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Critical metal deposits in terrestrial and oceanic environments and the Global Energy Transition

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ABSTRACT

Critical metals like rare earth elements (REE), Li, Co, Cu, Ni, and platinum group elements (PGE) are vital requirements for various green technology applications. These metals are essential components in rechargeable batteries, wind turbines, solar panels, electric vehicles, and for strategic applications. This overview presents a consolidated account of the different types of critical mineral deposits on land and in the deep oceans. The terrestrial deposits include various types of magmatic, hydrothermal, and sedimentary archives, currently the major sources for these critical metals. The potential marine mineral deposits include manganese nodules on the ocean floor, ferromanganese crusts on seamounts, hydrothermal sulphide deposits in the mid-oceanic ridges, phosphorite deposits on the ocean floor along continental margins and submerged mountains, and REY-rich mud representing deep-sea sediment deposits. Currently, exploitation of marine mineral deposits faces many challenges, including pollution and habitat destruction in the marine environment, as well as climate change, which can negatively impact the environment and the resources. Adhering to marine environmental protection standards, fostering global collaboration, and prioritizing the long-term health and resilience of marine ecosystems, including coastal ecosystems, is necessary. The shift to a low-carbon economy depends on securing a stable supply of these critical metals. While terrestrial mining remains dominant, deep-sea resources must be balanced with environmental protections. Sustainable strategies, including recycling and diversification of supply chains, with emphasis on circular economy, will be the key to ensuring a smooth energy transition. Coupled with supportive policies, technological advancements, and ethical practices, these strategies forge a resilient, low-carbon, and sustainable future.

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Research Highlights

- Climate change mitigation by renewable energy technologies depends on the availability of critical metals.
- Critical metals like REE, Li, Co, Cu, Ni, and PGE are vital requirements for renewable energy technologies.
- A brief account of the different types of critical mineral deposits on land and in the deep oceans.
- Significant surge in green power, and about 40% of our current energy is coming from green technologies.

1 Introduction

The Paris Agreement envisages climate stabilization at well below 2 °C global temperature rise by substantially decreasing CO_2 emissions (Balaram, 2023a; Hansen et al., 2025). The current global challenge to reduce emissions has led to a focused attention on renewable energy technologies, and these require huge amounts of critical metals/minerals. Unfortunately, the world's mineral wealth is distributed unevenly due to geological processes, tectonic activity, and climate, leading to significant variations in the occurrences of mineral deposits across different regions of the planet (e.g., Groves et al., 2025). This heterogeneous distribution is significantly impacting global economies and geopolitical concerns. Countries like China, Australia, South Africa, the US, Russia, and Canada are, in general, mineral-rich nations (Fig. 1). Some other countries, such as India, Greenland, Chile, and the Democratic Republic of Congo (DRC) are rich in specific mineral resources. According to a recent report of the Geological Survey of Denmark and Greenland, Greenland holds significant, largely untapped, reserves of various critical minerals, including REE, Li, graphite, and other metals (https://eng.geus.dk/about/news/news-archive/2023/june/great-potential-for-critical-raw-materials-in-greenland). Due to this heterogeneous distribution of critical metal mineral resources, most other nations have to depend on these nations for the supply of critical metals to combat the present climate crisis (Groves et al., 2025).

Critical minerals/metals such as rare earth elements (REE) Li, Cu, Ni, Co, Te, Ga, Ti, and graphite are essential components of growing green energy technologies—from wind turbines, solar panels, electricity generators and electricity networks to electric vehicles (Muller et al., 2024). Any metallic or non-metallic element or mineral is called critical if it is required for modern technologies required for combating the current climate crisis, and also required in national security and the country's economy (IEA, 2023). It is often possible that its supply chains could be disrupted. There is no universally accepted definition or list of "critical" minerals, and the concept of criticality is multifaceted. It is not just about a mineral's industrial importance or economic value, but also its vulnerability and risk of supply chain disruptions. These disruptions can be caused by factors like international conflicts, market instability, political decisions, natural disasters, geological scarcity, pandemics, and even war. For example, in 2024, Australia came out with a list of 31 resource commodities to be critical metals (Britt and Czarnota, 2024). Every country, such as the United States, the European Union, India, Japan, South Korea, and the United Kingdom, has its list of critical metals or minerals. Fig. 2 presents a list of the major metals identified as critical minerals/metals in some countries. Several important metals/minerals such as REE, Li, Co, Ni, and graphite are common in the lists of most countries. There is a rapidly growing demand for these materials as the energy transition is gathering pace. Today, some countries such as China, Australia, the US, Canada, Russia, Chile, South Africa, and the Democratic Republic of Congo are in a definite advantageous position with abundant resources of critical metals. Other than REE, other critical metals like Li, Co, Cu, and Ni are important for the development of renewable technologies, particularly in areas like batteries, wind turbines, and electric vehicles (Müller et al., 2025). China, the US, and Australia are three countries that are strong economically and also in critical metals reserves and mining (Table 1). A proper understanding of various deposits of critical metals, both on land and deep sea, and their formation mechanism is important in sustainable exploration and mining, as huge concentrations of these vital elements/minerals are required for the targets of the green transition. Here we present a summary and analysis of the availability of different types of deposits of the critical metals/minerals, both on land and in deep oceans, their role in the energy transition, and the obstacles in their extraction and related environmental issues. In this context, recycling or the circular economy is also important. Recycling critical metals such as REE, Li, Co, and Cu is essential for ensuring supply security, reducing environmental impacts, and supporting the circular economy. However, this is not easy due to several logistical, technological, and economic problems, such as collecting the end-of-life products, sorting/separating mixed metals, and applying eco-friendly extraction methods (Islam and Iyer-Raniga, 2022).

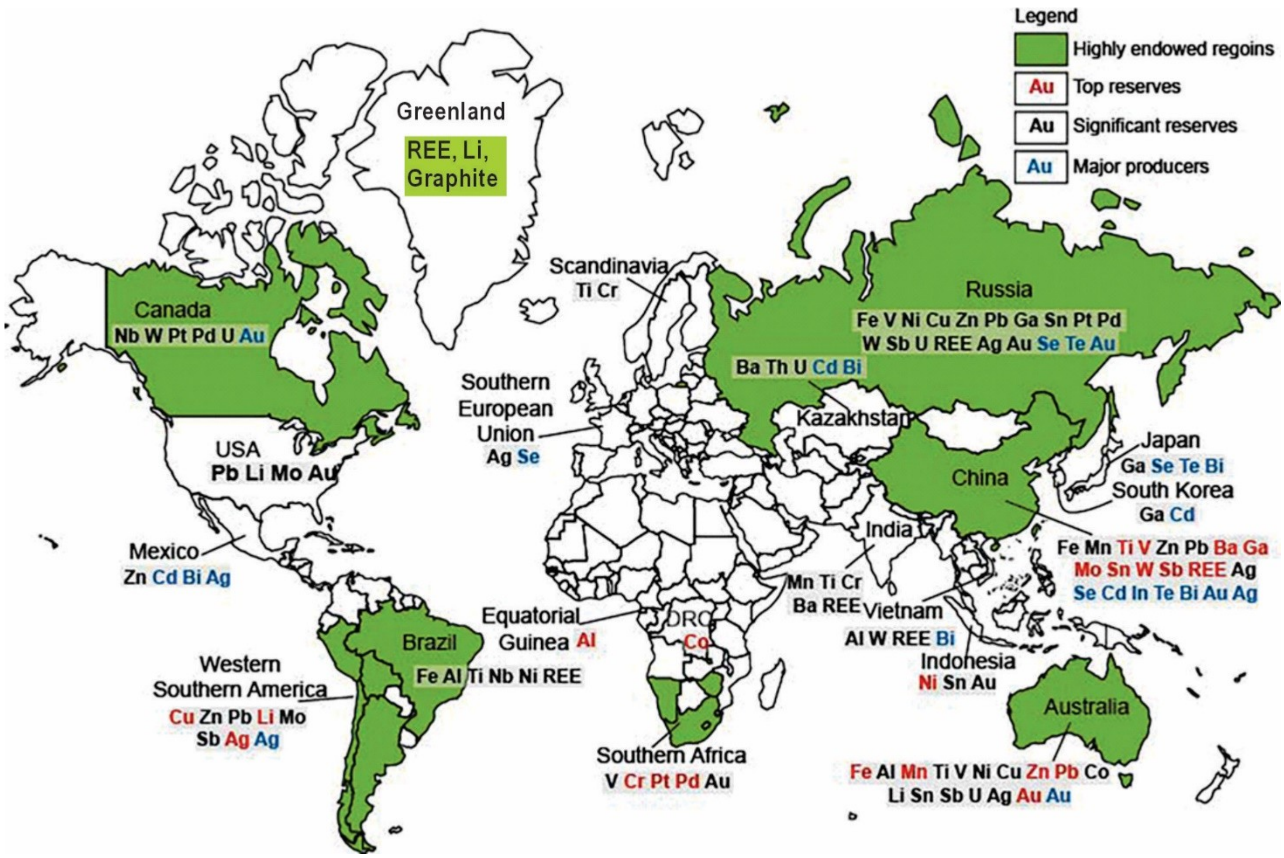

Fig. 1. Heterogeneous distribution of mineral resources in various countries of the world (modified after Groves et al., 2025). The abundance of individual deposits in each region is classified as highly endowed, top, significant, and major, and shown using different coloured fonts.

