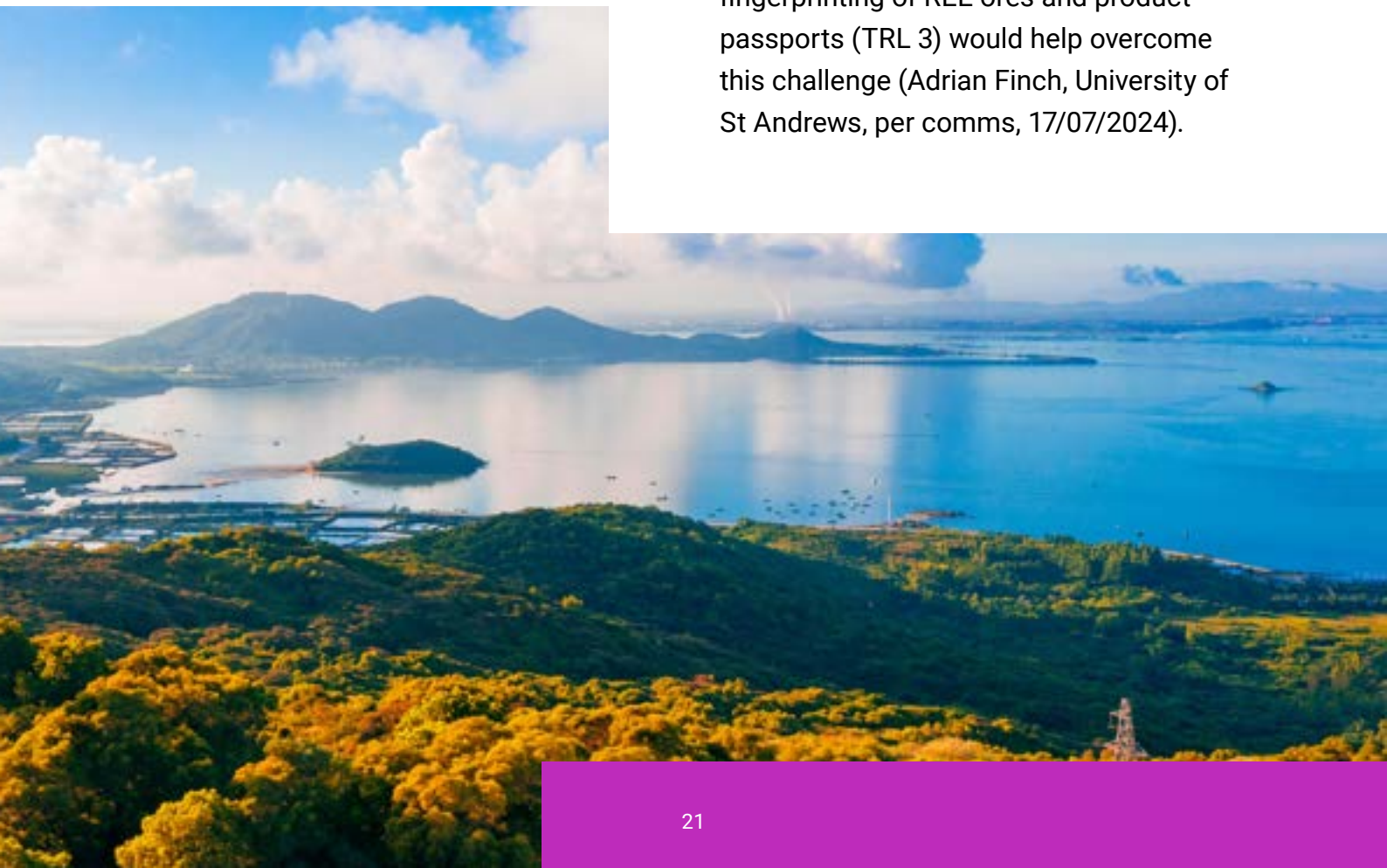
3.6 Responsible Sourcing and Mitigation of Environmental Implications

