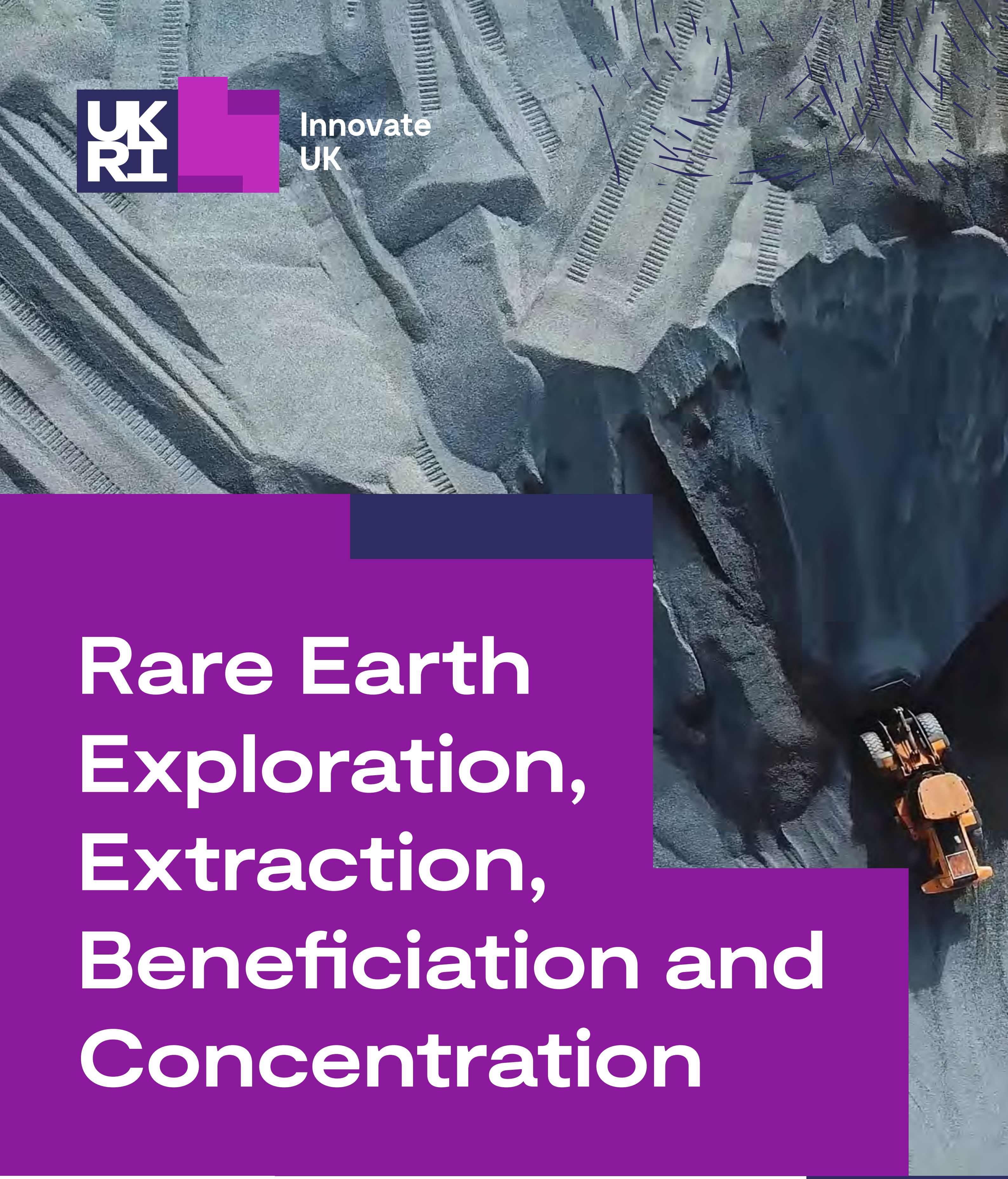

Rare Earth Exploration, Extraction, Beneficiation and Concentration

Innovation Landscape Report

Authors

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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 (REEs) 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 REEs.

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, causing a huge increase in the demand for raw materials. REEs form a fundamental component of low carbon technologies, such as wind turbines and electric cars. China currently dominates global REE supply, creating a large risk to future supply, and causing them to be classified as a critical raw material for the UK.

A thorough evaluation of the recent technological advances that have occurred in the global supply chain ranging from exploration stage through the beneficiation and concentration process of REE has been undertaken. Domestic expertise exists predominantly in the exploration stage of the supply chain, with large collaborative consortium projects enhancing understanding of deposit geomodels and exploration techniques. UK-based innovations have also been developed for deep-sea deposits, some beneficiation processes, and the mitigation of extraction-related impacts through life cycle assessments.

Without favourable geology in the UK to develop a primary domestic supply chain of REEs, it is important to develop innovations and initiate projects within the exploration stage or latter sections of the REE supply chain. However, this report has highlighted a disparity between developed technological innovations and adoption within the industry preventing their progression up the technology readiness levels to demonstration in an operational environment. The Chinese dominance of the REE market and historic influence over competitor ventures also provides poor incentive for financial investment into the diversification of the international REE supply chain.

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, deep-sea deposits, and the utilisation of AI and machine learning.

The report suggests 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.

This report highlights the challenges of growing the UK REE supply chain and identifies the key stakeholders. The capability gaps identified 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.

2. Background context

The rare earth elements (REEs) consist of the 15 lanthanides plus scandium and yttrium, which have been separated into the light (lanthanum to samarium) and the rarer and more valuable heavy REE (europium to lutetium, plus yttrium) by the European Commission (2014).

These metals are fundamental elements within modern technologies due to their luminescent, phosphorescent and magnetic properties. These include a huge array of uses, from medical and industrial to technologies aimed at reducing carbon emissions, such as permanent magnets in electric cars and wind turbines (Haque et al., 2014; Wall, 2014). A net zero energy transition will be a mineral intensive process (Ali et al., 2017; Depraiter and Goutte, 2023). Mineral demand is expected to quadruple by 2040 to meet the Paris Agreement goals regarding clean energy and an energy transition, with 40% of the demand being REE (Depraiter and Goutte, 2023). Current REE supply chains, especially for heavy REEs, may be an obstacle in achieving net zero emissions and energy transition goals (Wang et al., 2024). Implementation of new innovations and strategies, as well as the development of new REE supply chains requires international and national cooperation and is needed for achieving a net zero transition (Wang et al., 2024).

China dominates the global supply of REE, with a share of approximately 68 % of global mine production in 2023 (USGS, 2024), however, China's share of global REE processing and smelting has reached 90 % (Andrews-Speed and Hove, 2023).

As such, due to the high economic importance and supply risk associated with a metal dominated by a single country, the UK government has defined REEs as a critical raw material (see Figure 1; Mudd et al., 2024; DBT, 2022).

