Global rare earth element resources: A concise review

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A R T I C L E I N F O

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A B S T R A C T

Deposits enriched in rare earth elements (REEs) are abundant and diverse in mineralogy, but those of current economic value have extremely limited geographic distribution. Due to rapidly increasing demand and concerns about supply chain security, new and improved methods of prospecting, beneficiation, separation, purification, and recycling are needed. By overviewing the types and geographic distribution of REE deposits globally, their petrogenesis and major mineralogic assemblages, this review aims to deepen understanding of different types of REE deposits and distribution characteristics at the global level. Our review also seeks to provide a concise summary of important background information that is accessible to researchers from a variety of disciplines who are seeking to engage this rapidly expanding field.

1. Introduction

According to the International Union of Pure and Applied Chemistry (IUPAC), rare earth elements (REEs) constitute a group of seventeen elements, including scandium (Sc), yttrium (Y), and the lanthanide series (fifteen elements from Lanthanum (La) to Lutetium (Lu)) (Damhus et al., 2005). Generally speaking, REEs can be divided into two group of light REEs [LREEs, including La, cerium (Ce), praseodymium (Pr), neodymium (Nd), promethium (Pm), samarium (Sm), and europium (Eu)] and heavy REEs [HREEs, including gadolinium (Gd), terbium (Tb), dysprosium (Dy), holmium (Ho), erbium (Er), thulium (Tm), ytterbium (Yb), Lu, Sc, and Y]. REEs find extensive use in various consumer products due to their indispensability in electronic, optical, magnetic, aerospace, biomedicines, energy storage, quantum information sciences, and catalytic applications (Atwood, 2013; Binnemans et al., 2013; Zhou et al., 2017; Goodenough et al., 2018; Balaram, 2019). Additionally, they play a crucial role in energy efficiency improvement, environmental protection, and the advancement of digital technology. The current surge in demand for REEs is undeniable. However, it's crucial to note that global production is, in fact, keeping pace with this rising demand, as indicated by the relatively stable REE prices (Filho et al., 2023; Liu et al., 2023). What significantly influences the REE landscape are political initiatives aimed at mitigating reliance on China as a primary source of critical raw materials (Hu et al., 2023a). This shift is evident in the recent policy developments in countries like the USA, Canada, and the EU (Kalantzakos, 2020; Theodosopoulos, 2020; Lewicka et al., 2021; Oh et al., 2021; Bide et al., 2022). These geopolitical decisions play a more pivotal role than any inherent production-demand imbalance. For example, In June 2021, the White House released a one-hundred-day review report, utilizing the terms "strategic and critical materials" as substitutes for critical minerals. Among these materials, rare earths received the most attention in the report (White, 2021). This report has had a profound impact on the future of the rare earth industry and policies in the United States (Folkedahl et al., 2023; Vivoda, 2023). The geopolitical competition over controlling rare earth resources underscores the importance of REEs and the necessity for strategic management and conservation. (Geng et al., 2023).

Fig. 1 illustrates the known global occurrence of REEs mineralization (Orris and Grauch, 2002). The distribution of global REE reserves is highly concentrated in several countries, including China, Vietnam, Brazil, Russia, India, Australia, the United States, Greenland, Tanzania, Canada, and South Africa (Zhou et al., 2017; Balaram, 2019). Currently, the major processed/refined pure REE producers in terms of quantity are China, the United States, Australia, and Myanmar (U.S. Geological Survey, 2023). Over the past decade, China alone has accounted for around 70%–90% of global production and has been the leading producer of REEs since the 1980s (Mancheri, 2012; Liang et al., 2014; Patil et al., 2022). In order to preserve its REE resources to meet domestic demands and address environmental concerns, China has implemented various measures such as quotas, licenses, and taxes to restrict REEs

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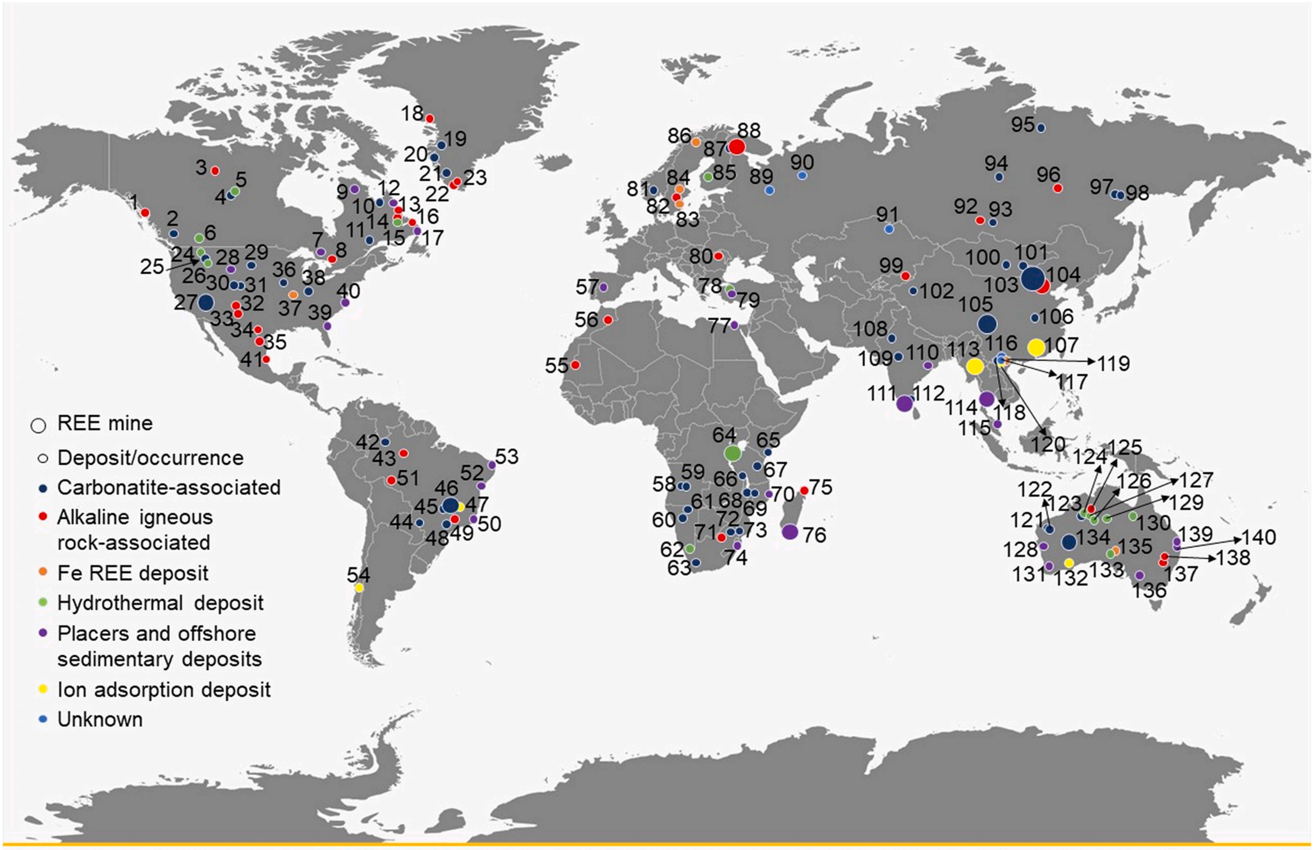