Aside from the generation of radioactive waste, the extraction of REE is associated with two main environmental impacts: the energy and chemicals used during beneficiation and cracking, and the use of high volumes of water. Kernow Mining Optimisation are a UK-based company specialising in digital optimisation and mining plant automation which helps reduce fuel consumption (Ericsson, 2018). AI and machine learning can also be utilised to design and validate REE processing flowsheets to reduce energy consumption and help improve efficiency at all stages (Kaack et al., 2020; Pathapati et al., 2024). However, it is the traditional oxidation roasting and acid leaching beneficiation processes that have the highest energy usage. Chlorination roasting and water leaching methods have been developed to run at lower temperatures (300°C) and over a much shorter time frame, reducing energy consumption and impacts of acidic effluent on the environment (Kumari et al., 2021).

Mining is a water intensive industry, requiring water for extraction and mineral processing (Kunz, 2020). Operations often occur in water sensitive areas, with global REE mining and extraction estimated to consume 17.35 million m³ of water in 2020 (Golroudbary et al., 2022). The sharing of water resources between mining and local communities can lead to friction and led to the development of the Water Stewardship Maturity Framework by the International Council on Mining and Metals, supporting the economic and socially acceptable management of water resources (ICMM, 2023). Innovations have been made by companies to reduce their water usage in sensitive environments (TRL 5-9), such as the use of seawater during beneficiation processes (e.g. Cisternas & Gálvez, 2017; McGregor et al., 2023), zero-discharge facilities (MP Materials, 2024), and recovering water from tailings (McGregor et al., 2023).

Life cycle assessments are a tool developed to determine the potential environmental impacts of a mining project and inform mitigation throughout the mine lifecycle (Pell et al., 2019a; Pell et al., 2019b). Minviro is a UK-based consultancy company who have applied life cycle assessments to REE projects, such as Songwe Hill, Malawi; Mount Weld, Australia; and Mountain Pass, USA. The reliability of the life cycle assessment depends on the quality of the data used, and therefore the validity of results produced can be uncertain (Pell et al., 2019b) and international standards are required. Life cycle assessments can be used for water use impacts (e.g. Halkes et al., 2024), but a similar water footprint tool is also used by mining companies to assess water usage of projects and ensure the sustainable use and management of water sources (Rodríguez et al., 2023).

Responsible sourcing of REE requires assurance that material has been legitimately sourced through a supply chain with demonstratable carbon footprints and environmental impacts which are compliant with international standards (Adrian Finch, University of St Andrews, per comms, 17/07/2024). The Circular System for Assessing Rare Earth Sustainability (CSyARES) programme is developing a combined life cycle assessment and blockchain database REE certification scheme in association with Minviro (Circularise, 2023). Minviro are also developing a mine to magnets life cycle assessment tool as part of the CLIMATES programme. Creation of a premium, fair trade REE supply chain, similar to that already achieved for gold and diamonds, would mean more expensive products and may be associated with challenges such as forgery of certificates or infiltration of certified supply. Development of 'geoforensic' fingerprinting of REE ores and product passports (TRL 3) would help overcome this challenge (Adrian Finch, University of St Andrews, per comms, 17/07/2024).





4. Discussion / Analysis

4.1 UK Capability and Stakeholder Mapping

The innovations identified and discussed in this report have various stages of technology readiness, ranging from concept to successful mission operations. These are summarised in Figure 5, following UKRI technology readiness levels (UKRI, 2022). Despite the lack of primary extraction in the UK, there are many stakeholders involved in the international and domestic REE supply chains (Figure 6). The UK has a wide range of stakeholders involved in the research and development of domestic expertise and technological innovations, such as the Camborne School of Mines (University of Exeter) and British Geological Survey. Domestic expertise surrounding geophysical and REE exploration is strong, ranging from

mineral exploration companies, such as Mkango Resources, to companies providing services to the exploration industry, such as Metatek and SRK. Beneficiation processes and projects have been developed in the UK by companies such as Pensana and Gravity Solutions. The mitigation of mining-related impacts is also a strong area of UK-based expertise due to such companies as Satarla and Minviro. Collaborative projects and funding opportunities over the last decade have developed the UK capabilities in several areas, such as conventional deposits and smart sorting (Table 2). These projects have also had the added benefit of enhancing stakeholder networking, collaboration, and enhancing UK expertise.