2 Securing critical metals/minerals is the key to climate action

Securing critical metals is indeed pivotal to effective climate action, as these minerals form the backbone of renewable energy technologies and low-carbon infrastructure. A lot of these critical metals, like REE, Li, and Co, are required for the development of green and renewable energy technologies to combat climate change and the required transition to net zero. For instance, producing an electric car requires six times more raw materials, including some of these critical metals, than a conventional vehicle, and an onshore wind plant demands nine times more minerals than a gas-fired power plant (Groves et al., 2025). Hence, a variety of critical metals, including Cu, Li, Co, Ni, and REE, are required in massive quantities for combating the ongoing climate crisis (Fig. 3). A successful transition to a net-zero economy requires a balanced approach that encompasses supply chain resilience, ethical practices, environmental stewardship, and innovation, as neglecting these aspects can lead to a slower, more expensive, and socially isolating transition. By integrating these elements, businesses can not only meet the environmental goals but also enhance the competitive advantage and foster a more equitable and sustainable future. Thus, strategic management of critical metals is not just an industrial concern but a cornerstone of holistic climate action and for the security of our planet.

3 Critical metal deposits in the terrestrial environment

All rocks are made of minerals, and minerals in turn are formed from elements. However, the distributions of both minerals and elements are not uniform on planet Earth, and their formation in diverse tectonic settings and different rock types in various regions is linked with the secular evolution of Earth (Santosh et al., 2024). The abundance of certain elements and minerals varies significantly among igneous, metamorphic, and sedimentary rock formations, and these rock types are all valuable targets for mining. The geological aspects of various types of critical mineral deposits are described in detail in a recent book by Müller et al. (2024).

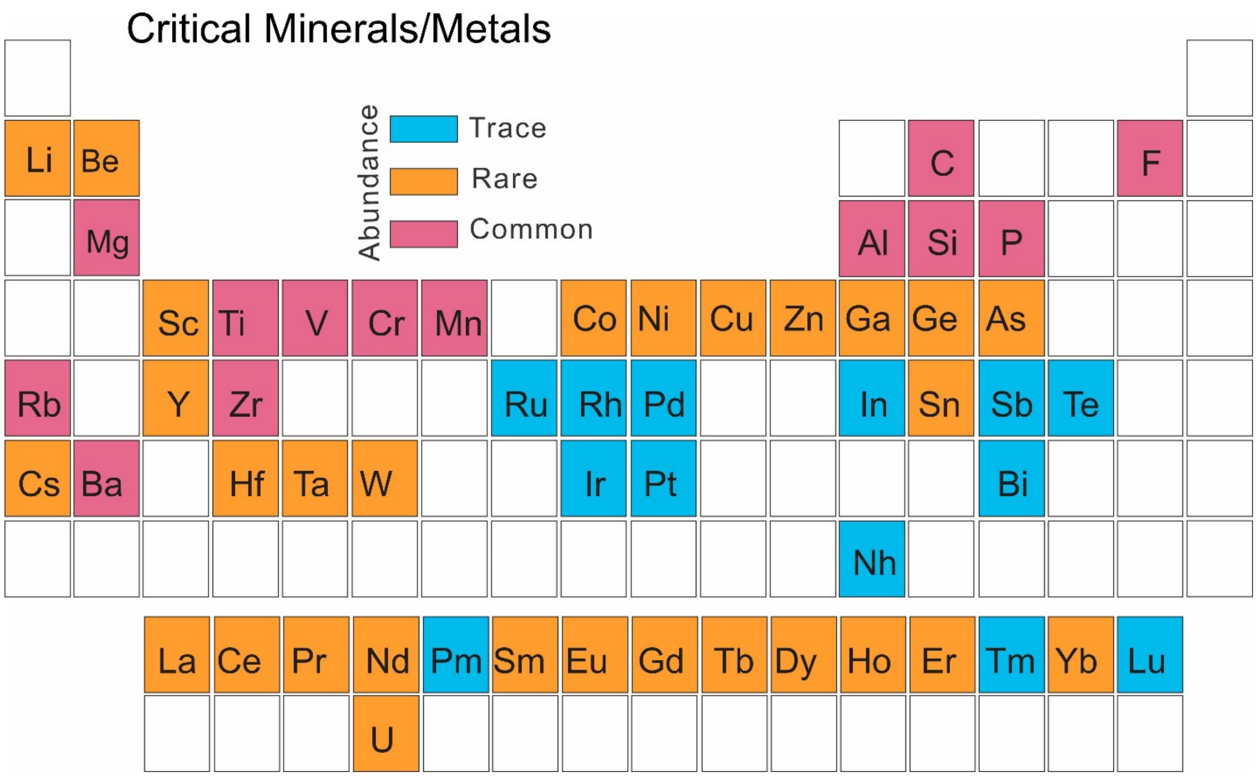

Fig. 2. Key critical metals/minerals in the periodic table that have wide application in the global energy transition.

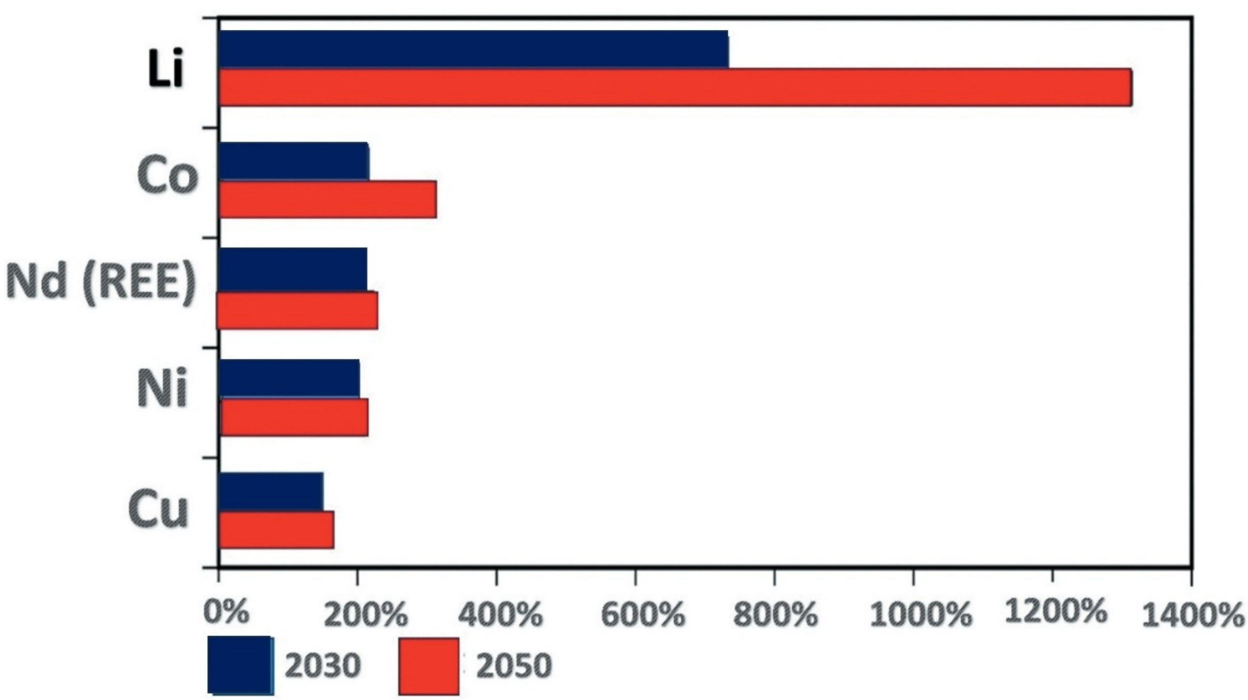

Fig. 3. The industrial demand for Li, Co, REE, Ni, and Cu is expected to increase many times compared to other critical metals in the coming decades (modified from Balaram et al., 2025).

Important critical metals	Major applications	Major producing countries	Reference
Lithium	Power sources Batteries for electric vehicles	Australia and Chile, China, the US	Balaram et al. (2025)
Cobalt	Batteries	Democratic Republic of Congo, Australia, Canada, Cuba, Russia, the US and Zambia	Rachidi et al. (2021)
Copper	Electricity transfer and storage	Chile, Australia, Peru, Russia, and Mexico	Tabelin et al. (2021)
Tellurium	Photovoltaic solar cells, thermal cooling devices, computer chips	China, the United States, Canada, and Sweden	Yin et al. (2023)
Gallium	Integrated circuits, LEDs, solar photovoltaics, and semiconductors	China, Russia, Japan, and South Korea	Long et al. (2023)
Nickel	Batteries	Australia, Indonesia, Brazil, Russia, and New Caledonia, a French colonial territory in the South Pacific	Nayak et al. (2023)
Antimony	Batteries and flame retardants	China, Tajikistan, Russia, and Turkey	Mostaghel et al. (2022)
Rare earth elements (REE) such as Nd, Dy	Renewable energy technologies such as high-performance magnets used in EV motors, wind turbines, and defence applications	China, the US, Myanmar, Australia, Russia, and India	Balaram (2022)
Platinum group elements (PGE)	Catalytic converters, fuel cells, cancer drugs, and jewellery	South Africa, Russia, Canada, Zimbabwe, and the United States	Hughes et al. (2021)
Niobium	High-T superalloys, next generation capacitors, superconducting resonators	Brazil and Canada	Barends et al. (2007)

Table 1. Critical metals, their important applications, and major producing countries.

3.1 Magmatic deposits

Magmatic metallic deposits are ore deposits formed by the cooling and crystallization of magma, resulting in the concentration of valuable metals like REE, Ni, Cu, Cr, Ta, Li, and PGE (Arndt et al., 2005). These deposits can be classified based on their composition and formation process, leading to different types of ore deposits with varying metal associations. Fig. 4 depicts an overall classification of magmatic mineral deposits. Following is a brief breakdown of the major magmatic deposit types and their associated critical metals.