1 Bokan Mountain, USA
2 Alay, Canada
3 Thor Lake, Canada
4 Nisikkatch, Canada
5 Hoidas Lake, Canada
6 Rock Canyon Creek, Canada
7 Elliot Lake, Canada
8 Kipawa/Zeus, Canada
9 Rex-Duquet/Rex South, Canada
10 Ashram/Eldor, Canada
11 Saint-Honoré, Canada
12 Fosse du Labrador, Canada
13 Strange Lake, Canada
14 Red Wine/Two Tom, Canada
15 Kwyjibo, Canada
16 Foxtrot/Deep Fox, Canada
17 Henley Harbour, Canada
18 Karrat, Greenland
19 Sarfartoq, Greenland
20 Qeqertaasaq, Greenland
21 Tikiusaaq, Greenland
22 Kvanefjeld, Greenland
23 Motzfeldt, Greenland
24 Snowbird, USA
25 North Fork, USA
26 Lemhi Pass, USA
27 Mountain Pass, USA
28 Bald Mountain, USA
29 Bear Lodge, USA
30 Iron Hill, USA
31 Wet Mountain, USA
32 Gallinas Mountain, USA
33 Pajarito Mountain, USA
34 La Paz, USA
35 Jemi, Mexico
36 Elk Creek, USA
37 Pea Ridge, USA
38 Hicks Dome, USA
39 Green Cove Springs, USA
40 Carolina Placers, USA
41 Sierra de Tamaulipas, Mexico
42 Morro dos Seis Lagos, Brazil
43 Pitinga, Brazil
44 Chiriguelo, Brazil
45 Catalão I/II, Brazil
46 Araxá, Brazil
47 Serra Verde, Brazil
48 Barra do Itapirapuã, Brazil
49 Poços de Caldas, Brazil
50 Riode Janeiro/Buena Mine, Brazil
51 Bom Futuro, Brazil
52 Bahia, Brazil
53 Guaju Mine, Brazil
54 Penco Module/ Biolantanidos, Chile
55 Bou Naga, Mauritania
56 Tamazeght complex, Morocco
57 Matamulas, Spain
58 Coola, Angola
59 Longonjo, Angola
60 Lofdal, Namibia
61 Etanero, Namibia
62 Steenkampskraal, South Africa
63 Zandkopsdrift, South Africa
64 Karonge (Gakara), Burundi
65 Mrima, Kenya
66 Nkombwa Hill, Zambia
67 Wigu Hill, Tanzania
68 Kangankunde, Malawi
69 Songwe, Malawi
70 Congolone, Mozambique
71 Pilanesberg, South Africa
72 Naboomspruit, South Africa
73 Phalaborwa complex, South Africa
74 Richards Bay, South Africa
75 Ambohimirahavavy, Madagascar
76 Mandena, Madagascar
77 Nile Delta and Rosetta, Egypt
78 Kizilcaören, Turkey
79 Aksu Diamas, Turkey
80 Ditrău, Romania
81 Fen, Norway
82 Norra Kärr, Sweden
83 Olserum, Sweden
84 Bastnäs, Sweden
85 Korsnas, Finland
86 Kiruna, Sweden
87 Khibiny complex, Russia
88 Lovozero complex, Russia
89 Inventory of monazite when USSR
90 Yaregskoe, Russia
91 Uranium Deposit, Mongolia
92 Zashikhinskoye, Russia
93 Beloziminskoe, Russia
94 Chuktokun, Russia
95 Tomtor, Russia
96 Seligdar, Russia
97 Gornoe Ozero, Russia
98 Khamna, Russia
99 Kutessay II, Kyrgyzstan
100 Mushgai Khudag, Mongolia
101 Lugin Gol, Mongolia
102 Wajiertage, China
103 Bayan Obo, China
104 Weishan, China
105 Maoniuping/Dalucao, China
106 Miaoya, China
107 IADs, South China
108 Sarnu, India
109 Amba Dongar, India
110 Orissa, India
111 Chavara, India
112 Manavalakurichi, India
113 IADs, Northern Myanmar
114 Thai Peninsula, Thailand
115 Perak, Malaysia
116 Then Chau deposit, Vietnam
117 Muong Hum deposit, Vietnam
118 Nam Xe deposit, Vietnam
119 Sin Quyen deposit, Vietnam
120 Dong Pao deposit, Vietnam
121 Gifford Creek/Yangibana, Australia
122 *, Australia
123 Cummins Range, Australia
124 John Galt, Australia
125 Brockman, Australia
126 Boulder Ridge, Australia
127 Browns Range, Australia
128 Eneabba, Australia
129 Nolans, Australia
130 Brightlands Milo, Australia
131 Jangardup, Australia
132 **, Australia
133 ***, Australia
134 Mount Weld, Australia
135 Olympic Dam, Australia
136 WIM 150, Australia
137 Narraburra, Australia
138 Dubbo Zirconia, Australia
139 Fraser Island, Australia
140 North Stradbroke Island, Australia

* 122 Gascoyne, Kingfisher, Mick Well, Arthur River, Mangaroon, Mt Clere
** 132 Circle valley, Cascade, Mt Ridley, Lort River
*** 133 Lake Labyrinth Shear Zone, Comet

Fig. 1. Known REEs mines and deposits globally. Deposits in black color are modified after (Deady, 2021); deposits in red color are from (Pham-Ngoc et al., 2016; Spandler et al., 2020; Liu et al., 2023).

production after 2010 (Hayes-Labruto et al., 2013; Wübbeke, 2013; Han et al., 2015; Lei et al., 2017; Hu et al., 2023b). Consequently, many countries have started exploring new REE deposits and expanding domestic rare earth production. Additionally, efforts to recycle, conserve REEs, and explore substitute materials have intensified in various countries (Lei et al., 2017; Van Gosen et al., 2017; Ciacci et al., 2019; Humphries, 2019; Mancheri et al., 2019).

The current geopolitical imbalance in REE production versus demand is driving new research and development for more efficient or novel methods of REE extraction, beneficiation, and separation/refining for mineralized deposits. This review seeks to help facilitate this effort by providing an overview of REE resource types, and their geographic distribution. We first summarize the chemical characteristics of some important REE-bearing minerals, also the classification of REE deposits. Next, we examine the worldwide distribution of REE resources, highlighting well-known REE deposits with significant current and/or future production potential. Finally, we conclude with some observations and considerations for future development in this general area of research.