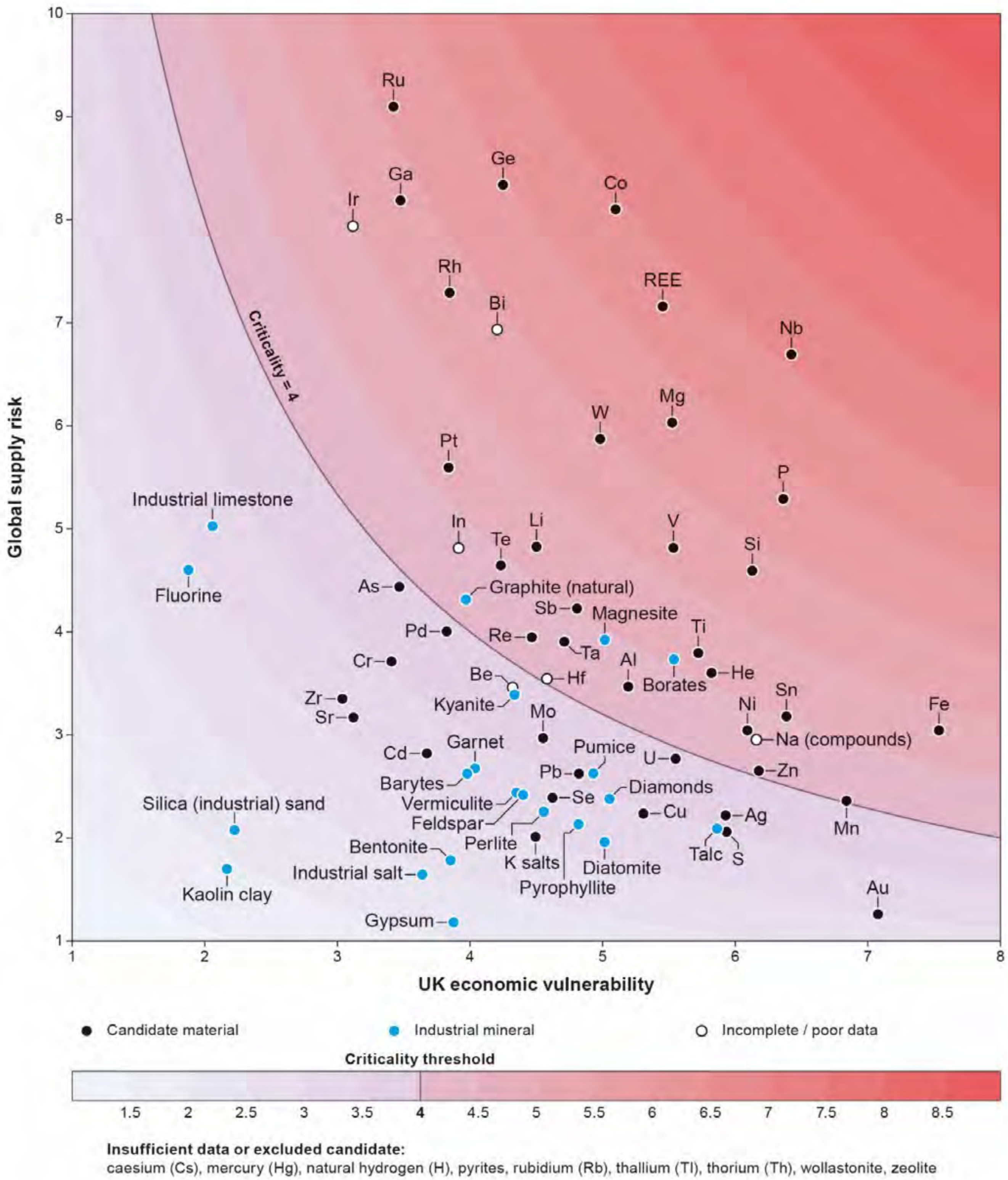
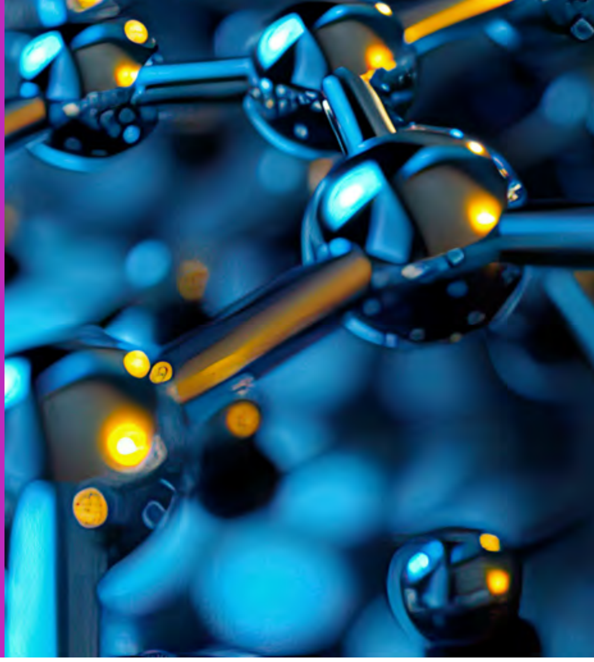


Figure 1: UK criticality assessment utilising global supply risk and economic vulnerability as assessment factors. Source: Mudd et al., 2024 BGS © UKRI 2021

3. Technology overview



3.1 REE deposits

Economic sources of REEs occur globally in a diverse range of deposit types (see Figure 2), reflecting different geological environments and processes which lead to their formation. Different deposit types have varying light to 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 extraction 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, comprising more than 50% carbonate minerals (Heinrich, 1966; Le Bas, 1981; Woolley and Kempe, 1989) that comprise high grade (1.3-8.9 wt. % total REE) but low tonnage deposits (29-798 Mt) (Smith et al., 2016), such as Mountain Pass, USA (Castor, 2008) and Bayan Obo, China (Smith, 2007).

Alkaline-silicate rocks are often associated with carbonatites and are igneous rocks with higher abundances of alkali elements (sodium and potassium) relative to silica and aluminium (Leelanandam, 1989; Mitchell, 1996). Large UK-led collaborative research projects, such as HiTech AlkCarb, EuRare, and SoSRare, have developed our understanding of these systems considerably leading to a high level of carbonatite and alkaline expertise and capability within the UK.

These projects led to the development of geomodels and exploration indicator concepts aimed at the exploration for and understanding of carbonatite and alkaline systems (e.g. Elliott et al., 2018a; Beard et al., 2023).

Ion adsorption deposits are the most important source of yttrium and heavy REEs, forming where REE-rich rocks are exposed and weathered under sub-tropical to tropical conditions. Mobilised REEs become adsorbed to clay minerals or incorporated into secondary minerals (Jowitt et al., 2017; Borst et al., 2020) from which the REEs can be easily leached by exchanging them with other cations, such as sodium or calcium (Wu et al., 2023).

Heavy REE supplies are predominantly sourced from ion adsorption deposits above granitic rocks in China (Borst et al., 2020) but the UK have capability and expertise developed during the European Commission funded EURARE project. Placer deposits or heavy mineral sands are also an important source of REEs where weathering and 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 REEs increases and uncertainty surrounding supply risk broadens, many countries are seeking to expand domestic supplies. Where conventional sources are lacking, exploration has widened to more unconventional sources of REEs, such as highly fractionated rhyolites, iron-bearing deposits, and nodular black shales. These unconventional deposits may be poorly understood, not yet undergoing commercial extraction, or newly recognised sources of REEs. As such, a better understanding of unconventional deposits is a high priority for innovation.

Deep-sea deposits of REEs are seeing an exponential 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 REEs, 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, gold, and lithium (Hein et al., 2013), therefore it is likely that REEs would 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.