3.1.1 Layered mafic-ultramafic intrusions

These are formed by fractional crystallization of basaltic magma, leading to dense metal-rich layers. The host intrusions are characterized by distinct 'layering' caused by the settling and sorting of minerals as the magma differentiates. They are some of the world's most valuable mineral deposits. Examples include the Bushveld Complex in South Africa, which is the world's largest PGE and Cr resource, and the giant Ni–Cu–PGE sulphide deposits in Norilsk-Talnakh, Russia. Land-based sulphide systems can host high potential PGE deposits with an average of 1–10 µg/g (e.g., Bushveld Complex). These deposits are characterized by magmatic sulphide ores formed from the interaction of sulphide liquids with large volumes of magma (Starostin and Sorokhtin, 2011; Thompson et al., 2025). The Precambrian Nuasahi ultramafic-mafic complex of Orissa, in India is one such important deposit (Jena et al., 2016). Understanding of these deposits is vital for securing the critical metals needed for renewable energy and advanced technologies.

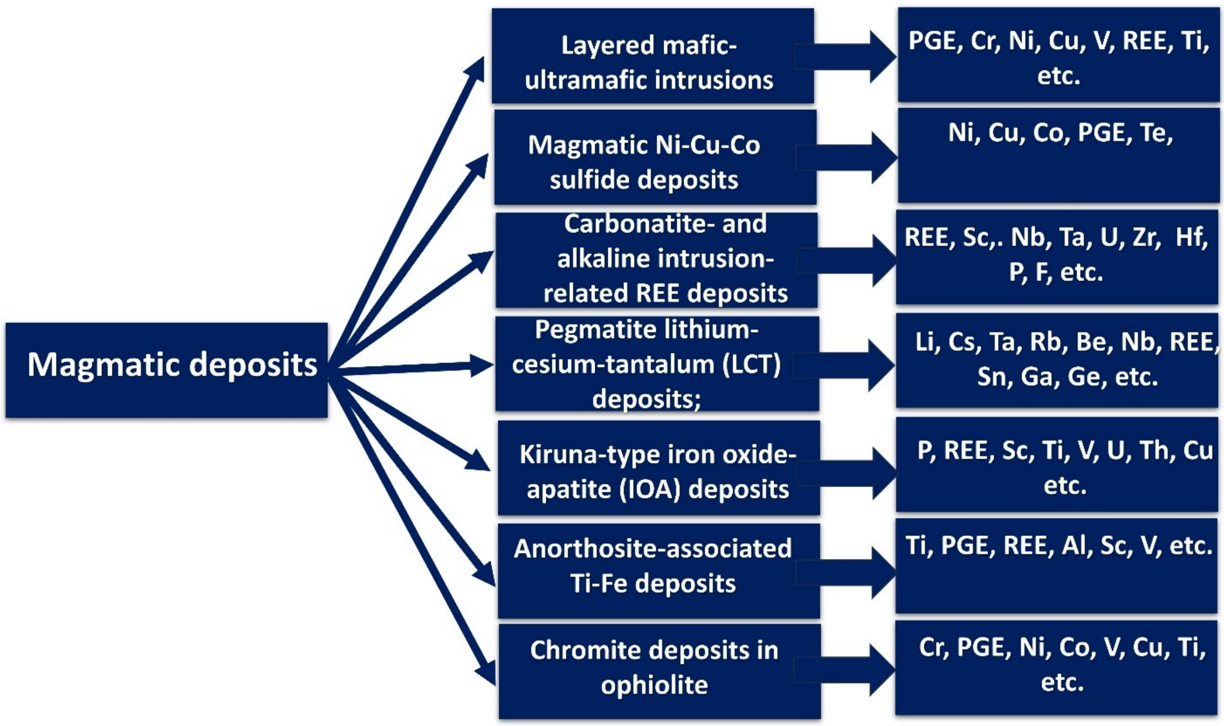

Fig. 4. Major magmatic deposits and associated key critical metals.

3.1.2 *Ni–Cu–Co sulphide deposits (magmatic sulphide deposits)*

These deposits are formed through the segregation and concentration of immiscible sulphide liquids from mafic or ultramafic magmas, where chalcophile elements like Ni, Cu, and Co are preferentially partitioned into the sulphide liquid. The Jinchuan Ni–Cu–PGE deposit in Jinchuan, China, is one of the largest Ni–Cu–PGE deposits in the world (Li et al., 2023). Other examples include meteorite-impact-induced magmatic sulphides in Sudbury Basin, Canada (Wright et al., 2010), and Komatiite-associated Ni–Cu sulfides of Kambalda, Australia (Cowden et al., 1986).

3.1.3 *Volcanic massive sulphide deposits (VMS Cu–Pb–Zn–Au systems)*

The VMS deposits are critical for base and precious metal production, forming in diverse volcanic settings through hydrothermal processes. They primarily contain Cu, Pb, Zn, and Au, with pyrite (FeS_2) as a common gangue mineral. Important examples include Iberian Pyrite Belt in in the southwestern Iberian Peninsula, spanning southern Portugal and parts of Spain (Martín-Méndez et al., 2023), world's largest VMS cluster like Neves-Corvo in south Portugal (Moura, 2005), and Kuroko VMS deposits in Japan, specifically in the northeast Honshu arc, are renowned for their rich Cu, Pb, and Zn ore, along with significant Au and Ag content (Yamada and Yoshida, 2011).

3.1.4 *Carbonatite- and alkaline intrusion-related REE deposits*

Igneous rocks, especially carbonatites and alkaline magmatic rocks, are the major sources of REE. The Bayan Obo supergiant carbonatite-related REE-Nb–Fe endogenetic deposit located at 150 km north of Baotou City in the Inner Mongolia Autonomous Region, is the largest REE resource in the world (Wang et al., 2020). Wang et al. (2024a) identified multi-stage metallogenic process in this world-class deposit involving REE-Nb mineralization during magmatic stage, with formation of Nb minerals fergusonite and ilmenorutile intergrown with REE minerals, such as monazite and bastnaesite (stages 1 and 2), followed by massive mineralization stage (stages 2 to 5). From the complex mineralogical assemblages and textural relationships, the authors constructed the history of multiple formation mechanisms to explain the large volume of REE-Nb–Fe resources in the Bayan Obo deposit and attributed to combined magma and hydrothermal fluid activities in the Mesoproterozoic (from stage 1 to stage 5), followed by reactivation of the ore materials previously deposited in the Paleozoic (stage 6). Typical mineralogical assemblages and reaction structures in each type of rocks/ores involved three types: mainly fluorinated alteration, intense fluorinated alteration and intense alkali alteration, and intense alkali alteration as well as fluorinated alteration (Fig. 5).

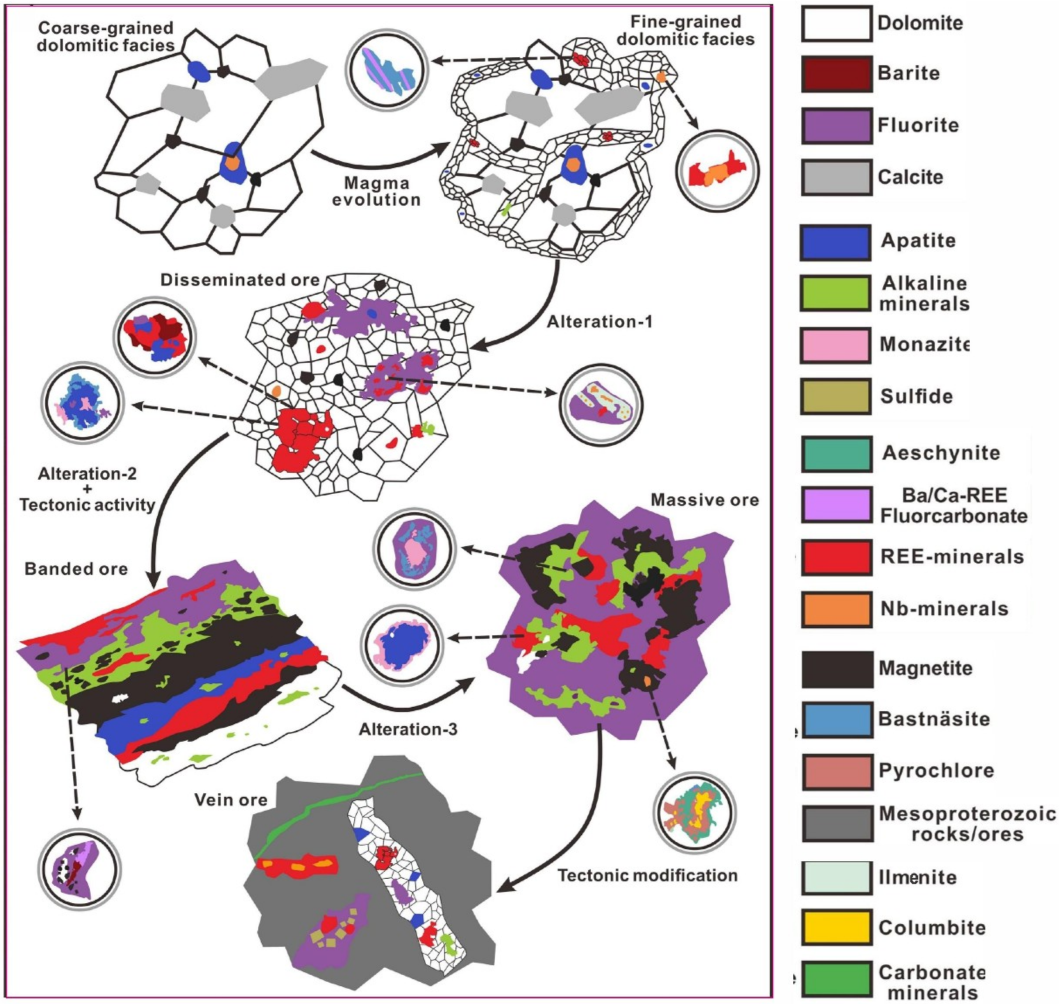

Fig. 5. Typical mineralogical assemblages and reaction structures in the different types of rocks/ores in the world-class REE deposit of Bayan Obo. Alteration-1: mainly fluorinated alteration, alkali alteration is weak; Alteration-2: Most intense fluorinated alteration and intense alkali alteration; Alteration-3: Most intense alkali alteration and intense fluorinated alteration (after Wang et al., 2024a).