2. Classification of REE minerals and their crystal chemical compositions

The total abundance of REEs in Earth's crust is approximately 169.1 ppm, including ~137.8 ppm of light REEs and ~31.3 ppm of heavy REEs (Rudnick and Gao, 2003). Among them, the most abundant REEs are Ce (~63 ppm), La (~31 ppm), Nd (~27 ppm), and Y (~21 ppm), which have average crustal abundances similar to some industrial metals, such as chromium (~100 ppm), nickel (~84 ppm), copper (~60 ppm), zinc (~70 ppm), cobalt (~25 ppm), lithium (20 ppm), and lead (~14 ppm) (Fig. 2) (Dushyantha et al., 2020). Therefore, despite the label "rare" in their name, they are not as scarce as the term implies. The word "rare" primarily indicates that even in enriched deposits REEs tend not to occur in compositionally pure mineral phases but rather as solid solution in relatively low concentrations, often as substituents for major ions in various compatible crystal structure types (Haxel et al., 2002).

REEs are found in a wide variety of mineral phases such as carbonates, halides, phosphates, and oxides (Möller, 1986; Jordens et al., 2013; Dushyantha et al., 2020). Currently, over 250 minerals have been identified as containing REEs, however, only a few minerals are commercially significant or have the potential to become so (Table 1) (Jordens et al., 2013). Among these minerals, bastnäsite, xenotime, and monazite are the three main kinds that are associated with the majority

Table 1
List of common REE-bearing mineral phases and their molecular formulas, and typical values of their rare earth oxide (REO) contents.

minerals	Formula	Approximate REO %
Aeschynite-(Ce)	$(Ce,Ca,Fe,Th)\ (Ti,Nb)_2(O,OH)_6$	32
Allanite-(Ce)	$(Ce,Ca,Y)_2\ (AI,Fe^{3+})_3(SiO_4)_3OH$	38
Apatite	$(Ca,Ce)_5(PO_4)_3(F,CI,OH)$	19
Bastnäsite-(Ce)	$(Ce,La)\ (CO_3)F$	75
Brannerite	$(U,Ca,Y,Ce)\ (Ti,Fe)_2O_6$	9
Britholite-(Ce)	$(Ce,Ca)_5(SiO_4,PO_3)_3(OH,F)$	32
Eudialyte	$Na_4(Ca,Ce)_2(Fe^{2+},Mn,Y)ZrSi_8O_{22}(OH,CI)_2$ (?)	9
Euxenite-(Y)	$(Y,Ca,Ce,U,Th)\ (Nb,Ta,Ti)_2O_6$	24
Fergusonite-(Ce)	$(Ce,La,Nd)NbO_4$	53
Gadolinite-(Ce)	$(Ce,La,Nd,Y)_2Fe^{2+}Be_2Si_2O_{10}$	60
Kainosite-(Y)	$Ca_2(Y,Ce)_2Si_4O_{12}CO_3{\cdot}H_2O$	38
Loparite	$(Ce,La,Na,Ca,Sr)\ (Ti,Nb)O_3$	30
Monazite-(Ce)	$(Ce,La,Nd,Th)PO_4$	65
Parisite-(Ce)	$Ca(Ce,La)_2(CO_3)_3F_2$	61
Xenotime	YPO_4	61
Yttrocerite	$(Ca,Ce,Y,La)F_3.nH_2O$	53
Huanghoite-(Ce)	$BaCe(CO_3)_2F$.	39
Cebaite-(Ce)	$Ba_3Ce_2(CO_3)_5F_2$	32
Florencite-(Ce)	$CeAl_3(PO_4)_2(OH)_6$	32
Synchysite-(Ce)	$Ca(Ce,La)\ (CO_3)_2F$	51
Samarskite-(Y)	$(Y,Ce,U,Fe^{3+})_3(Nb,Ta,Ti)_5O_{16}$	24
Knopite	$(Ca,Ti,Ce_2)O_3$	NA

Note: Data from reference (Walter et al., 2010). NA means not available.

of REE resources (Jha et al., 2016; Meshram and Pandey, 2019). Monazite and bastnäsite serve as the primary sources of the LREEs, predominantly containing Ce, La, and Nd. But some monazite exhibits a slightly distinct composition with lower amounts of La and higher levels of Nd and HREEs. It is worth noting that monazite also contains the radioactive elements thorium (Th) and uranium (U) (Andreoli et al., 1994; Hussain et al., 2020; Su et al., 2021; Dostal and Gerel, 2023). On the other hand, xenotime is characterized by the HREEs (such as Y, Dy, Er, Yb, and Ho) (Harben, 2002).

3. Major REE ore deposit types

REE ore deposits can generally be categorized into two main types: primary deposits formed through hydrothermal and igneous processes

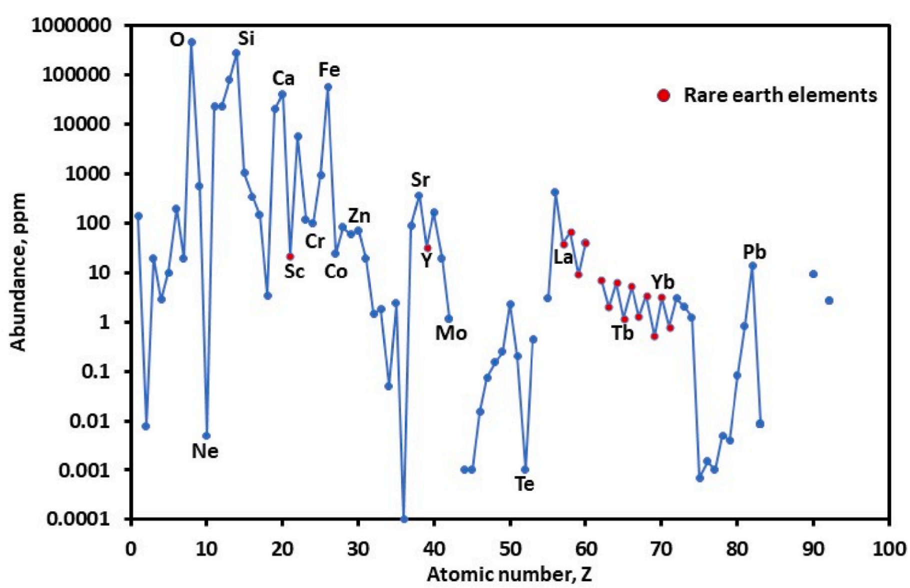

Fig. 2. Comparison of the abundance of various elements in the Earth's crust (Yaroshevsky, 2006).

and secondary deposits resulting from weathering and sedimentary processes (Walter et al., 2010). Here we follow a classification based on their mineralogic associations and the geological processes from which they have formed (Jaireth et al., 2014; Xie et al., 2019; Batapola et al., 2020; Dushyantha et al., 2020). These categories include.