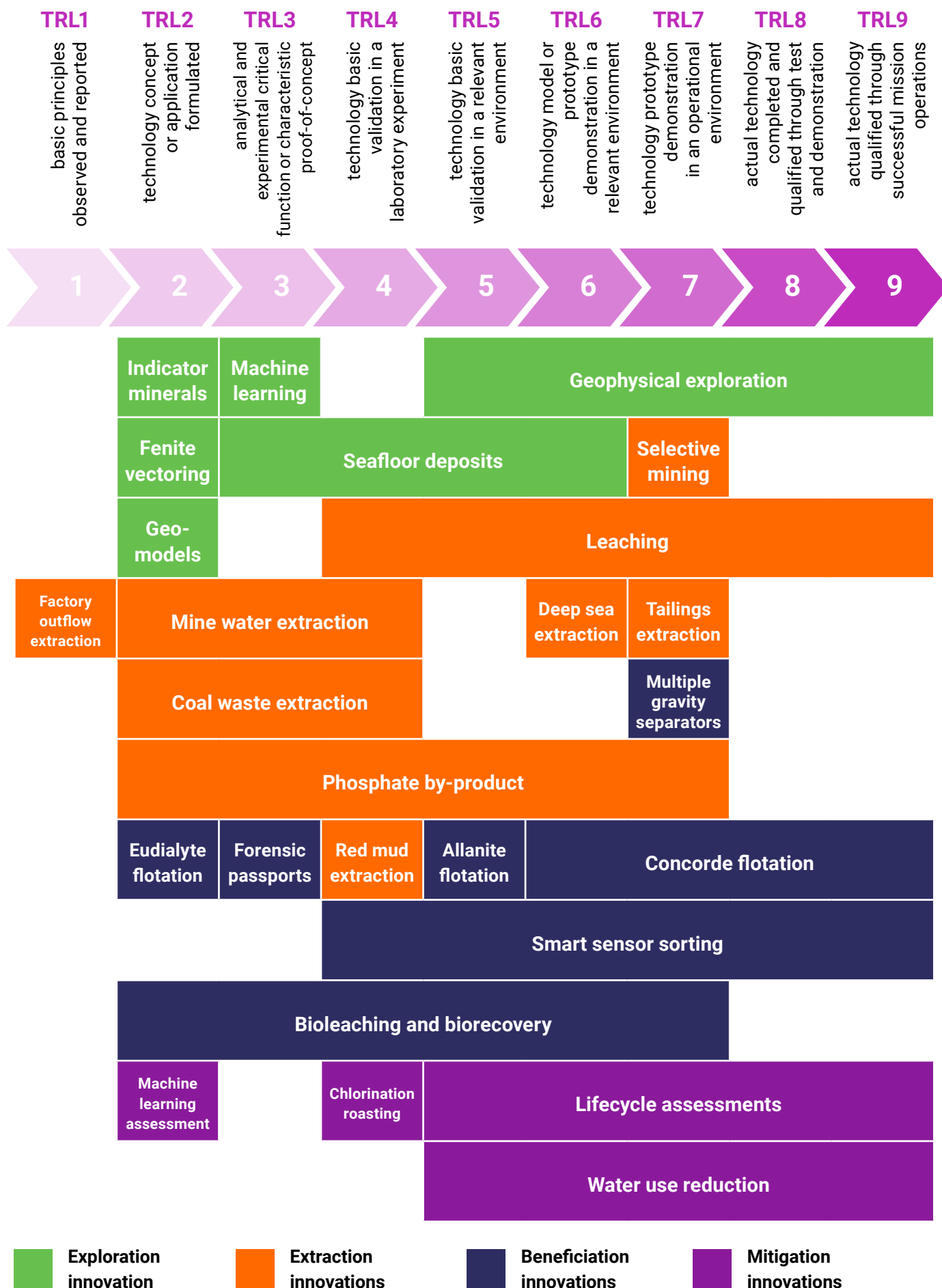


Figure 5: Author assessed technology readiness levels of innovations mentioned in this report, using UKRI definitions of technology readiness levels.