The Ambadongar carbonatite complex in northwest India is a significant source of carbonatite-hosted REE deposits. It is the largest such deposit in India and belongs to the late stages of alkaline-carbonatite magmatism associated with the Deccan Traps (Viladkar, 1981; Krishnamurthy, 2023). The Kamthai carbonatite in Rajasthan, India, is a significant REE deposit that is located within the Sarnu-Dandali alkaline complex near Kamthai, Barmer district, and is part of a Tertiary nepheline syenite-phonolite complex (Bhushan, 2015). These deposits are formed through the partial melting of metasomatized mantle rocks, with REE concentrating in the resulting melts and fluids, and further enriched during fractional crystallization and hydrothermal processes. They usually occur in intracontinental rifts and large igneous provinces, where mantle plumes and magmatic activity are common. Important examples include carbonatite-associated REE deposits of the Mount Weld carbonatite in western Australia, and the Mountain Pass deposit in California in the USA (Cook et al., 2023; Gadea et al., 2024). Table 2 shows a synoptic summary of the important REE deposits in the world.

3.1.5 Pegmatite lithium-caesium-tantalum (LCT) deposits

Pegmatites are formed at the residual stage of crystallization of mineral-rich magmas (Balaram et al., 2025). The source granitic magma must be rich in lithium and also undergo extreme fractional crystallisation to form pegmatite deposits (London, 2017; Sykes et al., 2019). Lithium-cesium-tantalum pegmatites form in orogenic hinterlands as products of plate convergence. The Greenbushes pegmatite deposit in Australia, which intrudes along a major northwest regional fault zone, is one of the largest Li deposits (Partington, 1990; Balaram et al., 2024).

Country	Types of deposits	Mining and processing facilities/remarks	References
China	Bayan Obo carbonatite deposits (Inner Mongolia), the world's largest REE deposit, and ion-adsorption deposits (Southern China)	Accounts for ∼70% of global mine production ∼90% of refined REE	Fan et al. (2016)
The US	Accounts ∼15% of global REE supply	Increasing domestic refining to reduce reliance on China	Chen et al. (2024)
Myanmar	Ion adsorption deposits	Export restrictions due to political instability	Chinkaka et al. (2023)
Australia	Mount Weld (Western Australia) carbonatite-derived laterite	Lynas Rare Earth processing facility in Kalgoorlie	
Russia	Tomtor deposit (pyrochlore-monazite-crandallite variety of phosphate-rare-metal ore deposit)	Solikamsk Magnesium REE processing Plant	Malkova et al. (2020)
India	Ambadongar and Kamthai carbonatite deposits and beach sands	Beach sand processing facilities located in Kerala, Tamil Nadu, and Odisha	Anitha et al. (2020)
Malaysia	Alkaline igneous rocks, pegmatites, placer deposits: monazite and xenotime, Ion adsorption clays (IAC), and laterite deposits	Pahang REE processing operated by the Australian company Lynas	Ibad et al. (2024)
Brazil, Vietnam, Canada, and Greenland are emerging producers of REE	Brazil holds the world's third-largest rare earth reserves	Several multinational exploration companies are investing heavily in Greenland's mining infrastructure, including refineries near REE sites	Liu et al. (2023)

Table 2. Major rare earth element (REE) deposits of the world.

3.1.6 Kiruna-type iron oxide-apatite (IOA) deposits

These are important sources of iron and potentially other elements like REE and phosphorus, characterized by massive, disseminated, brecciated, and/or vein-type magnetite + apatite + diopside and/or actinolite ores. Examples include Kiruna-type iron oxide-apatite El Romeral deposit, Chile (Rojas et al., 2018).

3.1.7 Anorthosite-associated Ti–Fe deposits

These deposits are formed by the crystallization of Ti-rich magmas in layered intrusions, which are significant sources of titanium and iron, often containing ilmenite and titaniferous magnetite, and are commonly found in Proterozoic anorthosite massifs. Examples include Ga Damiao Fe–Ti–P ore deposit, North China (Chen et al., 2013), and Fe-Ti deposits in Rogaland anorthosites in South Norway (Duchesne, 1999).

3.1.8 Chromite deposits in ophiolites

These deposits have economic and strategic importance, formed through a combination of magmatic processes, including partial melting of mantle rocks, melt segregation, interaction with fluids, and the accumulation of chromite crystals. Chromite deposit in the Kudi ophiolite in the NW Tibetan Plateau (Liu et al., 2024), and ophiolitic giant chromite deposits of Kempirsai, Kazakhstan (Melcher et al., 1997). The Naga-Manipur ophiolite deposit in India, a remnant of an ancient ocean floor, contains significant chromite deposits, primarily in the form of podiform chromitite (Chaubey et al., 2024). These chromite deposits are characterized by high Cr and are linked to the supra-subduction zone setting of the ophiolite (Kingson et al., 2023).

3.2 Hydrothermal deposits

Hydrothermal deposits on land are key sources of critical metals for the energy transition. Understanding their geology helps in sustainable exploration and mining. For example, hydrothermal lithium deposits are associated with magmatic or geothermal fluid activity. Hydrothermal lithium deposits, such as pegmatites, and geothermal brines form from high-temperature fluids derived from magma or deep-crustal circulation (Hunt et al., 2025). Examples include pegmatites (spodumene) formed from late-stage magmatic fluids, and geothermal brines linked to active hydrothermal systems (e.g., Salton Sea, US). Formation of hydrothermal deposits require a heat source such as the formation of magma, geothermal gradient, or tectonic activity; fluid sources like meteoric water, seawater, or magmatic fluids dissolve metals from source rocks; pathways such as fractures, faults, and porous rocks; and chemical reactions that cause mineral precipitation (Moeck, 2014). These processes occur in various geological environments, often related to tectonic activity or volcanic activity. Thus, these deposits are major sources of critical metals like Cu, Au, Ag, Zn, Li, and REE, and remain central to securing critical mineral resources for the energy transition and advanced technologies.

3.3 Sedimentary deposits

Sedimentary deposits are an important source for critical metals. These form through the accumulation and lithification of sediments enriched in metals by geological, chemical, or biological processes. Some of the challenges of sedimentary deposits include low-grade, processing complexity, and environmental concerns. A better understanding of the metal enrichment mechanisms and identifying improved extraction methods could make these deposits even more vital for the green energy transition. Exploration for critical metals in sedimentary rocks and basins worldwide is rapidly growing as they have become potential targets (Lawley et al., 2022). Fig. 6 presents the most important sedimentary deposits and associated key critical metals. In the sections below, we summarise the different types of sedimentary deposits hosting critical metals.

3.3.1 Placer deposits

These deposits form by concentrations of heavy minerals in riverbeds, beaches, and other sedimentary environments with the help of several processes such as natural weathering, gravity, tectonic activity, climate, water, wind, and ocean action. A variety of mineral compositions are exhibited by these deposits, containing a diverse range of mineral compositions such as ilmenite, rutile, zircon, monazite, xenotime, and garnet, formed from a wide range of geological and surficial processes. Examples include REE-bearing placer deposits, including monazite [(Ce,La,Nd,Th)PO_4], xenotime (YPO_4), which are high-density minerals that accumulate with the suite of heavy minerals (Sengupta and Van Gosen, 2016). Southern India has significant placer deposits of REE, primarily in the form of monazite, a mineral containing thorium, REE, and a small amount of uranium. These deposits are mainly found in coastal beach sands along the coasts of Kerala, Tamil Nadu, Andhra Pradesh, and Odisha (Rao and Mishra, 2025). Placer deposits in coastal areas between Neendakara and Kayamkulam, in Kerala, and the Manavalakurichi beach placer deposit in Kanyakumari district, Tamil Nadu, are major examples of these deposits (Anitha et al., 2020; Natarajan et al., 2023).

3.3.2 Banded iron formations (BIFs)

These were formed in seawater when oxygen was abundantly available, which precipitated the dissolved iron by a process known as oxidation, forming a thin layer on the ocean floor (Bekker et al., 2010). These sedimentary formations of iron deposits are associated with significant concentrations of Co, Ni, and REE (Santoro et al., 2022). Hamersley basin in Australia, Kryvyi Rih in Ukraine, and the Mesabi iron range in the USA are important examples of banded iron formations (Hagemann et al., 2016).

3.3.3 Phosphorite deposits

Phosphorite is a non-detrital sedimentary rock containing 18 wt% or more P_2O_5, which is also a potential economic source of REE. They are formed through a combination of geological, chemical, and biological processes, mostly in continental shelf areas which are rich in phosphate minerals, primarily apatite (Dar et al., 2025). Permian phosphoria formation in the western US, the Moroccan sedimentary phosphate basins, and offshore deposits along the Peru-Chile shelf are some important examples (McArthur, 1983; Hiatt and Budd, 2001; Bamiki et al., 2020). The Namibian shelf has significant phosphorite deposits, primarily located on the middle to outer shelf, between 180- and 500-meter water depth. These deposits are characterized by pelleted phosphorite sand and concretionary pebbles, rich in carbonate fluorapatite (francolite) (Compton and Bergh, 2016).