- Carbonatite-related deposits
- Deposits associated with alkaline igneous rocks
- Magmatic-hydrothermal deposits
- Residual weathering deposits
- Placers
- Offshore sedimentary deposits
- REEs in coals

Carbonatite-related deposits. According to the International Union of Geological Sciences, carbonatites are defined as igneous rocks consisting of over 50% by volume of primary carbonate mineral (Streckeisen, 1980). They commonly occur in stable regions of the crust, such as cratons, and often form carbonatite-alkaline complexes because they are associated with alkaline silicate igneous rocks, or isolated in various forms including stocks, sills, dikes, irregular-shaped masses (Walter et al., 2010; Linnen et al., 2013; Wang et al., 2020). Carbonatites vary in composition from calcic, dolomitic, to ferro-carbonate (subdivided into ankerite [$Ca(Mg,Fe^{2+},Mn)(CO_3)_2$] or siderite [$FeCO_3$]) (Schulz et al., 2017; Simandl and Paradis, 2018; Pirajno and Yu, 2022). There is currently considerable controversy regarding the formation of carbonatites. Some believe that carbonatites derive from silica-poor but carbon dioxide-rich magmas originating from the upper mantle, or from carbonate-bearing alkaline silicate magmas through immiscibility or fractionation (Rankin and Le Bas, 1974; Hamilton et al., 1979; Twyman and Gittins, 1987; Wallace and Green, 1988; Kjarsgaard and Hamilton, 1989; Baker and Wyllie, 1990; Harmer and Gittins, 1998; Wyllie and Lee, 1998; Veksler et al., 2006). Others argue that carbonatite magmas can directly originate from low-degree partial melting of carbonated mantle peridotite (Gittins, 1988; Woolley and Kjarsgaard, 2008) or partial melting of subducted oceanic crust (Walter et al., 2008). However, Anenburg et al. propose that regardless of the origin of carbonates, in order to enrich rare earth elements in carbonatite sources, especially for the largest economic deposits, one or more crucial processes must accompany the evolution of carbonatites. These include three main stages: igneous fractionation (>600 °C), brine-melt stage (600-400 °C), and hydrothermal fluid. While REE mineralization primarily occurs in the latter two stages, igneous fractionation plays a crucial role in the crystallization of REE-poor minerals in carbonatite melts, leading to the enrichment of rare earth elements in the residual melt (Anenburg et al., 2021). This intricate evolution process can also be inferred from fluid/melt inclusions in carbonatites, where the diversity of components mirrors processes such as fractionation, fluid exsolution, and subsequent fluid phase separation (immiscibility) (Walter et al., 2021).

Carbonatite-related REE deposits, such as Mountain Pass, USA, have been the primary source of LREEs since the 1960s, attributed to the fact that these deposits are usually enriched in LREEs (Van Gosen et al., 2017). However, there are a few exceptional cases where carbonatite deposits exhibit high enrichment in HREE, such as the Dashigou site in China and the Bear Lodge site in the USA (Song et al., 2015; Andersen et al., 2016, 2017; Smith et al., 2018; Cangelosi et al., 2020). This type of deposit is usually enriched in LREEs due to the significant LREE/HREEs fractionation in carbonatites (Xu et al., 2010). Multiple mechanisms contribute to LREE enrichment in carbonatites, encompassing their preferential incorporation into carbonatite melts within mantle sources (Foley et al., 2009) or into carbonatite liquids during immiscibility (Martin et al., 2013; Nabyl et al., 2020). Additionally, post-magmatic geological processes such as hydrothermal activity can further enhance the enrichment of LREEs or depletion of HREEs within carbonatite deposits (Broom-Fendley et al., 2017; Anenburg et al., 2020; Beland and Williams-Jones, 2021). The main REE minerals associated with carbonatites include bastnäsite, monazite, xenotime, and parisite. These minerals serve as the primary sources of REEs within carbonatite deposits (Wang et al., 2020).

Deposits associated with alkaline igneous rocks. Generally speaking, alkaline igneous rocks typically consist of amphiboles, alkali pyroxenes, and feldspathoids. They are formed when the magma has an excess of sodium and potassium content beyond what is required for feldspar formation, leading to the formation of feldspathoids. Alkaline igneous rocks exhibit a broad range of compositions, ranging from ultramafic to felsic (Dostal, 2017). In some cases, alkaline rocks may be referred to as peralkaline if their molar proportion of potassium plus sodium is higher than aluminum (Spandler and Morris, 2016; Dostal, 2017). Peralkaline rocks are characterized by their significant enrichment both in high-field strength elements (HFSEs, including titanium (Ti), zirconium (Zr), niobium (Nb), and REEs) and alkali metals (Dostal, 2017), and can be divided into two groups of agpaitic and miaskitic rocks. In the miaskitic rocks, REEs and HFSEs are predominantly hosted by minerals like zircon and titanite while the agpaitic rocks are featured by Na–Ca-HFSE minerals with structurally incorporated halogens (Beard et al., 2023). The main evidence suggests that (per)alkaline rocks form though extensive fractional crystallization of alkaline basaltic magmas, which originate from partial melting of mantle sources (Pilet et al., 2008). However, some researchers have proposed that the formation of peralkaline melts is often accompanied by metasomatic pre-enrichment of halogens, HFSEs, REEs, and other rare and incompatible elements in mantle sources. This process results in the unique enrichment of these elements observed in the subsequently produced peralkaline rocks (Upton et al., 2003; Marks and Markl, 2017). The mineralization of REEs in alkaline igneous rocks commonly takes place during the late stages of magma evolution, and typically hosted by nepheline syenites, peralkaline granites (such as pegmatites, felsic dikes), and peralkaline felsic volcanic rocks (such as trachytes) (Beard et al., 2023). The dominant alkaline igneous rocks related REE mineralization includes bastnäsite, loparite, eudialyte, xenotime, gittinsite, zircon, monazite, and fergusonite (Chakhmouradian and Zaitsev, 2012; Dostal, 2017). Peralkaline rocks related REE deposits generally exhibit comparatively low-grade mineralization, but are usually enriched in HREE (Castor and Hedrick, 2006; Spandler and Morris, 2016).

Magmatic-hydrothermal deposit. Some REE deposits are not obviously associated with carbonatites or alkaline igneous rocks. The iron oxide-copper-gold (IOCG) deposits are one of the most significant type of this group (Groves et al., 2010; Slack et al., 2016). The renowned Olympic Dam deposit in South Australia represents the first discovery of this deposit type (Roberts and Hudson, 1983; Tappert et al., 2013). The occurrence of REE minerals varies in different IOCG deposits, the main REE phases are allanite, carbonates and monazite, apatite and/or fluorite (Skirrow, 2022). Additionally, some magmatic hematite-magnetite bodies can concentrate economically valuable REE-bearing mineral, such as apatite. An example of this is the Pea Ridge Fe Oxide-REE Deposit (southeast Missouri, USA) (Sidder et al., 1993; Harlov et al., 2016). These deposits, primarily characterized by the presence of iron oxide ores, are alternatively referred to as iron oxide-apatite bodies (Reich et al., 2022; Yan and Liu, 2022). Besides, high REE concentrations are also discovered in vein and skarn systems where bastnaesite and monazite emerge as the primary REE mineral phases (Holtstam et al., 2014; Goodenough et al., 2018). An example of this is the Bastnäs-type Fe-REE-(Cu–Mo–Bi–Au) deposits in Bergslagen, Sweden (Holtstam et al., 2014). Occasionally, REE mineralization may be hosted within sedimentary rocks or mafic gneiss; however, REEs are typically concentrated through magmatic-hydrothermal processes or derived from hydrothermal fluids. An illustrative case is the accumulation of xenotime in the Music Valley area of southern California, USA, found within the Probable Precambrian-aged Pinto Gneiss (McKinney et al., 2015). Another example is the occurrence of REE-F-Ba mineralization hosted by the Cedared and Burnais formations in Rock Canyon Creek, British Columbia, Canada (Green et al., 2017; Simandl et al., 2021).