UK expertise spans the length of the REE supply chain but is strongest in research and development and exploration (Table 2). Large UK and EU-funded consortium projects have developed a high level of domestic expertise in the formation and enrichment of conventional REE deposits, such as carbonatites and alkaline-silicate rocks. Although these projects have addressed ion adsorption deposits, supply from these deposit types and reagent production is currently dominated by China, therefore

UK benchmarking will be low compared to an actively extracting country. Other unconventional deposits of REE are poorly understood and highlights a capability gap. Although there is no current active extraction and many countries, including the UK, have moratoria on deep-sea mining, interest continues in other countries, such as Japan. Therefore, the high level of expertise developed in the UK regarding deep-sea deposit formation, exploration, and extraction is still very relevant.

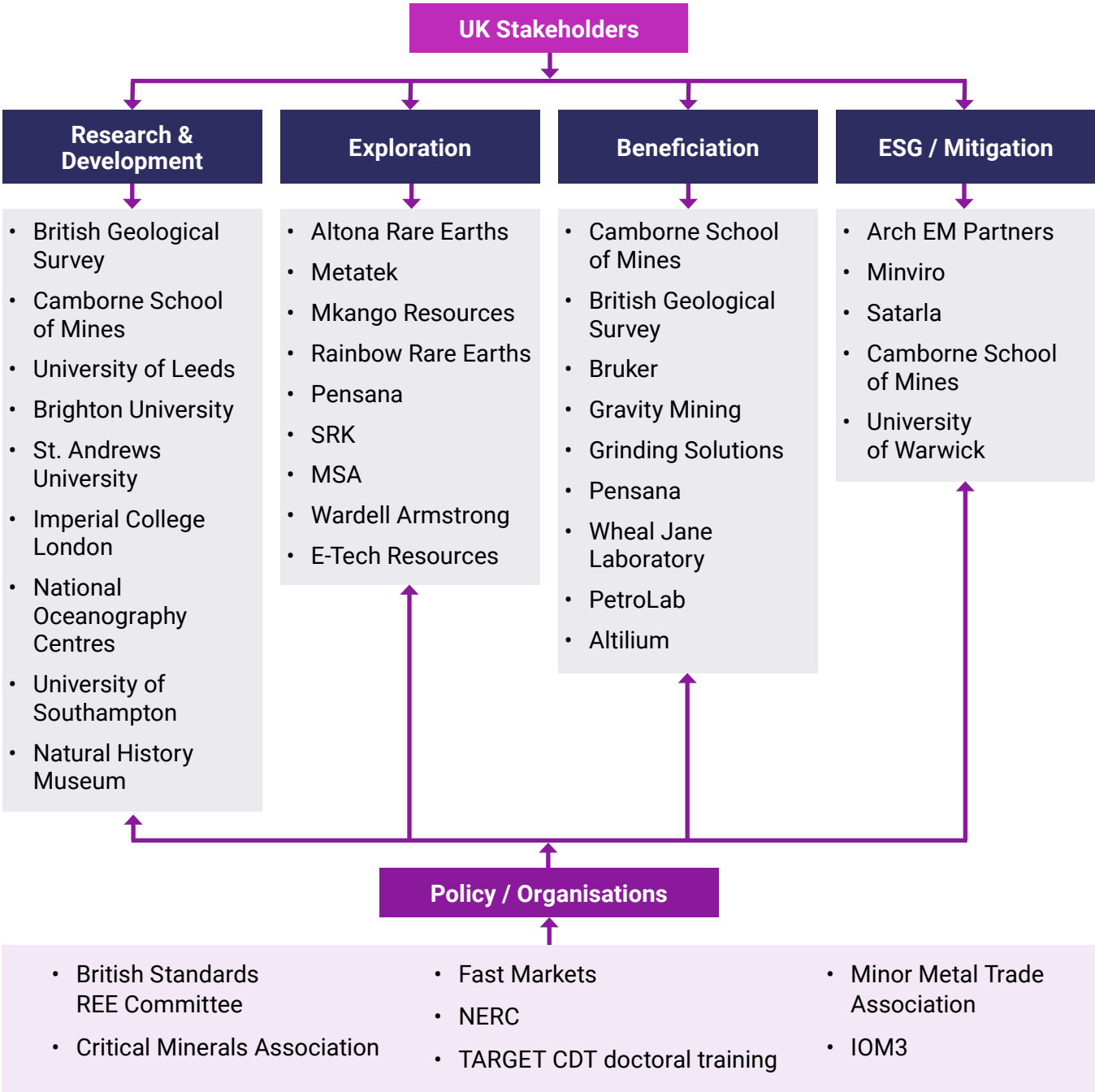


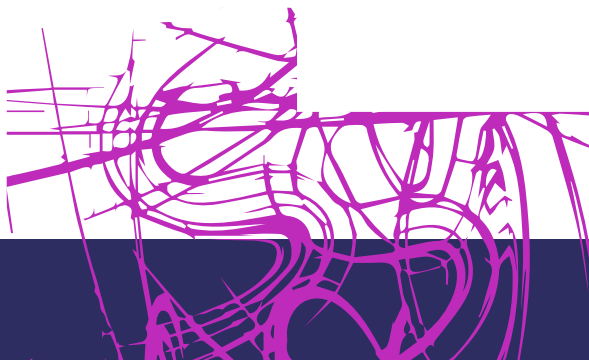
Figure 6: Mapping of key stakeholders in UK REE supply chain

Beneficiation and cracking of REE is an area of the supply chain currently dominated by China. However, UK-based developments have been made within the fields of bioleaching and recovery, smart sensor-based sorting, and tools used to develop sustainable practices throughout the REE supply chain. A challenge that may be addressed by technical expansion in Cornwall through the new Critical Minerals Equipment Hub (Good Growth, nd).

UK expertise rates well against the current international standard in environmental, social, and governance best practices. This area has been a major challenge for China and is undoubtedly an opportunity for ‘rest of the world’ companies.

Exploration • Carbonatite & alkaline-silicate geomodels • Ion adsorption clay deposits • Geophysical exploration • Vectoring • Indicator Minerals • Deep-sea deposits • Hyperspectral imaging • Exploration consultancy • Deposit characterisation & resource estimation	Extraction (mining) • Deep-sea deposits • Ion adsorption leaching
Beneficiation • Bioleaching/recovery • Fluorescence sorting	ESG / Mitigation • Life cycle assessments • Environmental and social impact assessments