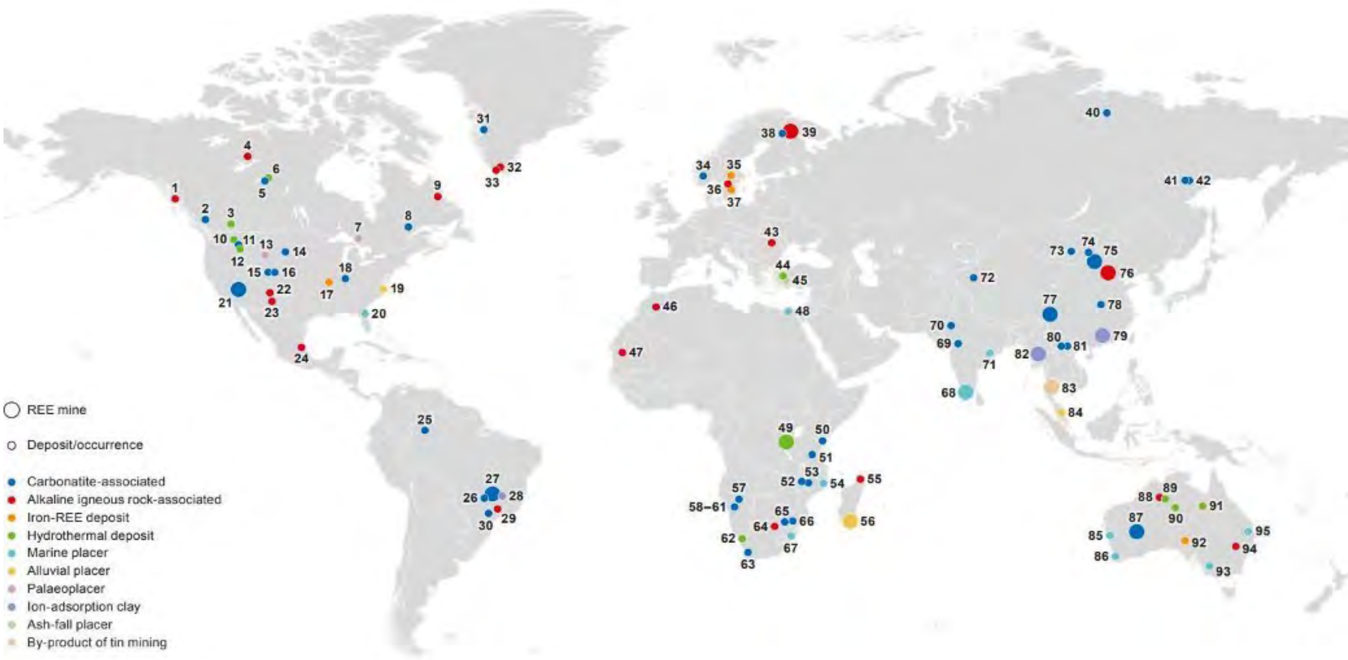


Figure 2: Global REE deposits categorised by deposit type and extraction stage. Source: Deady (2021) BGS © UKRI 2021.

3.2 REE deposit exploration

Exploration for mineral deposits that are not exposed at the surface, concealed, or have been extensively altered require the use of geophysical surveys or geochemical sampling to identify areas of 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 systems below the surface that may be concealed, covered, or deep targets for exploration (Dentith and Mudge, 2014) and allow 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.

The UK has a high level of geophysical exploration expertise, with several UK-based companies skilled in targeting mineral deposits, including Metatek and TerraDat. The UK-led and EU Horizon 2020 funded REE research project HiTech AlkCarb formulated best practices for the geophysical exploration of carbonatites and alkaline (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 utilising 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) (Booysen et al., 2020; Karimzadeh and Tangestani, 2022).

The use of machine learning as a prospectivity tool (TRL 3) has seen an exponential increase over the last decade (Shirmard et al., 2022), successfully having been utilised to determine element predictors of REE concentrations (e.g. Bishop and Robbins, 2024) and analysed geophysical maps to predict REE prospective areas on land and in the deep sea (e.g. Josso et al., 2023; Wang et al., 2024).

The use of machine learning and artificial intelligence within mineral exploration is still in the early stages of development and with many future applications that could still 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) must then be used to scope the site for nodule density by collecting near seabed side scan sonar, high resolution images, and collecting samples (Mudd et al., 2024; 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 Fe-Mn crusts is more challenging, however, (Neettiyath et al. 2024) and subsequently the China Ocean Mineral Resources Research and Development Association have developed 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. In addition, self-potential and magnetic sensors were successfully combined to create the largest integrated UAV-imaged topographic map of the seafloor (Blue Mining, 2018).

Deposit Type	Potential Geophysical Exploration Methods
Carbonatites and alkaline rocks	Gravity, magnetic, radiometric, resistivity and IP, 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).

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) in addition to heavy REE extraction from ion-adsorption clays. Carbonatites and ion adsorption deposits have replaced mineral sands as the primary source of REEs (Sengupta and Van Gosen, 2016), whilst REEs from alkaline-silicate rocks have been limited to by-products of apatite processing (Kogarko, 2018).

Ion adsorption deposits from weathered granites are the most important source of yttrium and heavy REEs (Jowitt et al., 2017). The REEs adsorbed to clay particles can be extracted or leached from the rock by exchanging them with other cations within reagents in situ or in tanks (Wu et al., 2023).

The predominant salt reagent used to exchange REEs from the clays is ammonium sulphate, a cheap and easily available fertiliser reagent. The in-situ leaching employed in Chinese and Myanmar ion adsorption deposits has caused considerable environmental damage including landslides and contamination. Although extraction from ion adsorption deposits has diversified outside of China, innovations are needed to make in-situ leaching possible in other locations without the associated environmental implications. Electrokinesis is being evaluated at bench and field scale for in situ leaching (TRL 4-9) (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 banning deep-sea mining until more evidence of the impacts of extraction are known (DEFRA, 2023; Delivorias, 2024). The decision made by the Norwegian Parliament in January 2024 to open an area of their exclusive economic zone for companies to apply for exploration licenses is expected to attract investment and research from the private sector to address these challenges and promote innovation (Stallard, 2024).

Some such innovations include clog-free vertical transport systems (Blue Mining, 2018), the Apollo II nodule harvesting and in situ processing vehicle (TRL 6) developed by Blue Nodules (2020), and the Eureka II autonomous underwater vehicles designed by Impossible Metals (2024a) to selectively harvest polymetallic nodules (TRL 6) and reduce environmental disturbance (Impossible Metals, 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).

Modelling has been used for many years to determine the potential environmental impacts of deep-sea mining. However, recent in situ and observable experiments have determined that disturbed sediment would only increase background sedimentation rates by 1 % (Muñoz-Royo et al., 2021) and that collectors that create turbidity currents promote local deposition of disturbed sediments compared to those that don’t, causing transport further afield (Muñoz-Royo et al., 2022).

Phytoplankton studies have shown that toxic metals do not readily leach from mined iron-manganese material into seawater (Dabrowska, 2019). As such, more in situ experiments with the ability to monitor impacts would benefit technology development (Bramley Murton, NOC Southampton, per comms, 19/07/2024).

3.4 REE extraction from waste streams

REEs can be found in low concentrations within many geological deposits and concentrated through processing and beneficiation processes in the waste material produced. Coal ash produced during the combustion of coal has been the focus of multiple research projects over the last decade (e.g. Franus et al., 2015; Rybak and Rybak, 2021; Vilakazi et., 2022; Liu et al., 2023).