Residual weathering deposits. Laterites are residual accumulations formed *in situ* through continuous tropical weathering processes, that results in the disintegration of primary rock-forming minerals. Subsequently, some labile elements (such as sodium, magnesium and calcium) leach out, leaving behind those relatively immobile elements (such as aluminum and iron) in place. Hence, if the parent rocks, like carbonatites and granites, are enriched in REEs, then economic deposits of REEs may form after weathering (de Oliveira and Imbernon, 1998; Witt et al., 2019; Zhukova et al., 2021). For example, laterite regoliths weathered from carbonatites typically exhibit high-grade mineralization, with REO contents ranging from 10% to 25% (Walter et al., 2010). One notable case is the Mount Weld REE deposit in Western Australia, which consists of a fully weathered thick laterite layer overlying the Proterozoic carbonatite (Zhukova et al., 2021). Although the primary carbonatite contains only 0.1–0.2% REO, the extreme enrichment at Mount Weld reaches 18.0% REO (Castor and Hedrick, 2006; Green et al., 2017). Ion-adsorption deposits (IADs), another type of residual weathering deposit, *viz.* residual deposits of REE-bearing clays, are a specific type of REE deposits where REEs adsorption happens on clay mineral surfaces in the weathering profile of certain rocks (Yang et al., 2013; Moldoveanu and Papangelakis, 2016; Estrade et al., 2019). The majority of these deposits have been exploited throughout southern China, and are hosted within the weathered REE-enriched granites' profiles, such as provinces of Hunan, Jiangxi, Fujian, and Guangdong (Kanazawa and Kamitani, 2006; Yang et al., 2013). Also, They have the potential to be found globally. In 2020, a major new clay hosted ionic REE deposit has been discovered at Mt Clere, Australia (Krakatoa, 2020). and some IADs have been discovered in SE Asia and Japan (Li et al., 2017; Yamaguchi et al., 2018). These clay minerals mainly consist of kaolinite, followed by varying amounts of illite, halloysite, montmorillonite, vermiculite, and chlorite (Huang et al., 2021b; Zhu et al., 2022b). Meanwhile, Fe–Mn oxides sometimes play critical roles in the enrichment of REE, especially for the element Ce, in a relatively oxidized environment, Ce undergoes conversion from Ce^{3+} to Ce^{4+}, thereby forming precipitates within Fe–Mn oxides or Ce-bearing minerals. This process leads to an enrichment of Ce in the weathered surface horizon (Bao and Zhao, 2008; Zhu et al., 2022a).

Placers. These deposits are sedimentary accumulations of durable, heavy minerals, along with sand and gravel, that are transported and deposited by coastal activities and/or river currents (Komar, 2007; Amalan et al., 2018). These detrital materials usually come from high-grade metamorphic or granitic rocks, because these parent rocks often contain enriched minerals of Ti, Zr, and REEs. Currently, more than 360 REE-enriched placer deposits have been identified (Orris and Grauch, 2002). However, the most economically significant placer deposits typically have marine origins, found on or near the current shorelines (Cronan, 1999). An example of such marine placer deposits with elevated levels of REE minerals occur along the Australian coast (Cronan, 1999). The primary REE-bearing minerals found in these deposits are monazite, with occasional xenotime, euxenite, fergusonite, allanite, samarskite, knopite, pyrochlore, and loparite (Möller, 1986). However, monazite is commonly derived from granites, leading to a relatively high thorium (Th) content, posing a significant challenge during processing.

Offshore sedimentary deposits. Phosphate rocks have the potential to serve as a substantial resource for REE, given their widespread production globally and high REEs contents (Pufahl and Groat, 2017; Wu et al., 2018; Rout et al., 2023). Currently, the proven marine sedimentary phosphorites account for the majority of global phosphate resources, approximately 95% of the total (Pufahl and Groat, 2017; Wang et al., 2023c). Wherein the marine sedimentary phosphate deposits are mainly composed of carbonate fluorapatite. REEs have ion radii similar to Ca^{2+} (Auer et al., 2017), and therefore, they preferentially replace Ca in the crystal lattice of phosphate minerals, leading to the widespread presence of significant amounts of REEs in phosphate ores. At present, some potential REE-enriched sedimentary phosphate deposits have been found in Australia (Emsbo et al., 2015; Valetich et al., 2022), USA (Emsbo et al., 2015), Venezuela (Linares et al., 2023), Northern Africa (Tunisia, Algeria) (Buccione et al., 2021), and Northwestern Saudi Arabia (Ahmed et al., 2022). Moreover, studies have indicated that Mn nodules and Fe–Mn crusts discovered in the Pacific Ocean's deep-sea regions have high levels of HREEs, that can be recognized as REE deposits (Huang and Fu, 2023).

REEs in coals. In recent years, REEs in coal have attracted widespread attention due to their stable geochemical characteristics and potential economic value. However, the REE concentrations in coal seams are typically not significantly higher than those found in normal sedimentary rocks. The significance of these resources lies in the large tonnage of rock rather than in exceptionally high concentrations of REE. According to statistics, the average abundance of REEs in coal worldwide was estimated to be 68 μg/g (Ketris and Yudovich, 2009). China's coal has rare earth content at 138 μg/g (Dai et al., 2008), approximately twice the global average. Other countries and regions, such as Turkey, North Korea, and the United States, have contents of 116, 77, and 62 μg/g, respectively (Finkelman, 1993; Zhang et al., 2015). However, the average REEs content in coal ash worldwide is 403.5 μg/g (Ketris and Yudovich, 2009), while in USA, the average REE content in coal ash is approximately 513 μg/g (Finkelman, 1993). This indicates that during the combustion process of coal, REEs are primarily enriched in the combustion products, with this enrichment being closely related to the coal compositions, combustion methods and characteristics of the ash. Higher temperatures can lead to the evaporation of more volatile elements, while a longer residence time of fly ash allows for greater absorption of REEs from the gas phase (Wu et al., 2022). The criterion set by the US Department of Energy for assessing raw coal as REEs resources specifies that the total REEs content should exceed 300 μg/g on a dry coal basis (Fu et al., 2022). Therefore, in the research report on rare earth elements published by the U.S. Department of Energy in 2017, it explicitly emphasizes that coal and its combustion products in USA can serve as potential sources of REEs (Conrad, 2017). Currently, REEs-enriched coals are primarily distributed in China (Dai et al., 2016; Yin and Song, 2022), Russia (Seredin, 1996; Seredin and Dai, 2012), USA (Taggart et al., 2016; Lin et al., 2018; Bagdonas et al., 2022). According to previous research, the genesis of REEs in coals can be classified into four types: terrigenous, tuffaceous, infiltrational or meteoric groundwater-driven, and hydrothermal types (Seredin and Dai, 2012). Furthermore, existing research indicates that REEs in coal exist in the forms of rare earth minerals, organic compounds, and ion adsorption (Jordens et al., 2013; Zhang et al., 2017; Finkelman et al., 2018).