3.3.4 Black shales and organic-rich mud rocks

These sedimentary deposits are formed when anoxic conditions prevail in marine environments where organic matter traps metals. These deposits are rich in Cu, Ag, V, Mo, Ni, Zn, U, and REE. The Kupferschiefer deposits in

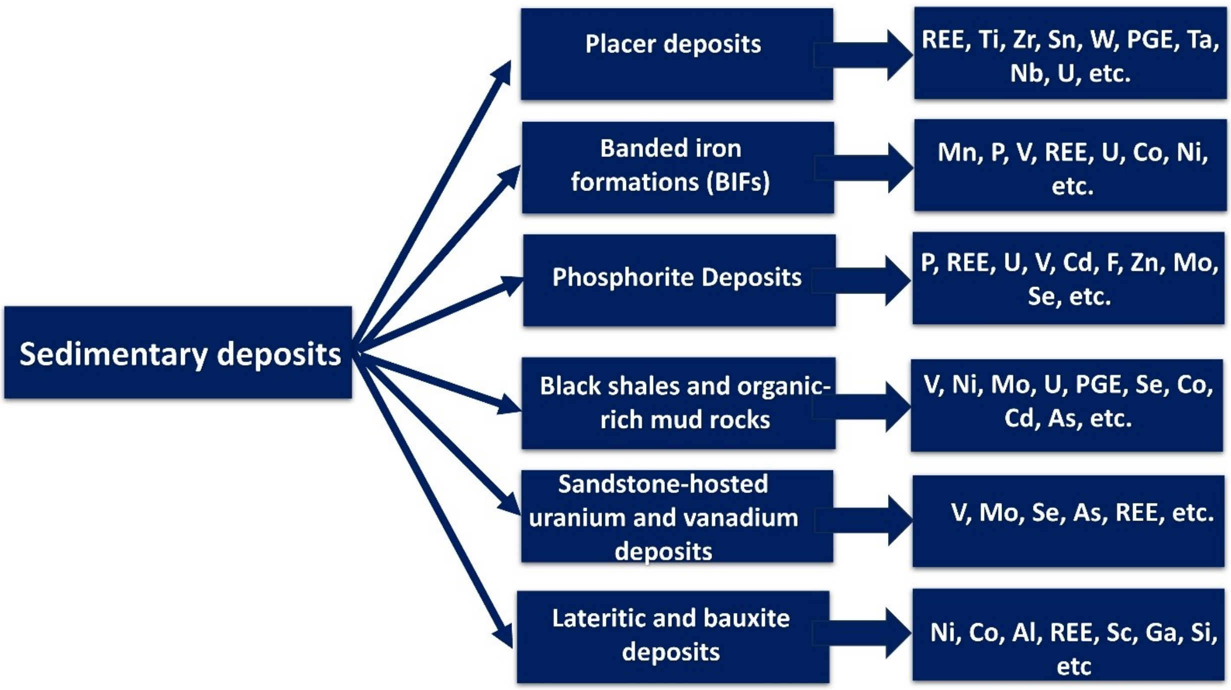

Fig. 6. Major sedimentary deposits and associated key critical metals.

Poland and Kazakhstan are very important in this category (Oszczepalski et al., 2019; Slack et al., 2022). Vanadium, used for the production of steel alloys, for glass coating, and as a catalyst, is present in considerable concentrations in black shales. Graphite can occur in black shale deposits, especially as a result of the transformation of organic matter under high temperature and pressure (Parviainen and Ruskeeniemi, 2019). Graphite is a form of carbon, and geological deposits can be classified as one of three types (amorphous, flake, and vein). Flake graphite is the main graphite type that is used as a battery raw material (Lusty and Goodenough, 2022). Arunachal Pradesh and Jammu and Kashmir (37%) hold the largest graphite deposits in India (Misra et al., 2017). Black shales may contain 50 to 250 µg/g uranium. Phosphorite deposits can also contain uranium oxides within apatite and fluorite minerals. Very high concentrations of vanadium ranging from 250 to 2300 µg/g were reported in Silurian black shales, Italy in addition to anomalous concentrations Ba, Sb, As, Se, Mo, and U (Boni et al., 2025).

3.3.5 Sandstone-hosted uranium and vanadium deposits

When oxidized groundwater transports metals, such as uranium and vanadium, which are precipitated under reducing conditions, often triggered by organic matter, sulphides, or hydrocarbons within the sandstone (Radwany and Barton, 2022). The role of organic matter in uranium mineralisation in Vempalle sedimentary dolostone in Cuddapah basin, India, was discussed by Goswami et al. (2017). Other important examples include the Bigrlyi tabular sandstone-hosted uranium–vanadium deposit in Central Australia and the sandstone-hosted uranium deposit in Colorado, USA (Schmid et al., 2020; Hall et al., 2023).

3.3.6 Lateritic and bauxite deposits

Lateritic and bauxite deposits form through intense, prolonged chemical weathering of a large variety of sedimentary, metamorphic, and igneous rocks in tropical and humid regions with high rainfall and temperature, resulting in the enrichment of iron (in laterites) and aluminium (in bauxites). Aluminium-rich bauxite deposits of Guinea, Australia, Brazil, and India, and nickel and cobalt-rich laterite deposits of Indonesia and the Philippines are well-known examples (Deb and Joshi, 1984; Ball and Gilkes, 1987; Sanoh et al., 2022; Barrientos, 2024; Soh Tamehe et al., 2024). Laterite deposits, which are intensely weathered bedrocks in tropical to sub-tropical climates, can contain significant concentrations of REE and Li. Lithium is mobile during weathering and can be incorporated into secondary minerals, such as clays, within the laterite profile (Balaram et al., 2025). REE get enriched in ion adsorption deposits primarily through the weathering of parent rocks, typically granites, and subsequent adsorption of REE ions onto clay mineral surfaces (Estrade et al., 2019). One particular type, ion-adsorption clays, which are formed by the intense weathering of granitic rocks, are massively mined in southern China as the world's main source of heavy REE. These elements are adsorbed onto the surface of kaolinite, halloysite, or illite. Sediment-host deposits of base metals such as lead, zinc, and copper are well known, Examples include sedimentary exhalative (SEDEX) deposits, Mississippi Valley-type (MVT) deposits, and sediment-hosted copper deposits (Zhu et al., 2024).

3.3.7 Sedimentary-evaporite deposits

Evaporite deposits such as bedded halite, sylvite, gypsum, anhydrite, and various potash salts form by the evaporation of saline lakes and thus concentrate dissolved metals by precipitation of solid mineral crystals from a concentrated solution brine. Evaporite deposits may be either marine or nonmarine (lacustrine) in origin. Lithium brine deposits are formed over millions of years through a complex combination of geological and hydrological processes involving evaporation, mixing, halite and hectorite dissolution, and precipitation (Warren, 2010; Rossi et al., 2022; Balaram et al., 2025). Lithium brine deposits are sedimentary-evaporite systems, whereas hydrothermal lithium deposits are associated with magmatic or geothermal fluid activity. Lithium is leached from volcanic rocks such as rhyolites and tuffs by weathering and transported by surface/subsurface water into closed basins where lithium gets concentrated by evaporation. Brines dominate global lithium production ($\sim$60%) due to their lower extraction costs compared to hard-rock mining. Formation waters in oil fields are often brine with high concentrations of dissolved salts and thus contain various minerals (Kumar et al., 2019; Balaram et al., 2025).

3.4 Residual deposits

Residual deposits are formed through intense in-situ chemical weathering processes that leach away soluble minerals/elements like silica, alkali, and alkaline earth metals are leached, leaving behind enriched residues of less soluble oxides/hydroxides (e.g., iron, aluminium) or adsorbed ions (e.g., REE on clays) like lateritic nickel-cobalt deposits, bauxite deposits, ion adsorption REE clay deposits. Ion adsorption-type REE deposits are a major source of HREE and Y (Borst et al., 2020). These deposits are significant sources of critical metals, which are vital for technology, energy transition, and national security.

4 Challenges in the exploration and mining of land resources

Exploration and mining of land resources face a range of technical, environmental, social, economic, regulatory, and legal challenges. These challenges often vary depending on the type of deposit, location, and scale of operations. Extraction and the use of land mineral resources face numerous challenges, including depletion of finite resources, environmental degradation, and social and economic impacts (Worlanyo and Jiangfeng, 2021). These challenges are further aggravated by unsustainable mining practices, growing global demand, and the need for responsible resource management. For example, there has been a constant decline in the ore grade ore grades, and now porphyry Cu deposits are mined at <0.5% Cu grade (Wood and van As, 2024). Currently, the exploration and mining activities are shifting more towards new deposits in underexplored regions like Central Asia, Africa, and South America.

Exploring critical mineral deposits for green technology applications requires a multifaceted approach that integrates geological, technological, environmental, and socioeconomic strategies. Geological studies include identifying regions of potential deposits using historical data as well as advanced mapping techniques (Tshanga et al., 2024). Geophysical techniques such as magnetic, gravitational, and seismic surveys are helpful to detect subsurface mineral anomalies (Kwan and Reford, 2025). Advanced geochemical techniques such as high resolution inductively coupled mass spectrometer (HR-ICP-MS) with both solution analysis as well as direct solid analysis using laser ablation accessory (LA) for elemental/isotope analysis as well as hand-held analytical instruments such as portable X-ray fluorescence spectrometer, (pXRF), laser ionisation break-down spectroscopy (LIBS) will be highly useful in the analysis of soil, water, and rock samples (McClenaghan, 2005; Sader and Ryan, 2019; Gong and Lu, 2024). For mineral analysis, both portable and laboratory X-ray diffraction spectrometers (XRD) and Raman spectrometer studies will be of immense help (Paulen and McClenaghan, 2024). Satellite and drone-based hyperspectral analysis offers a promising approach for mapping and detecting REE deposits in inaccessible areas, and these technologies can cover larger areas in a limited time (Balaram, 2022; Asadzadeh et al., 2024). Advanced data Integration and analysis methods, including artificial intelligence (AI) and machine learning (ML), are being used currently to analyse geological data and identify exploration targets (Zhang et al., 2022; Zhao et al., 2024).