Estimated coal fly ash global averages vary between 378-496 ppm (Ketris and Yudovich, 2009; Zhang et al., 2020) and may reach as high as 1.7 wt.% total REEs (Taggert et al., 2016), prompting the US Department of Energy to plan the building of a pilot plant capable of extracting 1-3 tonnes of REE oxides per day (DOE-NETL, 2023).

However, concentration of REEs in UK coal ash samples vary between 246-481 ppm (Blissett et al., 2014; Thompson et al., 2018). Circular economy practices in the UK already utilise coal fly ash within the construction industry and coal fed power stations are also due to be phased out by 2024 (BEIS, 2021). As such, extracting REE from coal ash is unlikely to be an economically viable option in the UK.

Tailings are waste products consisting of wet slurries formed from the processing of metal ores. Historic and contemporary tailings are increasingly being assessed as mineral exploration targets due to their potentially high concentrations of metals not extracted during processing. Their fine grain size and surface position negates 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 that was mined (see Figure 3), with extraction of niobium from carbonatites, phosphate mining, and bauxite processing for aluminium, all having the potential to produce REE as a by-product. However, historic tailings facilities are likely to be heterogenous, making active waste streams a more plausible target. Acidic water at both metallic and coal mine sites can also mobilise metals, with a strong correlation between REE concentration and low pH of the 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).

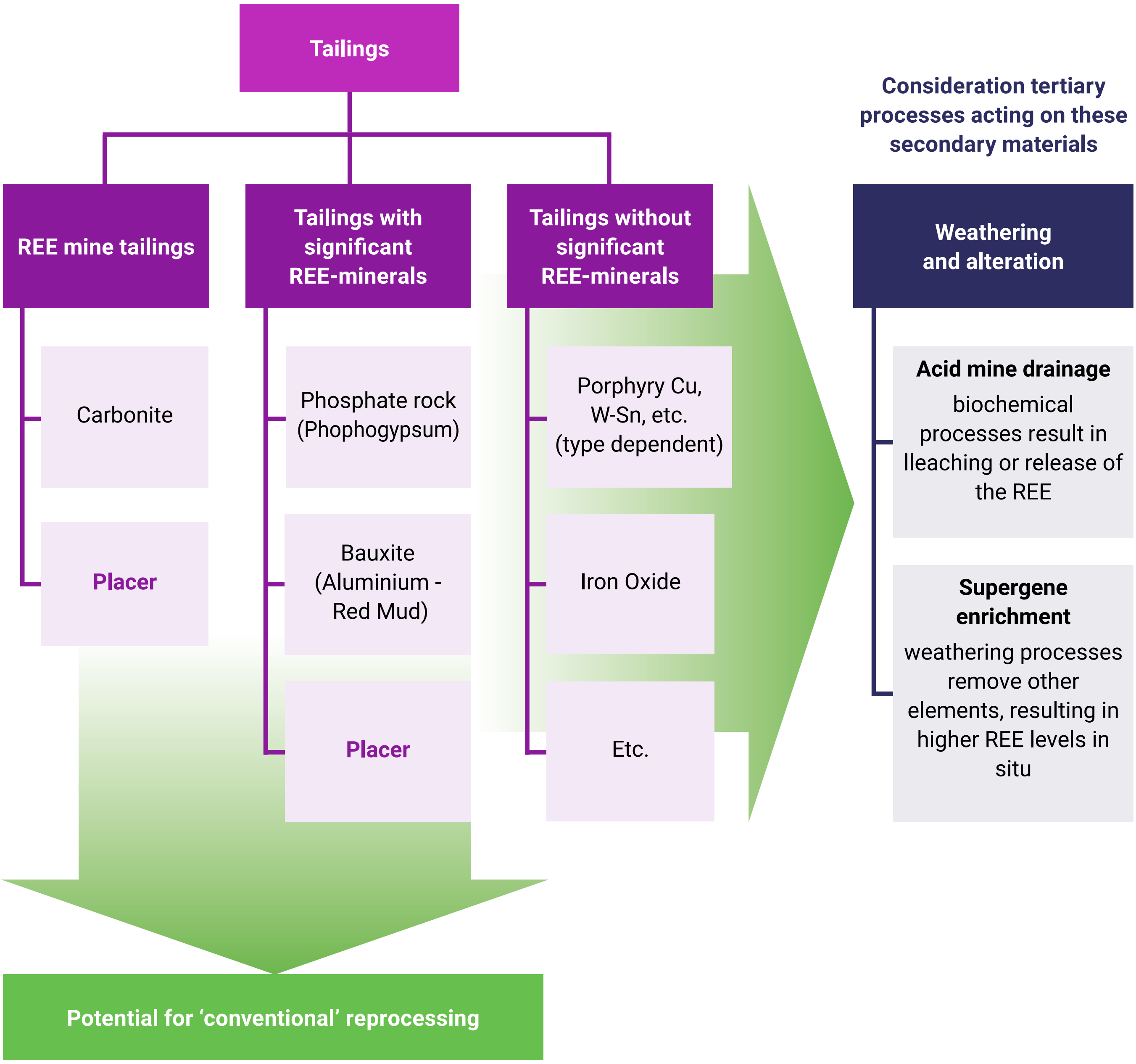


Figure 3: REE-enrichment in tailings based on type of deposit being extracted and processed (Marquis and Hudson Edwards, in progress) Reproduced with permission. All rights reserved.

Bioleaching and biorecovery have also been highlighted as having potential to recover REEs from tailings, acid mine drainage, and wastewater, using microbes that are able to liberate REEs from liquid streams. Therefore, allowing both remediation and critical metal recovery.

Microbes are currently being used for metal recovery of copper, nickel, uranium, and gold, but not yet REEs, 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 bioleaching would be understanding the active microbial processes required to extract REEs from solid minerals.

3.5 REE beneficiation

Mined material is upgraded to a purer REE concentrate through a series of physical and chemical processes, known collectively as beneficiation. These processes may involve crushing and grinding to liberate target ore minerals, before using their physical properties to separate them using gravitational and magnetic methods.

Flotation involves adding chemicals or reagents to the crushed ore to create a slurry, which is then agitated with air bubbles. The REEs attach to the bubbles and rise to the surface, where they can be collected and separated from other minerals. Beneficiation methods have been developed and commercialised for bastnäsite, monazite, and xenotime, however many REE-rich deposits contain unconventional minerals, such as eudialyte and allanite, for which commercial REE extraction has not yet been developed.

Innovations aimed at the comminution of ore and liberation of target minerals involves the application of high-voltage electric pulses by the UK company Lightning Machines. Gravity Mining Limited, another UK company, has collaborated with Lindian Resources to develop Multi Gravity Separators (TRL 7) to concentrate monazite, which will be installed at the Kangankunde Carbonatite mine, Malawi, during 2024.

Many developments and innovations have been made in the area of smart sorting, which involves utilising a variety of sensor-based techniques to sort ore minerals from the surrounding crushed rock (TRL 4-9). 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).