4. The global distribution of REE deposits and some major deposits

REE deposits have been identified in over 34 countries, with a total estimated 130 million metric tons of global REEs reserves based on REO content (Table 2). The leading countries in terms of reserves are China (~33.8%), Vietnam (~16.9%), Brazil (~16.2%), Russia (~16.2%), India (~5.3%), Australia (~3.2%), and the USA (~1.8%) (U.S.G.S., 2023). Since the late 1990s, China has been dominating the REE market, both in the supply of raw ores and processed/purified products, accounting for over 90% of global production from the 2000s to the early 2010s (Drobniak and Mastalerz, 2022). However, in recent years, due to adjustments in the international REE market, there has been an increase in REO production outside of China. As shown in Table 2, China's contribution has now fallen to the range of 55%–70% of global production (U.S. Geological Survey, 2021, 2023), while the production in the United States, Vietnam, and Thailand is increasing year by year.

4.1. China

China's REE deposits are distributed mainly in Inner Mongolia, Sichuan, Fujian, Guangdong, Hunan, Jiangxi, Shandong, and Yunnan

Table 2
Worldwide reserves of REEs (REO basis) in 2022 and global REE production from 2019 to 2022 (unit: metric tons, data from references (U.S. Geological Survey, 2021, 2023)).

	Reserves	Mine Production			
		2019	2020	2021	2022
China	44000000	132000	140000	168000	210000
Vietnam	22000000	1300	1000	400	4300
Brazil	21000000	710	1000	500	80
Russia	21000000	2700	2700	2600	2600
India	6900000	2900	3000	2900	2900
Australia	4200000	20000	17000	24000	18000
United States	2300000	28000	38000	42000	43000
Greenland	1500000	–	–	–	–
Tanzania	890000	–	–	–	–
Canada	830000	–	–	–	–
South Africa	790000	–	–	–	–
Myanmar	NA	25000	30000	35000	12000
Burundi	NA	200	500	200	–
Madagascar	NA	4000	8000	6800	960
Thailand	NA	1900	2000	8200	7100
Other countries	280000	66	100	60	80
total	130000000	220000	240000	290000	300000

Note: NA, not available. – Zero.

(Wübbeke, 2013; Lei et al., 2017; Wang et al., 2018). Among these deposits, the most economically significant are the carbonatite-related REE deposits, notably the Bayan Obo deposit, recognized as the largest REE deposit in the world (Li et al., 2022; Wei et al., 2022), and the Maoniuping deposit, which is China's second-largest REE resource (Weng et al., 2022a, 2022b). Additionally, there are numerous REE-bearing ion-adsorption clay deposits located in the southeastern provinces of China (Ou et al., 2022; Zhao et al., 2022), and also some alkaline-related REE deposits, such as Weishan deposit (Zhao et al., 2023). China began REO production in the 1980s, and had emerged as the dominant producer in the global market by the mid-1990s (Drobniak and Mastalerz, 2022). In the early 2000s, the Chinese government introduced export quotas for REEs, which were significantly reduced since 2010 (Lee and Dacass, 2022).

4.1.1. *Carbonatite-related REE deposits*

China has identified over 20 carbonatite-related REE deposits or sites, including the giant Bayan Obo and Maoniuping deposits, as well as the large Dalucao and Miaoya deposits. Additionally, there are several medium to small REE deposits and mineralized sites (Xie et al., 2020). These carbonatite-related REE deposits typically exhibit enrichment in LREEs, while a minority of locations, such as Dashigou, demonstrate higher enrichment in HREEs. The HREE-enriched minerals in these deposits are predominantly fluorcarbonates, with secondary REE mineralization occurring through the replacement of primary magmatic monazite-(Ce) by minerals like xenotime-(Y) and churchite-(Y) (Smith et al., 2018; Cangelosi et al., 2020).

Bayan Obo deposit. The Bayan Obo Fe-REE-Nb deposit is situated in the northwest region of Baotou in Inner Mongolia Autonomous Province (Kanazawa and Kamitani, 2006). It is hosted within the Bayan Obo group, which consists of nine Paleo-Mesoproterozoic sedimentary units, termed as H1 to H9 in ascending stratigraphic order, but the division of H8 lithology is controversial (Tang et al., 2021). These units primarily comprise slates and meta-sandstones, but H8 is predominantly composed of dolomitic marbles, Featuring both fine- and coarse-grained forms. The H8 unit forms a spindle-shaped stratiform body extending from east to west, measuring over 18 km in length and more than 1 km in width. It serves as the primary host rock for the majority of the ores (Chao et al., 1992; Yang et al., 2009, 2011a). Within the deposit, carbonatite dikes in different types are widely distributed (Yuan et al., 1995; Yang et al., 2011b). The genesis of this deposit remains a topic of debate due to the complex ore-forming process, primarily attributed to extensive and intense hydrothermal alterations and transformations during the late stages of mineralization and metamorphism (Yang et al., 2009, 2017; Lai et al., 2015; Smith et al., 2015; She et al., 2021). Fig. 3a–d illustrates one possible model for the genesis of this deposit. The evolution of carbonatite involves distinct stages: a magmatic phase featuring Mg–Fe-carbonatite (original ore-hosting dolomite), a carbothermal stage driven by Ca-carbonatitic fluids, and a hydrothermal stage with significant fluorite deposition and alkali alteration. After that, intense geological tectonic movement has led to local modification and REE-Nb enrichment. The complex multi-stage REEs mineralization primarily results from metasomatism where fluids derived from Ca-carbonatite interact with slightly preceding Mg–Fe-carbonatite intrusions. Moreover, it should be noted that while the Mg–Fe-carbonatite magma exhibited enrichment in REEs, the substantial contribution to the eventual REEs enrichment in the ore-hosting dolomite, forming the mined orebodies, came from post-magmatic fluids associated with Ca-carbonatite (Liu et al., 2020). The main REE-bearing minerals found in the Bayan Obo deposit include bastnaesite-(Ce) and monazite-(Ce), along with various other REE and Nb minerals such as huanghoite, aeschynite-(Ce), felgusonite, and columbite (Fan et al., 2016). The deposit contains approximately 800 Mt of REE reserves with an average grade of 6% total REO. Additionally, it is estimated to hold 2.2 Mt of Nb reserves with an average grade of 0.13% Nb_2O_5, as well as at least 1500 Mt of total Fe reserves with an average grade of 35% (Fan et al., 2014). The deposit is particularly rich in LREEs, which account for up to 97% of the total REEs present (Su, 2009; Yang et al., 2013).