5 Environmental issues

Land mining, while essential for extracting critical metals and resources, poses significant environmental challenges. These impacts vary depending on the mining method (e.g., open-pit, underground, placer) and the type of resource extracted. Current mining practices pose significant environmental challenges, including deforestation, water pollution, air pollution, soil contamination, acid mine drainage, toxic tailings, and biodiversity loss, which can have long-lasting impacts on ecosystems and human health (Dehkordi et al., 2024). Land mining is indispens-

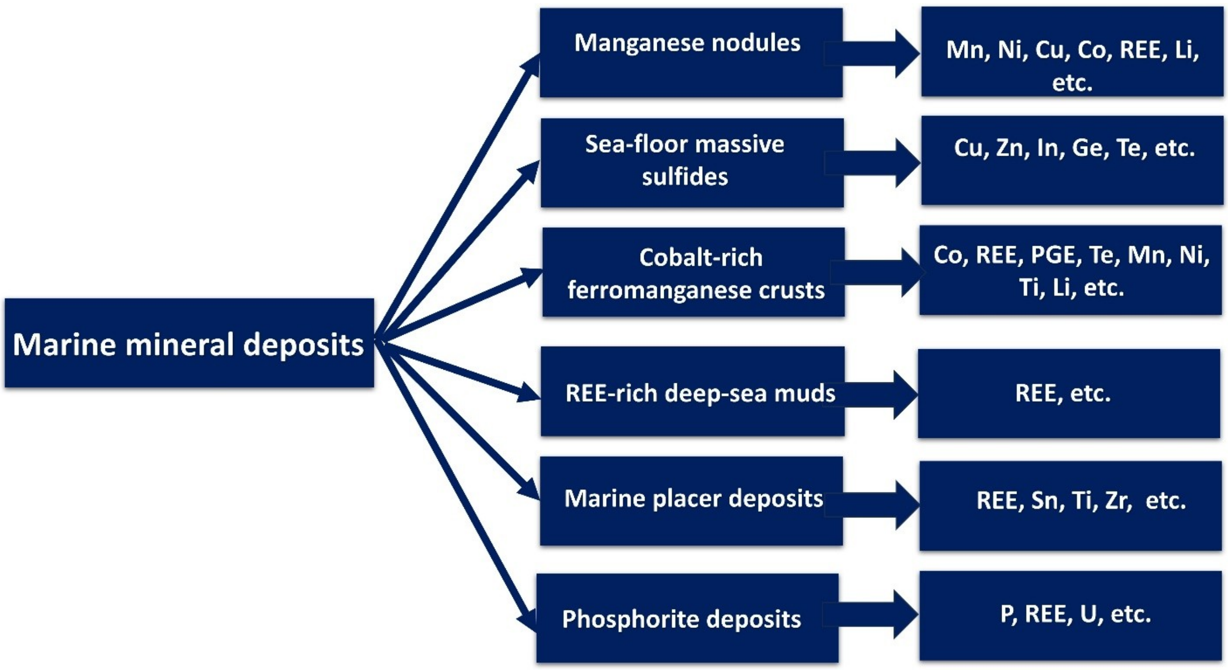

Fig. 7. Major marine mineral deposits and associated key critical metals.

able for the transition to carbon neutrality, but its environmental costs are profound. Balancing resource extraction with ecological preservation requires innovation, stringent regulation, and global cooperation to minimize harm and promote sustainable practices.

6 Potential future alternate sources for critical metals

Recent studies revealed that coal and coal by-products are potential resources for REE and Li (Reedy et al., 2024), Several studies demonstrated the potential of phosphorite deposits worldwide to meet a growing demand for REE, particularly, that of HREE (Buccione et al., 2021; Dar et al., 2025). Malaysia has potential shale/coal deposits, with some focus on river, lake sediments, and marine sediments (Ibad et al., 2024). Red mud, a by-product of the Bayer process used to extract alumina from bauxite, has significant potential as a source of REE (Vind et al., 2018). While REE are already concentrated in red mud during the alumina extraction, further processing techniques like oxalic acid leaching can selectively extract and enrich them. This process, followed by mineral acid extraction, offers a promising pathway for recovering REE from this industrial waste (Li et al., 2022).

7 Critical metals in oceanic environments

In addition to land resources, there is a vast reserve of REE and other critical metal resources in deep-sea sediments. Due to depleting terrestrial deposits and rising demand for critical metals, currently, the ocean resources have come to focus. The vast seabed in the oceans across the planet holds huge resource potential that can provide essential materials for future green technology applications for centuries (Toro et al., 2020). Marine sediments especially the manganese nodules, ferromanganese crusts, hydrothermal sulphide deposits near mid oceanic ridges, hold enormous potential for many critical metals such as REE, Co, Ni, Cu, Mn, Li, and platinum group elements (PGE) (Hein et al., 2013; Lusty et al., 2018; Balaram, 2023b; Balaram et al., 2025). Fig. 7 summarises the most important marine mineral deposits and associated key critical metals. The following provides more details on the critical metal potential of individual important marine mineral deposits.

7.1 Manganese nodules

These are also known as polymetallic nodules, found on the seabed mostly at depths of 3,000 to 6,000 metres, which contain spherical precipitates of manganese, iron oxides, and other metals. In general, the metal ions and complexes in seawater are sorbed onto the two major host phases, FeO(OH) with a positively charged surface and MnO_2 with a negatively charged surface (Hein et al., 2013). These nodules contain significant concentrations of critical metals such as Mn, Cu, Co, Ni, Li, and REE. The Clarion-Clipperton Zone (CCZ) between Hawaii and Mexico in the Pacific Ocean alone holds an estimated 21 billion dry tons of manganese nodules (Li et al., 2021). The other potential areas include the Penrhyn Basin-Cook Islands exclusive economic zone (EEZ), and the Central Indian Ocean Basin. The metals in nodules have two sources of supply: bottom seawater (hydrogenous) and sediment pore water (diagenetic). The abundance of manganese nodules at the bottom of the Pacific Ocean is mostly between 5–30 kg/m^2 (Wang et al., 2024b). Manganese nodules abundance, particularly in the Clarion-Clipperton Zone (CCZ) in the Pacific Ocean, is 15 kg/m^2 (Petterson and Tawake, 2019). The Indian Ocean has an average abundance of 5–15 kg/m^2, the Atlantic Ocean has an average abundance of 1–5 kg/m^2 (sporadic distribution), and the Southern Ocean (Antarctic) shows the lowest abundance of <1 kg/m^2 (rare occurrences) (Petterson and Tawake, 2019; Wang et al., 2024b). Fig. 8 presents the abundances of manganese nodules at the bottom of different oceans. The factors that influence the abundance are sedimentation rate, bottom currents, oxygen supply, water depth, and biological activity, as microbial processes contribute to metal precipitation. Most important is the tectonic activity, which can influence ocean currents and sedimentation patterns, indirectly affecting nodule growth and incorporation of the metals (Heye et al., 1979).

7.2 Ferromanganese crusts

Deep-sea ferromanganese (Fe–Mn) crusts, which are also referred to as cobalt-rich crusts, are a significant potential source of critical metals, including Co, Ni, Pt, REE, and several other economically important minerals (Balaram et al., 2012; Yang et al., 2024). These crusts are found on seamounts, ridges, and oceanic plateaus. The enrichment of critical metals in Fe–Mn crusts is primarily controlled by slow hydrogenous precipitation from seawater, low sedimentation, and optimal oceanographic conditions at depths of 800–2,500 meters. The strong scavenging ability of Mn and Fe oxides, combined with stable geological settings, allows these crusts to accumulate economically valuable metals over millions of years. While most ferromanganese crusts are hydrogenous, some areas near hydrothermal vents show significant enrichment of metals like Cu and Zn, suggesting a mixed hydrothermal and hydrogenous origin for these crusts (Staszak et al., 2022; Balaram, 2023b). Cobalt-rich crusts in the Pacific Prime Crust Zone and the Canary Islands Seamounts and the Rio Grande Rise in the Atlantic Ocean, and seamounts of Afanasy Niktin in the Indian Ocean (Balaram et al., 2012) are some important examples.

7.3 Hydrothermal sulphide deposits

Seafloor massive sulphides generally contain low concentrations of PGE but can reach levels of economic interest in exceptional cases. These deposits are known for Cu–Zn sulphides with minor PGE enrichment (Paropkari et al., 2010). Hydrothermal sulphide deposits also contain significant concentrations of platinum group elements (PGE: Pt, Pd, Rh, Ru, Ir, Os), though their enrichment varies depending on geological and hydrothermal conditions. For example, ultramafic-hosted systems, ophiolites, have significant amounts of PGE. Oman ophiolitic complexes contain high concentrations of Cu, Ni, and significant concentrations of PGE (Wilde et al., 2002). PGE-bearing sulphides in submarine hydrothermal systems can concentrate them (Lorand and Juteau, 2000). Seafloor massive sulphide deposits in the EEZs of Papua New Guinea, Japan, and New Zealand, as well as the Mid-Atlantic Ridge and the three Indian Ocean spreading ridges, are potential targets.

7.4 Marine evaporite deposits

These sedimentary mineral deposits are formed when seawater evaporates, when the rate of evaporation exceeds the rate of water input into a body of water in closed areas, leading to the concentration and precipitation of dissolved salts in restricted basins or coastal areas. Halite (NaCl), gypsum ($CaSO_4 \cdot 2H_2O$), anhydrite ($CaSO_4$), and various potassium and magnesium salts are some important examples (Chen et al., 2019). Large evaporite deposits are formed in the Dead Sea due to its arid climate and high salinity, resulting in the precipitation of minerals like halite, gypsum, and anhydrite (Garber et al., 1987).