Table 2: Areas of UK REE expertise outlined in this report





4.2 Challenges to the UK REE supply chain

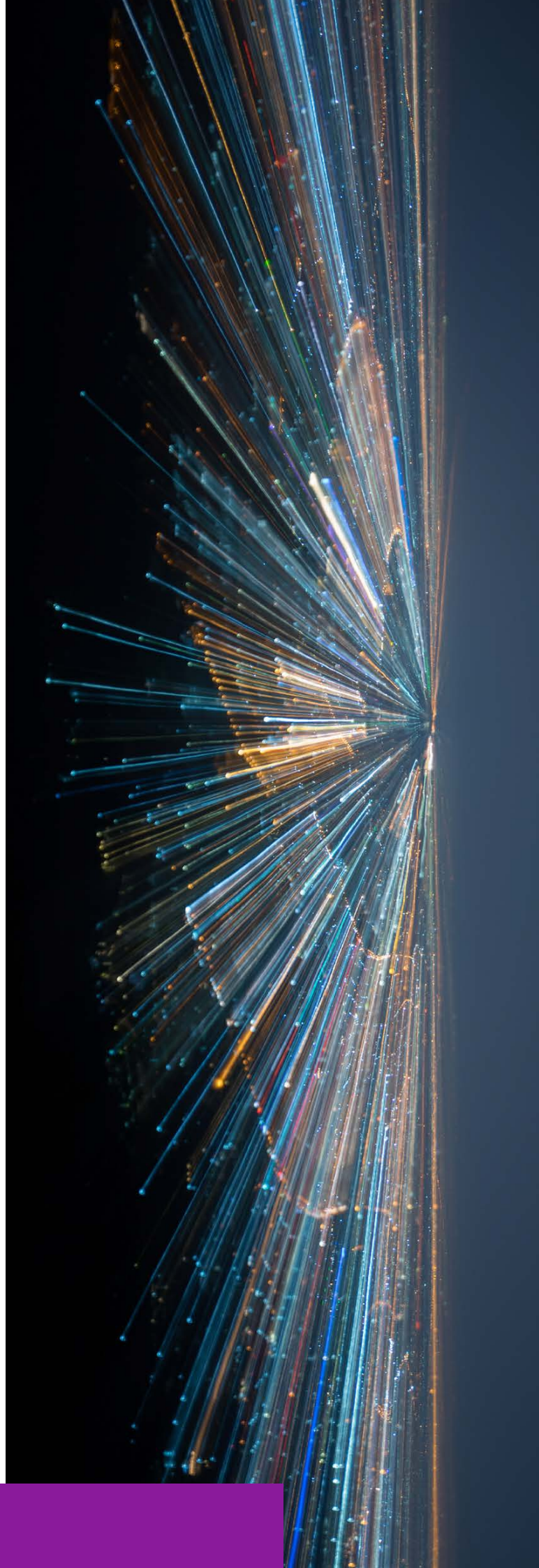
Although REE deposits occur globally, the UK does not have favourable geology for extraction and domestic primary production. As such, the UK must reduce risks to the supply of REE through bringing its areas of strength to international exploration and collaboration and developing other sections of the supply chain, such as beneficiation.

A disparity exists between the development of technological innovations and their uptake or adoption by industry and, consequently, there is an inability to progress innovations from proof of concept (TRL 3) and validation in a laboratory environment (TRL 4) to successful demonstration in an operational environment (TRL 7). This may be due to a lack of knowledge-exchange between

stakeholders. Adoption of innovations by industry stakeholders is unlikely to occur without the successful demonstration of a technology. However, successful demonstration is in turn challenging without collaboration with industry stakeholders. Incorporation of new beneficiation technology is much more likely to occur in a pre-existing operational plant alongside an established process, allowing production to continue in the event of technology failure (John Goode, per comms, 04/07/2024). Therefore, finding companies who are willing to trial unproven technologies is a challenge to supply chain development which makes it easier for China to maintain a monopoly on the REE market.

Chinese dominance of the REE supply chain is the predominant factor affecting the criticality of REE. Although primary production has diversified to other countries since 2012 (e.g. USA, Myanmar, Australia, and Madagascar), much of the REE concentrate is shipped to China for processing and magnet production. Chinese dominance enables it to influence global REE prices by changing export quotas. Historic events have shown that reducing exports causes REE prices to rise, incentivising investment in smaller ventures. Later relaxation of REE export quotas causes prices to fall, causing many of these ventures to fall into bankruptcy, retaining the Chinese control on REE processing (Dreyer, 2020). Therefore, China's knowledge of and ability to impact the development of competitor ventures lessens the incentive for financial investment.

International collaboration is key to the development of new primary sources of REE that might come to the UK. Countries with worldclass REE deposits are keen to add as much value in-country before shipping material overseas, therefore raw ore is unlikely to be shipped to the UK. As such, the UK focus should be on aspects that maximise the value to the collaborating country. This requires a multidisciplinary approach, utilising technical, business, governance, and socioeconomic expertise.