Smart sensor-based sorting may also allow the processing of lower grade materials, waste dumps, and deposits/materials once determined to be uneconomic to process (TOMRA, 2024). Although x-ray transmission sorting technology has not been tested on REEs in the UK, Cornish Metals Inc. completed metallurgical test work at South Crofty mine using TOMRA x-ray transmission sorters (see Figure 7), which produced 'excellent' results (Cornish Metals, 2023). Despite the many innovations in beneficiation, there are challenges involved in the industrial adoption of more recently developed spectroscopic sensors, including the requirement for industrial partners to allow progression from concept to pilot plant (Adrian Finch, University of St Andrews, per comms, 17/07/2024).

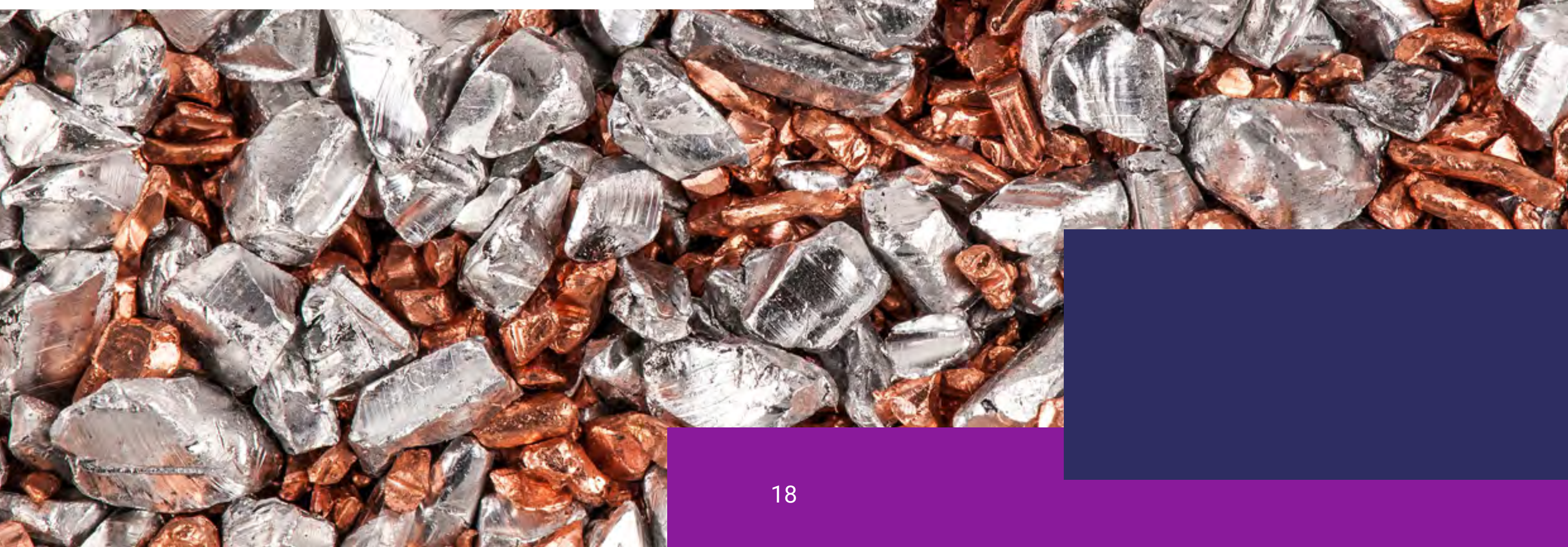
Figure 4: TOMRA XRT Sorter being used at Cornish Metals' South Crofty Mine in Metallurgical Testwork, from Cornish Metals (2023).

Flotation techniques are typically most effective at concentrating REE minerals, however most flotation reagents are currently produced by China. Therefore, to reduce the REE supply chain risks, a major opportunity for improvement and innovation would be the development of new international flotation reagents that are selective and cost-effective. Many flotation reagents perform best at high temperatures, therefore there is room for development of new reagents requiring less heat to reduce the carbon footprint of REE beneficiation (John Goode, per comms, 04/07/2024).

Artificial intelligence, and artificial neural networks can be used to find more reagents and optimise selective reagents, as well as predicting flotation efficiencies (Labidi et al., 2007; Bendaouia et al., 2024). Research into the flotation of the minerals allanite and eudialyte are 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 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 and then later to separation plants followed by REE permanent magnet producers (see Figure 8).

Although these hydrometallurgy processes are well established for bastnäsite, monazite, and xenotime, these methods use hot acid and alkaline leaching and precipitate thorium compounds (Jha et al., 2016; Lynas, 2024), hence 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 failed to be developed (Beard et al., 2023), providing opportunity for innovations.



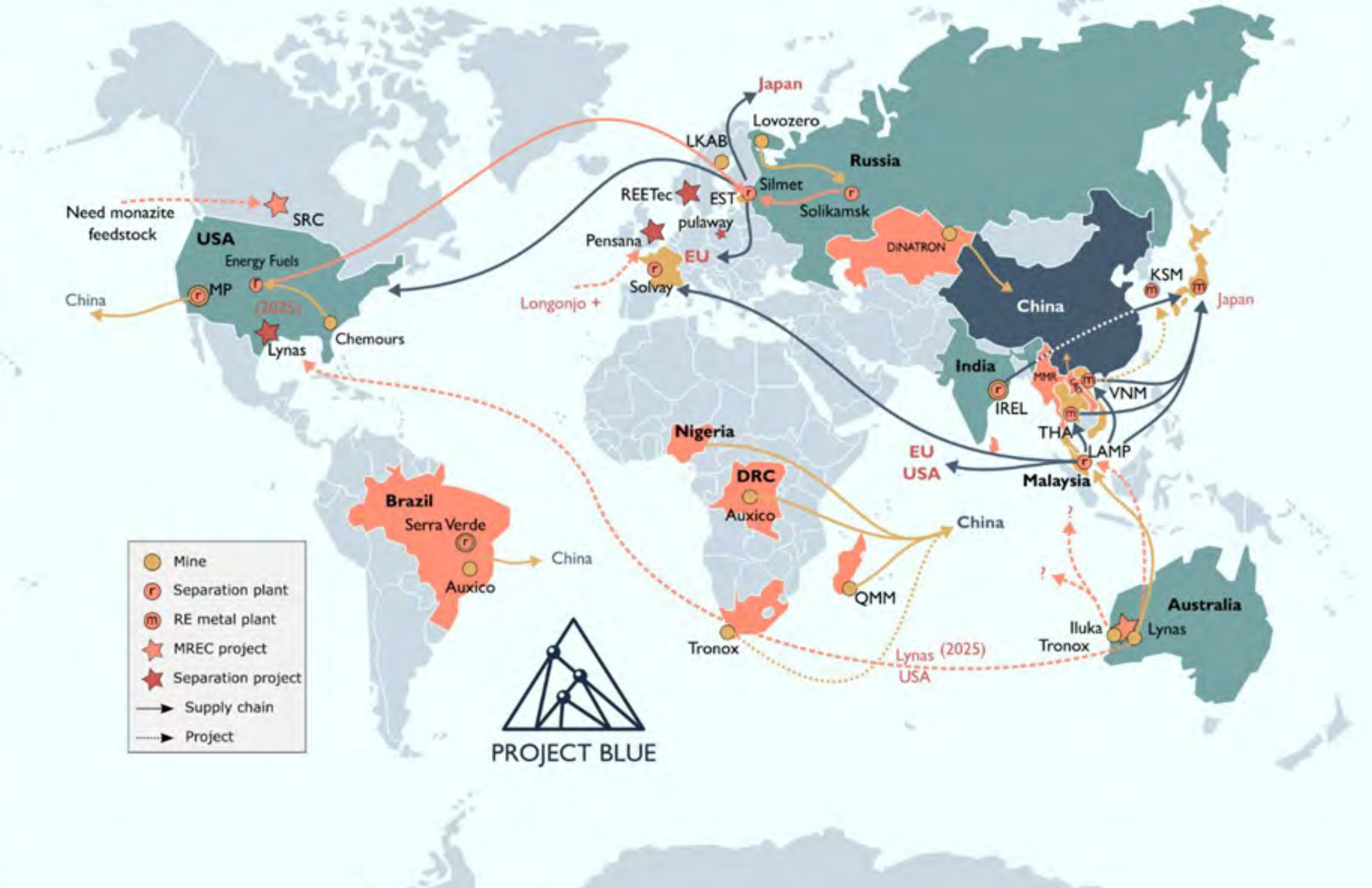


Figure 5: Worldwide shipping destinations for REE mineral concentrates, MREC, and metals.
Source: Project Blue (2024)