Maoniuping deposit. This deposit is situated in the western region of the Yangtze Plate and the eastern region of the Tibetan Plateau, controlled by the Panxi rift (Liu et al., 2015; Wang et al., 2020). Host rocks are composed of Devonian-Permian argillaceous clastic sediments, limestones, and Tertiary talus. Igneous rocks in the area consist of Yanshanian granite, an alkaline syenite-carbonatite complex, and Mesozoic rhyolite, which are widely distributed across the deposit. REE mineralization happens within a vein system, primarily consisting of pegmatitic veins of barite and calcite, as well as line veins found within the Maoniuping northeast-trending syenite-carbonatite complex. This complex extends approximately 1400 m in length and has a width ranging from 260 to 350 m (Yuan et al., 1995). A study of fluid inclusions has been conducted to investigate the origin of this deposit, as illustrated in Fig. 3e. The evidence suggests that the ore-forming fluids originated from carbonatite-syenite complexes. Fenitization happened during the hydrothermal stage I, followed by the appearance of immiscible fluids in hydrothermal stage II. The final stage witnessed the occurrence of rare earth mineralization (Zheng and Liu, 2019). However, a recent study proposes that shallow-seated, sustained mantle-derived magma underintrusion coupled with stable regional thermal anomalies contributed to the favorable conditions for REE formation (Weng et al., 2022a). The principal REE-bearing mineral in this deposit is bastnäsite-(Ce), accompanied by minor amounts of parisite-(Ce) and monazite-(Ce). The estimated REE reserves are typically enriched in LREEs (Yuan et al., 1995; Zheng and Liu, 2019). Other associated reserves include 3.78 Mt of barite, 0.33 Mt of Pb, 2.40 Mt of fluorite, and 174 tons of Ag (Xu et al., 2012).

4.1.2. *Ion-adsorption clay deposits*

In Southern China, another typical REE deposit are found as weathered-crust elution deposits and termed "ion adsorption deposits (IADs)". These deposits usually contain high value of LREE (Huang et al., 2021a; Wang et al., 2023b), with a minority being rich in HREE content (such as Gd–Lu) (Kynicky et al., 2012; Moldoveanu and Papangelakis, 2016; Xie et al., 2020). The variations in compositions within IADs are primarily influenced by the diverse chemical compositions of the parent rocks (Chu et al., 2024). These deposits form under relatively stable tectonic geological conditions (low uplift and low erosion rates) and are restricted to certain areas of Southern China (Takeda and Okabe, 2014). The formation of ion adsorption REE deposits occurs through the process

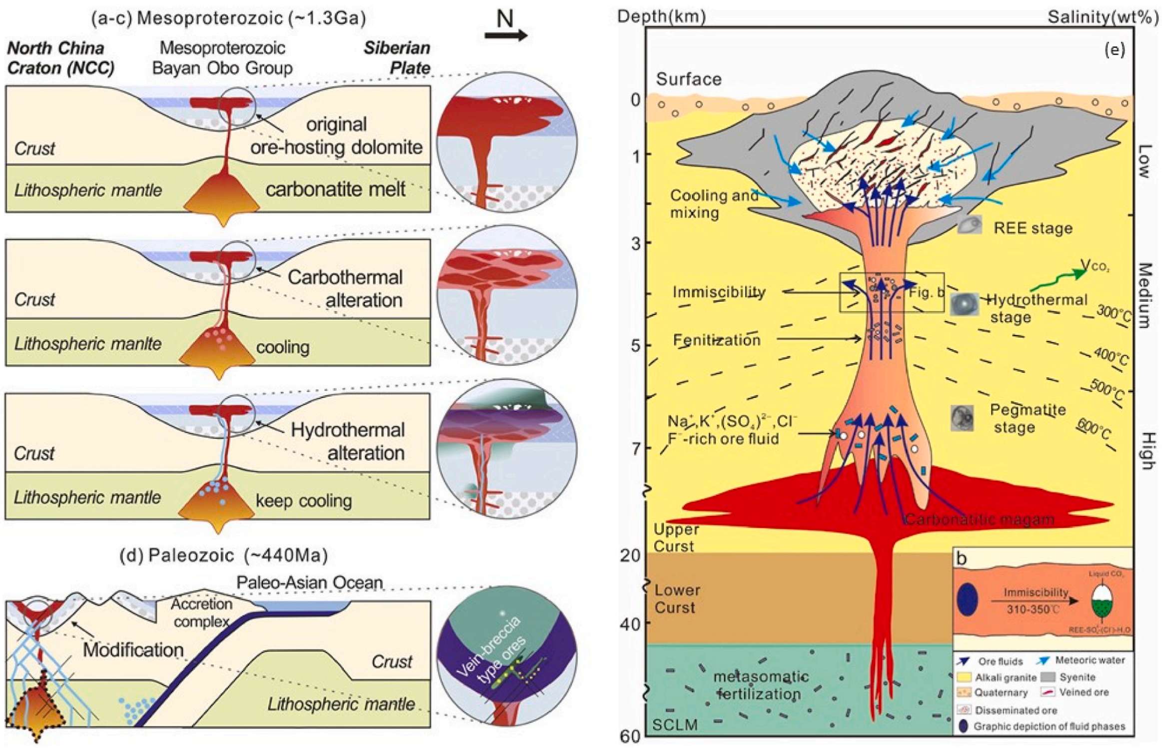

Fig. 3. Left: Models for formation of the Bayan Obo REE deposit (Liu et al., 2020) ((a) original ore-hosting dolomite formation, (b) carbothermal stage, (c) hydrothermal stage, (d) geological tectonic movement) and Right: ore-forming fluid evolution and mineralization process in the Maoniuping REE deposit (Zheng and Liu, 2019).

of weathering and leaching of parent rocks (particularly granite, gneisses, and granite porphyry) by water in warm and high-humidity near surface environments. During migration, the dissolved REE ions are adsorbed by clay minerals (Van Gosen et al., 2014; Estrade et al., 2019). Microbes can also act a positive effect in the mobilization and fractionation of REEs during weathering (He et al., 2023). The weathered zone is rich in REEs, with a thickness typically ranging from 3 to 10 m. Based on the mineralogy, it can be divided into four layers (Bao and Zhao, 2008): an upper soil layer (0–2 m); a fully weathered horizon (5–10 m) that constitutes the main REEs orebody with general REE concentrations of 0.03–0.15% (Yang et al., 2013), a semi-weathered parent rock horizon (3–5 m); and a parent rock horizon or weakly weathered layer, a typically case is shown in Fig. 4. The advantage of this type deposit is that the adsorbed REEs can be easily extracted from the clay through ion exchange (Wall, 2014; Deng et al., 2019). Hence, despite the relatively small scale, and low REE concentrations of these deposit, it is still economically feasible to extract REEs from these clay deposits. According to the data, ion-adsorption clay deposits only account for 2.9% of China's total REE reserves, but they have contributed to 26% of China's total REE production from 1988 to 2008 and up to