7.5 Phosphorites

Deep-sea phosphorite deposits may become viable as terrestrial reserves deplete. These marine phosphorite deposits are sedimentary accumulations of phosphate minerals, primarily composed of apatite ($Ca_5(PO_4)_3(OH,F,Cl)$) (Bamiki et al., 2021; Ahmed et al., 2022). Marine phosphorites are known to concentrate REE and Y during the early diagenetic process during their formation. Hein et al. (2016) reported REE up to 161 µg/g in continental-margin phosphorites and REE 727 µg/g in seamount phosphorites. Seamount phosphorites have 4–6 times higher individual REE contents with extremely high concentrations of HREE. These deposits are a key source of phosphorus, which is essential for agriculture (fertilizers), industry, and chemicals. These deposits are of biogenic origin and primarily formed from the remains of marine organisms, especially plankton, as their exoskeletons decay and sink to the seafloor, and also by bacterial activity in oxygen-minimum zones (OMZs), which releases phosphate into pore waters, leading to precipitation (Klar et al., 2018). Marine phosphorite deposits are found in continental margins, seamounts, and oceanic plateaus, particularly in regions with high biological productivity, upwelling currents, and low-oxygen conditions. Morocco phosphorite deposit and phosphorite deposits of the Peru-Chile Margin are among the world's largest deposits (Burnett, 1974). Other potential

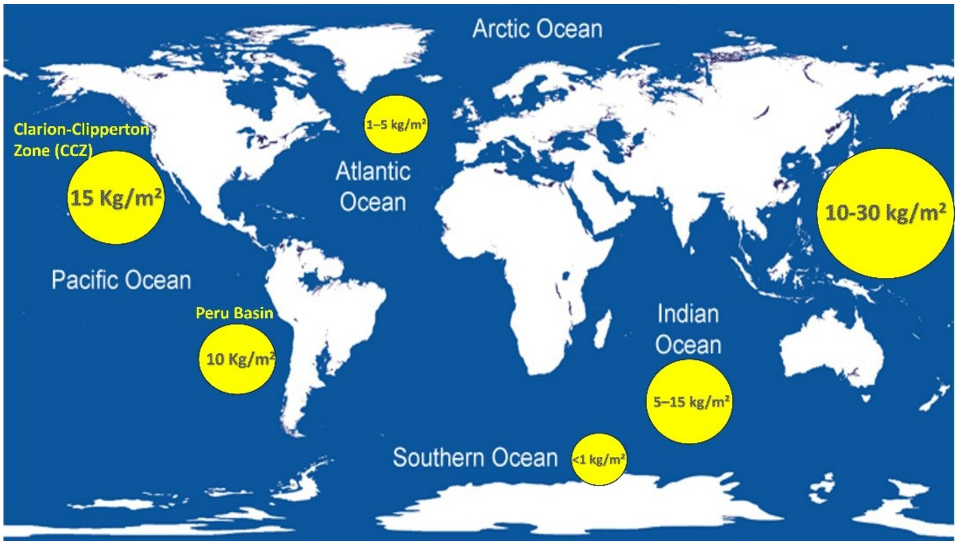

Fig. 8. The abundance of manganese nodules at the bottom of oceans (after Petterson and Tawake, 2019; ISA, 2024; Wang et al., 2024b). Areas of the circles are not to scale.

zones for marine phosphorites are in Chatham Rise, offshore Baja California, and on the shelf off Namibia (Sakellariadou et al., 2022). Continental, seamount phosphorite deposits worldwide are very good resources of REE, with reported concentrations of ΣREE up to 18,000 µg/g (Dar et al., 2025). Several studies demonstrated the potential of phosphorite deposits worldwide to meet a growing demand for REE and, more importantly, that of HREE (Emsbo et al., 2015).

7.6 Marine mud

The deep-sea muds around Minamitorishima Island in the equatorial North Pacific near Japan were found to contain concentrations of REE up to 5000 µg/g. In the North Atlantic Ocean, REY concentrations are highest in slowly accumulating pelagic red clays, especially in samples that contain ferromanganese micronodules. In situ analysis of individual micronodules showed high ΣREY concentrations up to 3620 µg/g (Menendez et al., 2017).

8 Challenges in the exploration and mining of marine resources

Deep-sea mineral resources represent a promising but controversial source of critical metals. While they could reduce reliance on terrestrial mining, environmental concerns and regulatory challenges must be addressed before large-scale exploitation becomes viable. There are challenges to marine resource exploitation, which include marine pollution, habitat destruction in the marine environment, and climate change (Kvamsdal et al., 2023). These challenges threaten the health of marine ecosystems and the long-term availability of resources. Environmental risks of deep-sea ecosystems are poorly understood. Mining could destroy fragile habitats as activities like dredging, mining, and extraction of metals can destroy critical habitats like coral reefs and mangroves, impacting millions of marine species and the overall health of the ocean (Niner et al., 2018). Specifically, sediment plumes from mining operations can smother marine life, and noise pollution from mining equipment and vessels can affect vulnerable species like whales (Christiansen et al., 2020). The International Seabed Authority (ISA) is actively framing rules and regulations to address the challenges posed by the ocean's vastness, complexity, and the lack of international cooperation, legal, and regulatory clarity in areas beyond national jurisdiction. The ISA's mandate includes authorizing and controlling mineral-related activities in the Area, while also protecting the marine environment from harm (ISA, 2024). This includes regulating deep-sea mining and exploration to protect the marine environment while balancing the potential benefits of resource extraction. Currently, new and eco-friendly technologies involving smart robotic systems and advanced AI-based monitoring tools are being developed to offer opportunities for marine resource exploitation with minimum damage to the marine ecosystem (Khaskheli et al., 2023; Aguzzi et al., 2024). These advances in deep-sea mining technologies and stronger environmental safeguards will determine their future role in their global supply chain for green technology applications.

9 Global political, environmental, and social issues

The global transition to clean energy and advanced technologies have intensified competition for critical minerals like Li, Co, REE, Ni, and Cu. The demand for these elements is expected grow manyfold (Fig. 3). Though mining is crucial for the economy of several countries, significant environmental and social challenges, including pollution, illegal mining, deforestation, community displacement, and health hazards, require sustainable practices, international labour standards, and responsible management, need to be addressed (Hilson, 2009; O'Driscoll, 2017). Geopolitical dynamics are a major source of risk to the supply of critical metals. If very few countries dominate the production of a particular critical metal or mineral, meaning they can control large parts of the supply, causing a significant dependency on only a few producing countries. For example, in the cases of Li, Co and REE, the world's top three producers, namely China, Australia, and Chile, control well over three-quarters of global output. China controls ∼60% of global REE mining and ∼85% of processing (https://www.mining-technology.com/analyst-comment/china-global-rare-earth-production/). China restricted REE exports to Japan during a territorial dispute in 2010, causing price spikes. Currently, the US, EU, and Japan rely heavily on Chinese REE for defence and green technology needs. The Democratic Republic of Congo (DRC) supplies ∼70% of the world's cobalt. However, cobalt extraction also faces significant challenges related to the use of child labour in artisanal and small-scale mining (Nkulu et al., 2018). On the other hand, the 'Lithium Triangle' (Chile, Argentina, Bolivia) holds ∼55% of global lithium reserves (Balaram et al., 2024). This high geographical concentration can hamper the mineral production stream (Birol, 2022). Amid the ongoing trade war between the US and the rest of the countries, China imposed export restrictions on critical metals like REE, which are very important for the manufacturing of a range of gadgets like super magnets required for green technology applications. The requirement of critical metals for renewable energy technologies is much more than that of conventional fossil fuel technologies, such as coal-powered thermal stations and petrol/diesel-driven cars. Thus, the geopolitics of critical minerals is shaping energy security, military power, and economic competitiveness of individual countries. The International Energy Agency (IEA) made six key recommendations to ensure mineral security. These recommendations include: (i) accelerating the diversification of mineral supplies; (ii) maximizing the potential of technology and recycling; (iii) promoting transparency in mineral markets; (iv) enhancing the availability of reliable information; (v) creating incentives for sustainable and responsible production; and (vi) fostering international collaborations (IEA, 2023).

Mining activities pose significant global environmental issues, including habitat destruction, water and air pollution, climate change, and loss of biodiversity (Worlanyo and Jiangfeng, 2021; Arendt et al., 2022). Surour et al. (2024) emphasised the need for sustainable mining practices and environmental management to mitigate the random impacts of artisanal mining for gold, as such practices involve the use of toxic chemicals like cyanide and mercury, which pose severe environmental hazards. Greenland has become a new geopolitical battleground because of its vast critical mineral resources beneath its ice and its potential to offer climate solutions.

Mining necessitates the destruction of habitats such as forests and causes pollution of surrounding water sources. On the other hand, the extraction and refining processes will also have significant negative environmental impacts, leading to human health problems.

The International Seabed Authority (ISA), an autonomous organization created by the United Nations Convention on the Law of the Sea (UNCLOS) and is responsible for the mineral exploitation and environmental protection of the seabed. The ISA that regulates seabed mining in international waters is being adopted by 167 countries for the extraction of highly coveted seabed minerals that lie outside of national marine borders. Kiribati, a Pacific nation is planning to mine the seafloor deposits of Co, Ni, and Cu in collaboration with China. Other Pacific nations, Cook Islands and Nauru also trying to push mining at the depths of the ocean. Kiribati holds rights for deep-sea mining exploration across a 75,000-square-kilometre Clarion Clipperton Zone in the Pacific Ocean with Canada-based Metals Company to mine the ocean floor for polymetallic rocks, or nodules, that contain significant concentrations of Mn, Co, Cu, and Ni. But neighbours Palau, Fiji, and Samoa are strongly opposing due to marine ecological issues (Petterson and Tawake, 2019). Deep-sea and seabed mining will have a considerable impact on fishing and other sources of livelihoods. Last year, Norway temporarily halted the licensing process to permit Arctic seabed mining for critical metals. However, the government maintains that progress will resume soon, with a licensing round tentatively set for 2026. The President of the United States has signed a controversial executive order aimed at stepping up deep-sea mining within the US and in international waters by Metals Company. This move of allowing exploration outside its national waters has been met by condemnation from China, saying that it is a clear-cut violation of international law (https://www.bbc.com/news/articles/cx2v37z333lo). These are some important developments in the area of deep-sea mining in recent times. We need to wait and see what holds for the deep-sea mining in the future.