Naturally occurring radioactive materials, such as thorium and uranium, are often incorporated into REE minerals during geological processes (Kanazawa & Kamitani, 2006). Although degrees of radioactivity vary greatly between deposits and mining operations, there is a positive correlation between REE and radioactive element concentration (Wall et al., 2017). Beneficiation processes cause the enrichment of both REEs and radioactive elements, followed by the production of a radioactive waste stream during hydrometallurgical cracking processes.

This not only produces challenges in the storing of tailings, but also shipping of concentrates, with any material registering as Class 7 Radioactive Materials having to be transported according to international and national regulations as 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 incorporated by Energy Fuels in Utah, USA. Research reactors in Norway have also tested the potential for using thorium-based fuels (Emblemsvåg, 2022).

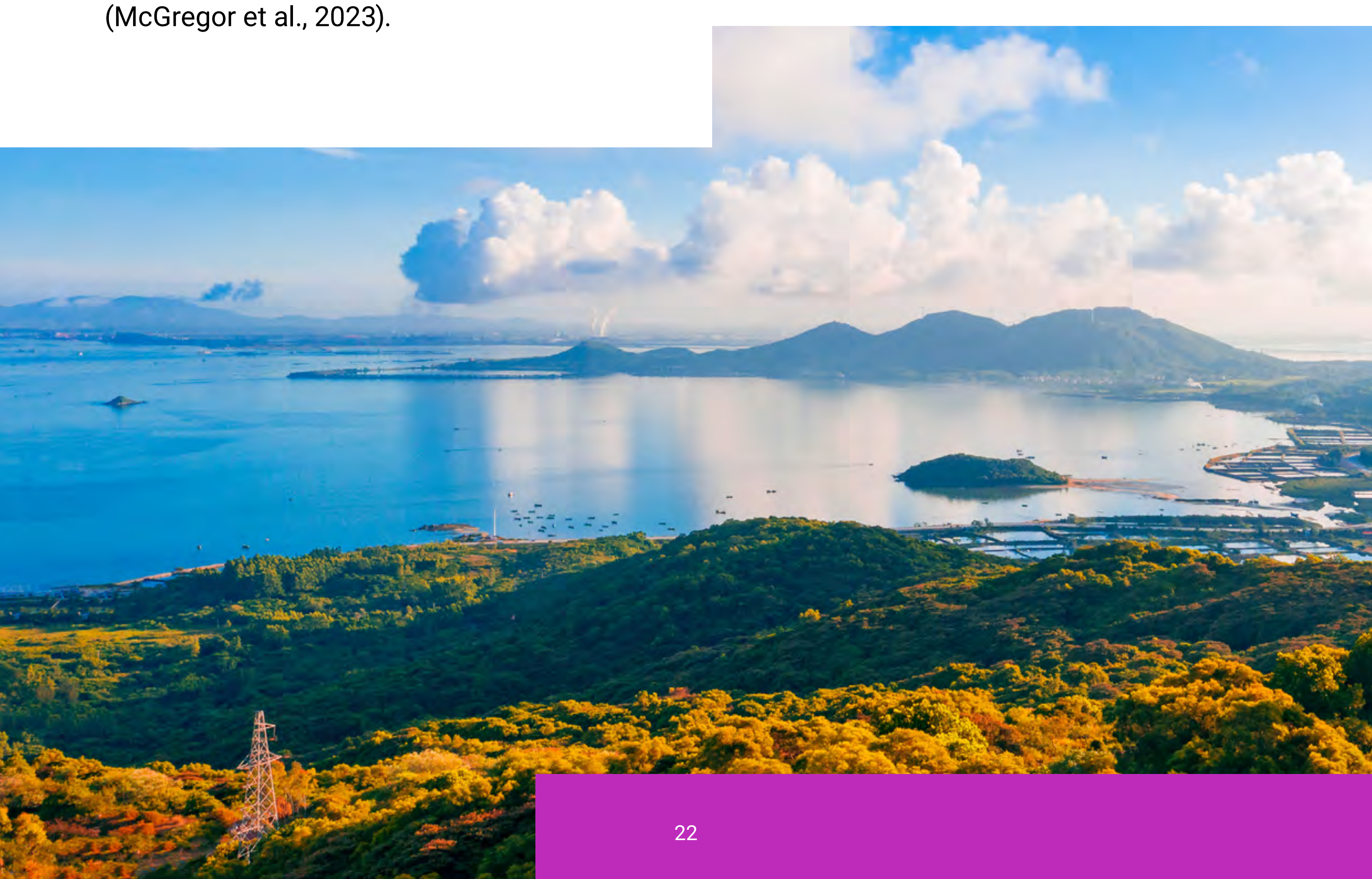
Fingerprinting REEs and developing forensic passports (TRL 3) aims to generate reputable sources of REEs with demonstrable carbon footprints and environmental impacts which are compliant with international standards (Adrian Finch, University of St Andrews, per comms, 17/07/2024). The Circular System for Assessing Rare Earth Sustainability (CSyARES) programme is developing a software-based REE certification scheme in association with the British consultancy Minviro (Circularise, 2023). However, the creation of a premium, fair trade REE supply chain, similar to that already achieved for gold and diamonds, would mean more expensive products, incentivising the forgery of certificates. Therefore, a geoforensic method of checking a REE product's site of origin is required (Adrian Finch, University of St Andrews, per comms, 17/07/2024).

3.6 Mitigation of environmental implications

Aside from the generation of radioactive waste, the extraction of REE is associated with two main environmental impacts: the energy used during beneficiation and cracking processes, and the use of high volumes of water. Kernow Mining Optimisation is 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 processes during REE beneficiation 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 of 3 hours, reducing energy consumption and impacts of acidic effluent on the environment (Kumari et al., 2021).

Mining is a water intensive industry with projects requiring water for extraction and mineral processing techniques/processes (Kunz, 2020). Operations often occur in areas that are classified as water sensitive, however global REE mining and extraction was estimated to consume 17.35 million m^3 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 mitigating planning decisions through the mine lifecycle (Pell et al., 2019a; Pell et al., 2019b). Minviro is a UK-based consultancy company with world-leading expertise in the development and utilisation of life cycle assessments, which have already been applied to REE projects, such as Songwe Hill, Malawi, Mount Weld, Australia, and Mountain Pass, USA. However, the reliability of the life cycle assessment is dependent on the quality of the available data used, and therefore the validity of results produced can be uncertain (Pell et al., 2019b). A similar tool termed water footprints are utilised by mining companies to assess the water usage of projects and ensure the sustainable use and management of water sources (Rodríguez et al., 2023).