4.3 Opportunities and Recommendations

There are opportunities for the UK to build on its research, innovation and industrial strengths in REE deposit knowledge, exploration and consultancy, including resource estimation and deposit characterisation, and ESG-related activities. Examples of these include life cycle assessments and supply chain assurance, particularly in collaboration with international partners or UK-listed companies with overseas deposits and in multidisciplinary teams. There are also opportunities to innovate to overcome capability and knowledge gaps highlighted in this report, as outlined below:

- 1. Fertility of REE deposits:** the locations of deposits with REE are well established and innovations have been made in deposit exploration. However, there is little knowledge of the REE potential of these systems without expensive drilling campaigns. Developing REE fertility indicators could determine which exploration targets are worth investment and progression.
- 2. Unconventional REE deposits and minerals:** the mineralisation and beneficiation processes of these deposits are poorly understood but can contain higher proportions of the heavy REE and offer a chance for many countries to enhance domestic supply. As such, unconventional deposit exploration, extraction, and beneficiation innovations could diversify REE sources, reducing risks to REE supply.
- 3. REE extraction from waste streams:** REE have the potential to be recovered as a by-product during the extraction of many commodities. Understanding where REE reside in waste and integrating recovery into existing beneficiation processes, would allow full value mining and projects less affected by price fluctuations.
- 4. AI and machine learning:** these methods could help process exploration data quickly and efficiently and increase beneficiation recovery rates. Very few UK-based companies are developing AI solutions within the mineral industry.
- 5. Small-scale mining:** there is a lack of awareness and understanding of how small scale and artisanal mining can contribute to global mineral supply chains without the often associated social and environmental issues.



Considering the capabilities and expertise of UK stakeholders, the following recommendations could reduce the impacts of the identified challenges, enhance domestic REE supply, and improve international supply chain resilience:

1. Invest in UK research and development:

to develop areas of strength and close capability and knowledge gaps. Examples include REE fertility indicators, leaching reagent production, understanding unconventional deposits and by-products.

2. Enhance awareness of UK capability and expertise: promotion and awareness of UK capabilities and expertise overseas will assist in developing partnerships with international trade partners, diversifying the international REE supply chain and delivering the UK Critical Minerals Strategy.

3. Facilitate stakeholder connections and fund TRL progression: much newly developed technology is not being adopted by the REE industry. Facilitation of connections and promotion of innovations would assist in building stakeholder collaborations. Supplying innovator funds to support pilot testing would progress innovation technology readiness levels and facilitate industry adoption.

4. ESG innovations and assurance:

awareness of the need for sustainable mining practices opens the opportunity for development and certification of a premium REE 'fair trade' supply chain and associated 'geoforensic' methods.

5. Promote full value mining and reporting standards: incentivising or requiring the analysis of all metals present in a deposit would determine potential by-products and identify resources stockpiled in tailings facilities for future processing.

6. Support UK-based companies with global projects: the UK lacks favourable geology for REE mining and domestic supply could be enhanced by UK-based companies developing overseas projects and establishing downstream processing plants in the UK. However, financial support and political protection is required to ensure embryonic projects can withstand price fluctuations.

7. Develop REE processing research: developing beneficiation processes for less conventional minerals could open a wide range of deposits for extraction.



5. Conclusions

Without favourable geology within the UK to develop a primary domestic supply chain, it is important to develop innovations, support UK-based companies with global projects, and instigate projects in collaboration with overseas partners. This report highlights the many innovations that have recently been developed in the exploration, extraction, and beneficiation of REE deposits. However, there are many challenges standing in the way of their adoption by REE stakeholders. The promotion of innovations, instigation of partnerships, and facilitation of progression up the technology readiness levels would allow successful validation within an operational environment and adoption of technologies.

The UK has a wide range of expertise in the genesis, enrichment, and exploration methods of conventional REE deposits that can be used to work with industry partners. It is a leader in providing expertise for

the development of projects with strong ESG credentials. However, there are other capability gaps that have been highlighted as potential areas for the UK to develop domestic expertise, such as the formulation of REE fertility indicators, an understanding of unconventional deposits and mineralogy, REE extraction from waste streams, and production of leaching and flotation reagents outside of China. Enhancing the UK expertise and developing innovations within these areas will strengthen the delivery of the UK Critical Minerals Strategy, which involves utilising domestic expertise to collaborate with and support the development of international trade partners. Collaboration and sharing of information will build new and help enhance existing partnerships, allowing diversification and enhancement of the international REE supply chain, reducing risk to future supply and improving resilience.

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