10 The mining potential of exclusive economic zones (EEZs) of coastal countries

The exclusive economic zone (EEZ) of a country, extending up to 370 km from its coastline, holds significant potential for mineral resources, such as manganese nodules, ferromanganese, hydrothermal sulphide deposits, and phosphorites, in addition to oil, gas, and gas hydrate deposits. Mining in EEZ does not require permission from the International Seabed Authority (ISA), as coastal states have the sovereign right to explore, exploit, conserve, and manage the natural resources within their EEZ and must not cause harm to the marine environment (https://deepseamining.ac/article/12#gsc.tab=0). In 2024, both Norway and Japan started mining operations in their respective EEZs. The Cook Islands in the South Pacific want to initiate mining within their EEZ, which holds abundant resources of seabed manganese nodules (Petterson and Tawake, 2019). The challenges in EEZ mining include environmental concerns as the deep-sea ecosystem gets disturbed, and high cost and technological barriers for some countries.

11 Land-based critical mineral deposits vs. marine resources

Marine sediment mineral resources have relatively low ΣREE contents, compared to the large terrestrial LREE-rich carbonatite-hosted, but show characteristics that are consistent with those of terrestrial HREE-rich ion-adsorption clay deposits (Pak et al., 2019). But a careful examination of the data on the Clarion Clipperton Zone (CCZ), shows that it is a vast abyssal plain in the central Pacific Ocean, located between Hawaii and Mexico, which is known for its abundant polymetallic nodules rich in valuable minerals (Fig. 9). This area of 4.5 million square kilometres of sea floor makes up about 1.25%, which is relatively a small fraction of the world's total ocean floor of 335 million square kilometres (Hein et al., 2013). Table 3 presents a comparison of land and ocean resources for some important critical metals (in million tons). These calculations illustrate that depicts huge potential of marine deposits compared to the land resources. However, land mining is more established but faces sustainability and depletion issues. Marine mining offers greater potential but comes with higher marine ecological risks and costs. A balanced approach for the improvement of land mining sustainability is required while carefully regulating deep-sea mining. The deep-sea resources have relatively low ΣREE contents, which are characteristically similar to the land-based ion adsorption REE deposits where REE do not sit in the crystal lattice and there is no requirement for crushing and/or pulverizing during ore processing. In addition, very low concentrations of Th and U reduce the risk of adverse environmental impacts (Pak et al., 2019). Concerning lithium, while terrestrial sedimentary deposits showed a high value of lithium up to 7250 µg/g, the marine sedimentary deposits recorded a high of 781 µg/g (Balaram et al., 2025). The extraction technologies for the valuable metals from sources such as manganese nodules, ferromanganese crusts, and phosphorite deposits usually involve the application of pyrometallurgical and hydrometallurgical methods. For eco-friendly requirements, and improve utilization efficiency, methods such as bioleaching, are gaining increasing attention (Wang et al., 2024b). However, some believe that depletion of land resources must not be an excuse to mine the ocean floor. The mining industry must increase mineral production on land to save global biodiversity (Tunnicliffe et al., 2025). While marine mining offers vast untapped mineral resources, its high costs and uncertainties make terrestrial mining more economically feasible for now. However, as demand grows and land-based reserves deplete and become low-grade, deep-sea mining may become necessary. Beyond 2035, marine mining could become viable if spectacular technological improvements (e.g., robotic miners, efficient processing) are achieved, and if the ISA finalizes rules making deep-sea mining cost-competitive.

12 Recycling of critical metals

Recycling is a cornerstone of addressing the critical metals demand for the green energy transition, offering a sustainable alternative to virgin mining. The shift to a renewable energy system requires substantial quantities of critical metals, the extraction of which requires vast investments in new mining, extraction, and refining, and addressing environmental issues. While recycling does not eliminate the need for mining investment, it creates a valuable secondary supply source that reduces reliance on new mines and enhances supply security, especially for countries importing minerals (Ma et al., 2024). Circular economy is emerging as a key word in resource utilization. There is considerable interest in the recycling of critical metals like Co, Ni, Al, Pt, Pd, and REE. Limited recycling infrastructure is available for many critical metals. For example, copper is one of the world's most recyclable metals. Though recycling is important in meeting the demand for critical metal requirements for the energy transition, the challenges, such as setting up e-waste collection centres, scaling recycling infrastructure, advancing eco-friendly extraction technologies, and robust policy frameworks, are not easy. By 2050, recycling could halve the need for virgin mining of key metals, ensuring a cleaner, more secure supply chain for renewables.

13 Conclusions and future scope

While the challenges, such as the economic cost, technological gaps, political resistance, and social equity concerns, are discouraging, the imperative to act is urgent. Several countries are making significant strides in the green energy transition, with some, like Costa Rica and Norway, demonstrating high levels of renewable energy generation. Costa Rica, for instance, produces over 98% of its electricity from renewable energies such as hydropower, geothermal, wind, biomass, and

Fig. 9. Location of the Clarion-Clipperton Fracture zones in the Pacific Ocean. Inset shows examples of polymetallic nodules from this region (source: https://eos.org/features/the-2-year-countdown-to-deep-sea-mining).

Critical metal(s)	**Clarion-Clipperton Zone (CCZ) Nodules** (Hein et al., 2013)	**Land Resources** USGS (2025)
ΣREE	15*	90*
Li	2.8	30
Co	44	11
Cu	226	0.98
Ni	274	>130
V	9.4	18
W	1.3	4.4
Nb	0.46	>17
Mo	12	15
*Rare earth element oxides.		

Table 3. Comparison of land and ocean resources of some important critical metals (in million tons).

solar power (https://www.smithsonianmag.com/sponsored/more-than-98-percent-of-costa-ricas-energy-is-renewableheres-how-180984371/). Such successful examples demonstrate that progress is possible with sustained investment, innovation, and inclusive policies.

The transition from fossil fuel power to renewable and green energy requires massive amounts of critical metals. While countries and industries worldwide explore new deposits of critical minerals, a major question arises: how can these mining, extraction, and utilisation activities be done without the same environmental and human costs associated with fossil fuels?

Marine sediments are a vast reservoir of critical metals, but their exploitation requires balancing economic benefits with environmental sustainability. Ongoing research focuses on mapping deposits, improving extraction methods, and assessing ecological impacts. In marine environments, hydrothermal sulphide deposits, especially those in ultramafic settings, can host locally significant concentrations. Advances in exploration and processing may make them more viable in the future. Deep-sea mining research and experiments over the past 40 years have shown that marine sediments host huge deposits of critical metals, especially REE, Co, Ni, and Cu. For example, mining of REE-containing polymetallic nodules leads to the disappearance of the substrate that helps to sustain the local ecosystems and can put seafloor creatures at risk by disrupting their habitats. So far, we do not have examples of deep-sea mining and how it affects the marine ecosystem, and predicting ecological damage is difficult based on models. Certainly, deep-sea mining operations can release sediment plumes into the water column, and the debris could interfere with the behaviour and equilibrium of marine life, and disrupt food webs. Therefore, it is difficult to issue a conclusive risk assessment of the effects of large-scale commercial seabed mining. However, there are claims that with the recent advances in deep-sea mining technology, such as self-propelled crawlers, hydraulic pipeline lifting, and intelligent equipment, resources like manganese nodules can be mined with minimum disturbance to the marine biota and marine ecosystem (Zhang et al., 2025). The Metals Company and Impossible Metals, are the two players currently active in the field. A recent investigation on the biological impacts on organisms, including sediment macrofauna, mobile deposit feeders, and even large-sized sessile fauna, reveals that a strip of the Pacific Ocean seabed that was mined for metals more than 40 years ago has still not recovered completely (Jones et al., 2025). Half a century after the world's first deep sea mining tests picked nodules in the 1970s from the a deep-sea mountain range on the Blake Plateau off the coast of North Carolina in US, the damage has barely begun to heal, and the traces of those first rudimentary tests on the Blake Plateau are still visible even today after 50 years, and this example demonstrates the effects of deep-sea mining could have on the ocean ecosystem if it were to be conducted at a larger scale. In another example, before and after data from a mining simulation in an analogous area in the CCZ, Pacific Ocean, poised to be a deep-sea mining hotspot, suggests these ecosystems take hundreds of years to bounce back (https://www.greenpeace.org/aotearoa/story/deep-sea-mining-scars-remain-fifty-years-on/). Hence, cautious approaches are needed in the attempts to mine pristine areas like the Arctic or deep jungles, which can raise logistical and environmental risks.

Although the global temperatures are rising and extreme weather has ramped up, there were also some significant positive breakthroughs for the climate in the year 2024. The UK closed its last coal-fired power plant, which means this country stopped burning coal for power in 2024. World surpasses 40% clean power by December 2024, as renewable energies see record rise (https://ember-energy.org/latest-updates/world-surpasses-40-clean-power-as-renewables-see-record-rise/). The transition to green technology is extraordinarily complex, requiring coordinated efforts across governments, industries, and societies.

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Credit authorship contribution statement

V. Balaram: Conceptualization, Validation, Writing—original draft, Writing—review & editing.

M. Santosh: Conceptualization, Writing—original draft, Writing—review & editing

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. Co-author M. Santosh is Executive Advisor of this journal, and was not involved in the review-processing or Editorial decisions of this paper.

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