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 have been summarised in Figure 6, utilising the UKRI technology readiness levels (UKRI, 2022). Despite the lack of primary extraction in the UK, there are a number of stakeholders that are involved in the international and domestic REE supply chain (see Figure 7).

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 and British Geological Survey. Domestic expertise surrounding geophysical and REE exploration is strong, hosting companies and consultancies, such as Metatek and Mkango Resources. Beneficiation processes and projects have also 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 (see Table 2). These projects have also had the added benefit of enhancing stakeholder networking, collaboration, and enhancing UK expertise.

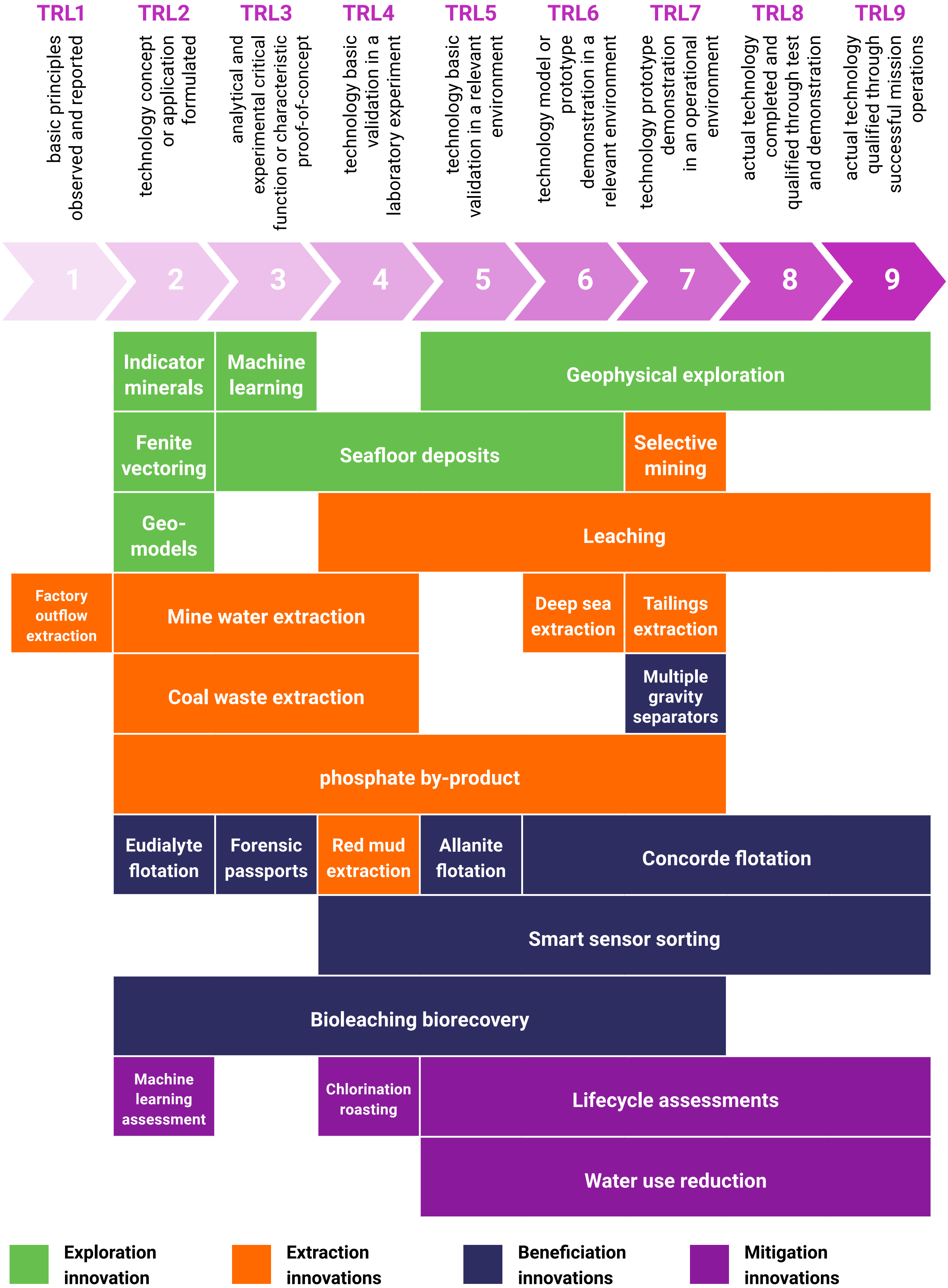


Figure 6: Author-assessed technology readiness levels of innovations mentioned in this report, using UKRI definitions of technology readiness levels.

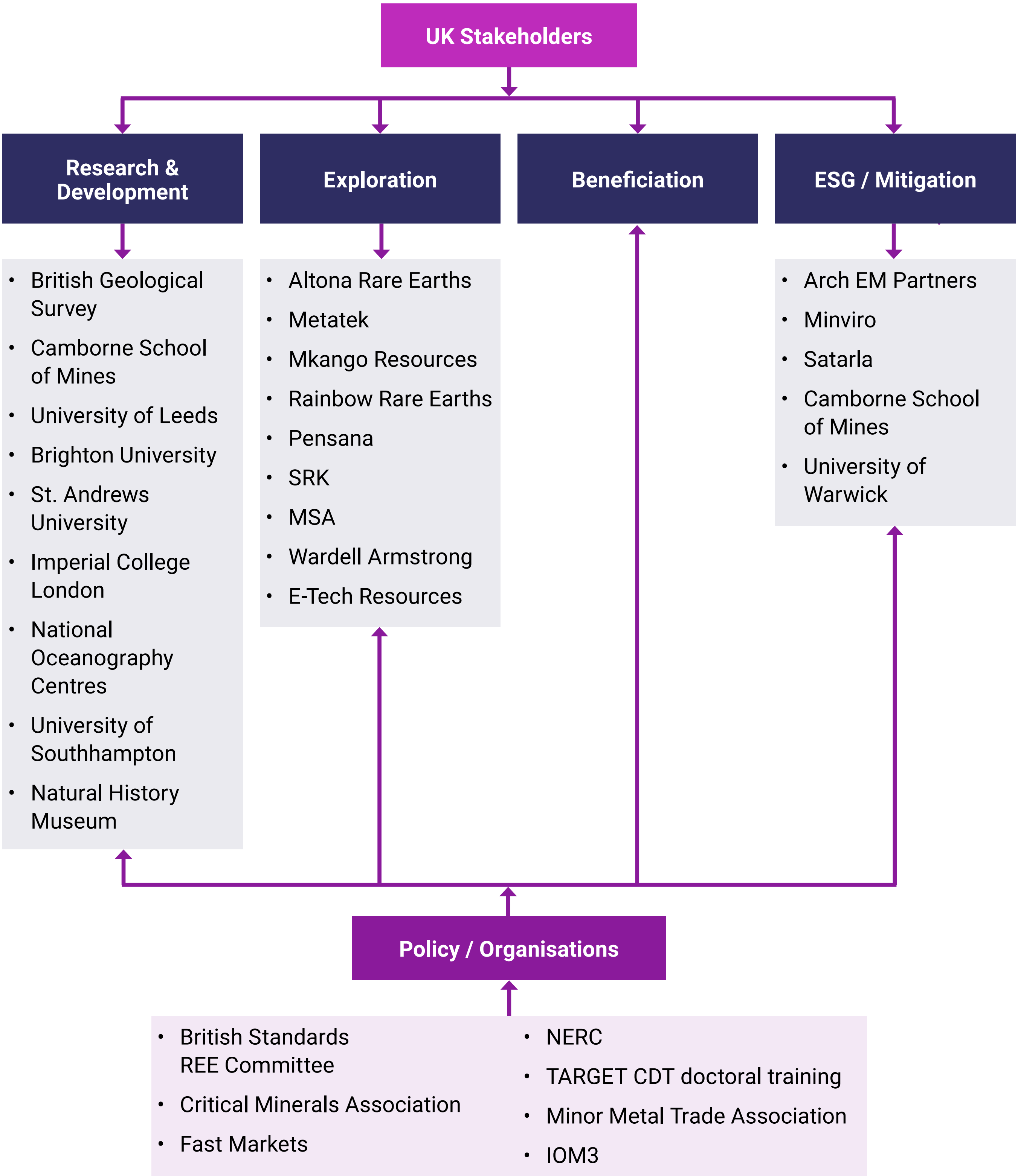


Figure 7: Mapping of key stakeholders in UK REE supply chain

UK expertise spans the length of the REE supply chain but appears to be strongest within the exploration stage (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 REEs are poorly understood and highlight a capability gap.

Lacking any domestic mining of REE, the UK has developed a high level of expertise in the exploration for and extraction of deep-sea deposits, related to a range of associated research projects, such as TRIDENT, ULTRA, Blue Mining, and MarineE-tech. Although no extraction is actively occurring from deep sea deposits, international interest in these deposits remains high, therefore it is possible that other international technological innovations are on par with or higher than that of the UK.

Beneficiation and cracking of REEs is another area of the supply chain which is dominated by China, and as such, benchmarking of UK beneficiation knowledge is much lower than that of China. However, 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. Therefore, UK expertise is benchmarked highly against the current international standard in environmental, social, and governance best practices.

Exploration	Extraction (mining)
• Carbonatite & alkaline-silicate geomodels • Ion adsorption clay deposits • Geophysical exploration • Vectoring • Indicator Minerals • Deep sea deposits • Hyperspectral imaging • Exploration consultancy • Deposit characterisation & resource estimation	• Deep-sea deposits • Ion adsorption leaching
Beneficiation	**ESG / Mitigation**
• Bioleaching/recovery • Fluorescence sorting	• 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 can be found globally on each continent, the UK does not have favourable geology to allow for extraction and domestic primary production. As such, the UK must reduce risks to the supply of REEs through international collaboration and developing other sections of the supply chain, such as beneficiation and recycling.

A disparity exists between the development of technological innovations and their uptake or adoption by industry. This may be due to a lack of communication and therefore knowledge exchange between stakeholders but may also result from an inability to progress up the technology readiness levels from proof of concept (TRL 3) and validation in a laboratory environment (TRL 4) to successful demonstration in an operational environment (TRL 7). Adoption of innovations by industry stakeholders is unlikely to occur without successful demonstration of a technology.

However, successful demonstration is in turn challenging without collaboration with industry stakeholders. The incorporation of new beneficiation technology is much more likely to occur within 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 that are willing to trial unproven technologies is a challenge to supply chain development that makes it easier for China to maintain a monopoly on the REE market.

This Chinese dominance of the REE supply chain is the predominant factor increasing the criticality of this commodity. Although primary production through mine extraction has diversified to other countries since 2012, such as Burma, Australia, and Madagascar, much of this ore and concentrate is still shipped to China for processing and smelting. This Chinese dominance creates the ability 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 caused 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 is poor incentive for financial investment.

4.3 Opportunities and Recommendations

A series of capability and knowledge gaps have been highlighted which provide opportunities for the UK to innovate and enhance domestic capability within the international REE supply chain. A range of these capability gaps have been outlined below:

1. **Fertility of REE deposits:** the locations of deposits with REEs are well established and innovations have been made in deposit exploration. However, there is little understanding or knowledge about the REE potential of these systems without expensive drilling campaigns. Developing REE fertility indicators would determine which exploration targets are worth investment and progression.
2. **Unconventional REE deposits and minerals:** these deposits are poorly understood, often lack beneficiation processes but contain higher proportions of heavy REEs and offer a chance for many countries to enhance domestic supply. As such, unconventional deposit exploration, extraction, and beneficiation innovations would diversify international supply, reducing the risk to REE supply.
3. **REE extraction from waste streams:** extraction processes of many commodities have the potential to recover REEs as a by-product. Greater understanding of distribution and integration of recovery into existing beneficiation processes, would allow full value mining and a supply less affected by price fluctuations.
4. **AI and machine learning:** these methods have the capability to process exploration data quickly and proficiently, increase the recovery rate of beneficiation processes, and allow efficient recovery from lower grade ores. However, very few UK-based companies are developing AI and machine learning solutions.
5. **Deep-sea mining environmental implications:** public perception and social license to operate would be greatly improved by increasing certainty surrounding the environmental implications of deep-sea extraction. Much of this knowledge is based on computer modelling, whereas in situ observable experiments allow validation or adaptation of models to allow designing of technology to mitigate environmental impacts.
6. **Artisanal mining:** there is a lack of awareness and understanding of how artisanal mining can contribute to global mineral supply chains and help meet demand for critical metals in a sustainable way, without the often associated social and environmental issues.

Utilising the pre-existing capabilities and expertise of UK stakeholders, a series of recommendations have been made to reduce the identified challenges and enhance the UK domestic REE supply and resilience of the international supply chain:

1. **Invest in UK research and development:** capability and knowledge gaps provide opportunities to enhance UK domestic expertise and innovations. Examples include REE fertility indicators, leaching reagent production outside of China, and understanding of unconventional deposits and ore minerals.
2. **Enhance awareness of UK capability and expertise:** promotion and awareness of UK capabilities and expertise 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. **REE fingerprinting / passport:** awareness of the need for sustainable mining practices opens the opportunity for development and certification of a premium REE 'fair trade' supply chain. The additional value of this premium product would incentivise certificate forgery, requiring verification of REE concentrate or magnet sources through 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. Full value mining and recovery of critical metals as by-products creates a supply less at risk of bankruptcy resulting from price fluctuations, and a more resilient and sustainable supply of critical metals.
6. **Incentivise REE processing in the UK:** the UK lacks favourable geology for REE mining and must therefore ensure a reliable domestic supply by attracting projects further down the supply chain. Processing plants in the UK could attract ore from global sources and cause a shift from net consumer to processor and exporter of REEs. However, financial support and political protection is required to ensure embryonic projects can withstand price fluctuations.
7. **Develop a marine minerals strategy:** many technological innovations exist for the exploration and extraction of deep-sea deposits; however, the UK lacks the robust regulatory framework which exists in many other countries that would allow the stability and assurances to promote financial investment and commitment within the industry.

5. Conclusions

Without favourable geology within the UK to develop a primary domestic supply chain, it is important to develop innovations and initiate projects involved in the latter sections of the supply chain. This report highlights the many innovations that have recently been 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, initiation 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. However, there are many 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 enhancing resilience.

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