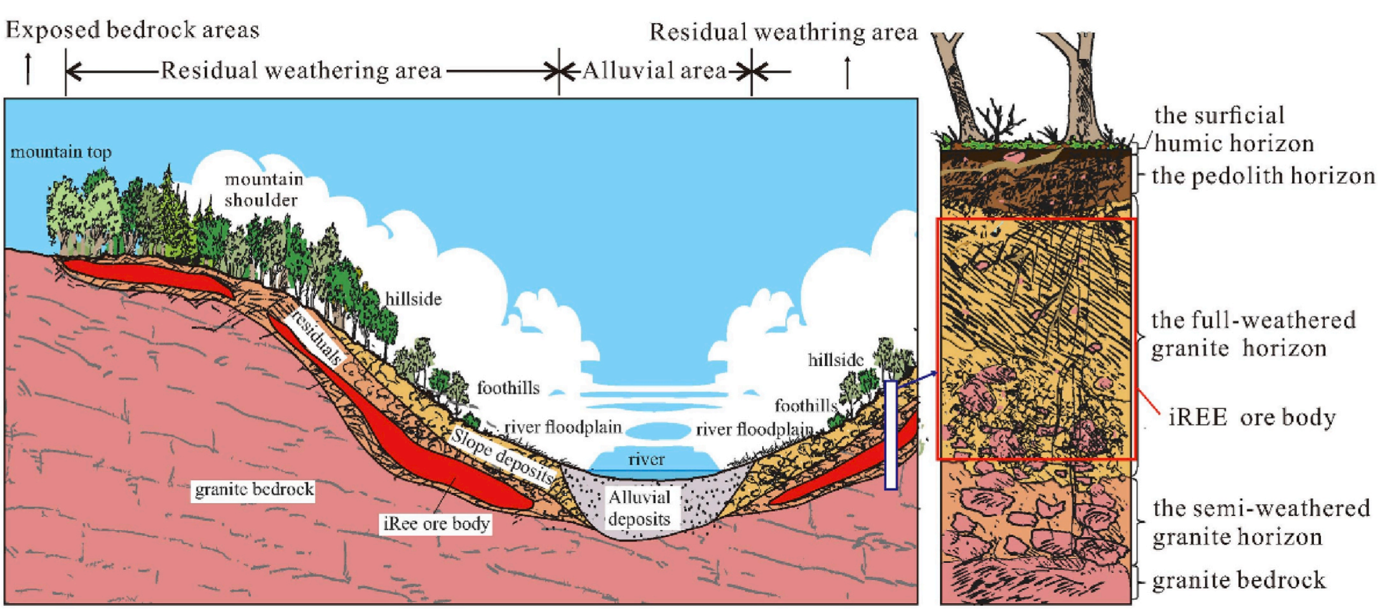

Fig. 4. A typical model of ion-adsorption clay deposits in West Yunnan, China (Zhu et al., 2022b).

35% since 2009 (Su, 2009). Recently, Wang et al. reported a new technique, *viz*. electrokinetic mining for the selective recovery of REEs from ion-adsorption clay deposits in a more environmentally friendly and efficient manner (Wang et al., 2023a). In contrast to conventional techniques, the new method attains ~2.6 times higher recovery efficiency, reduces leaching agent usage by around 80%, and diminishes metallic impurities in the obtained REEs by approximately 70%.

4.2. Vietnam

The earliest REE deposits discovered in Vietnam were the Nam Xe and Dong Pao REEs deposits in the northwest province of Lai Chau. After 1990, four other major REE deposits were discovered: Sin Quyen in Lao Cai province, Yen Phu in Yen Bai province, Then Chau in Lai Chau province, and Muong Hum in Lao Cai province (Moody, 2013). Fig. 5 shows the distribution of REE deposits in the northwest part of Vietnam. Despite having the second-largest REE reserves, Vietnam produced only 4300 tons in 2022, accounting for 1.5% of the global total production for that year (Table 2).

4.2.1. Carbonatite-related REE deposits and their weathered residuum

Nam Xe carbonatites, located in the northwestern region of Vietnam, the only reported occurrence of carbonatite in Vietnam, are found in the intracontinental rift-Song Da zone (Nguyen Thi et al., 2014). Two main types have been identified: ferrocarbonatite and calciocarbonatite. The origin and formation of the Nam Xe carbonatites have been a subject of debate for years. Some previous studies suggested that ferrocarbonatites have hydrothermal/metasomatic origins, while calciocarbonatites are of igneous origin (IIa et al., 1961; Thanh et al., 2002; Chi et al., 2008; Nguyen Thi et al., 2014). Others have proposed that the carbonatites originated from the high-K subvolcanic intrusions of the Pu Sam Cap complex and have strong associations with Paleogene lamprophyres and lamproites in the region (Huong, 1994; Chi, 2003; Chi et al., 2008). Thi et al. reported a crystallization age of 30.2–31.6 Ma for the ferrocarbonatite based on U–Th–Pb isochrons (Nguyen Thi et al., 2014).

Nam Xe REEs deposit. This deposit is located on both sides of the Nam Xe River valley and divided by the east-west striking Ban Pan-Phong Tho fault into a northern and a southern part (Möckel et al., 2019). The southern deposit comprises carbonatitic dyke-like structures in the host rocks of Triassic trachyandesite and Permian limestone, where the northern deposit is a deeply weathered residual with a thickness up to 40 m, laying on top of Permian limestone (Phan et al., 2019). In the northern deposit, the weathered profile has a total REOs head grade of 4–5 wt% while the primary ores in the southern deposit show an average content of total REOs about 1.4 wt% (Cardenas-Vera et al., 2022). The Nam Xe orebodies are exceptionally rich in HREEs, especially Y, Eu, and Gd, and REEs associated minerals are parisite, bastnaesite, gadolinite, apatite (Moody, 2013).

4.2.2. Alkaline granitic rocks and their weathered residuum

Alkaline granitic rocks are widely distributed in the Tu Le basin and Phan Si Pan (PSP) Uplift area in Northwestern Vietnam. These areas lie along the boundary between the Archean-Proterozoic South China Block and the accreted Gondwanan terranes of Southeast Asia. The northern part of this region is known as the Ailaoshan-Red River shear zone, while the southern area is defined by the Song Ma suture (Fig. 5) (Pham et al., 2020). The PSP uplift primarily consists of alkaline and sub-alkaline Phanerozoic granitoids found in the areas of the Phu Sa Phin, Muong Hum, Ye Yen Sun, and Phan Si Pan. Besides, Archean metagranitoids of the Ca Vinh complex, as well as Paleoproterozoic Xom Giau and Neoproterozoic Po Sen granitoid complexes are also developed in this region (Usuki et al., 2015). In contrast, the Tu Le basin is composed of rhyolite and trachyte of Jurassic to Cretaceous age (Luong, 1988; Anh et al., 2004). Related REE deposits are located in Dong Pao, Muong Hum, Yen Phu, and Then Chan. The Dong Pao REEs deposit is famous for its ion-adsorption clay deposits (Tao et al., 2022).

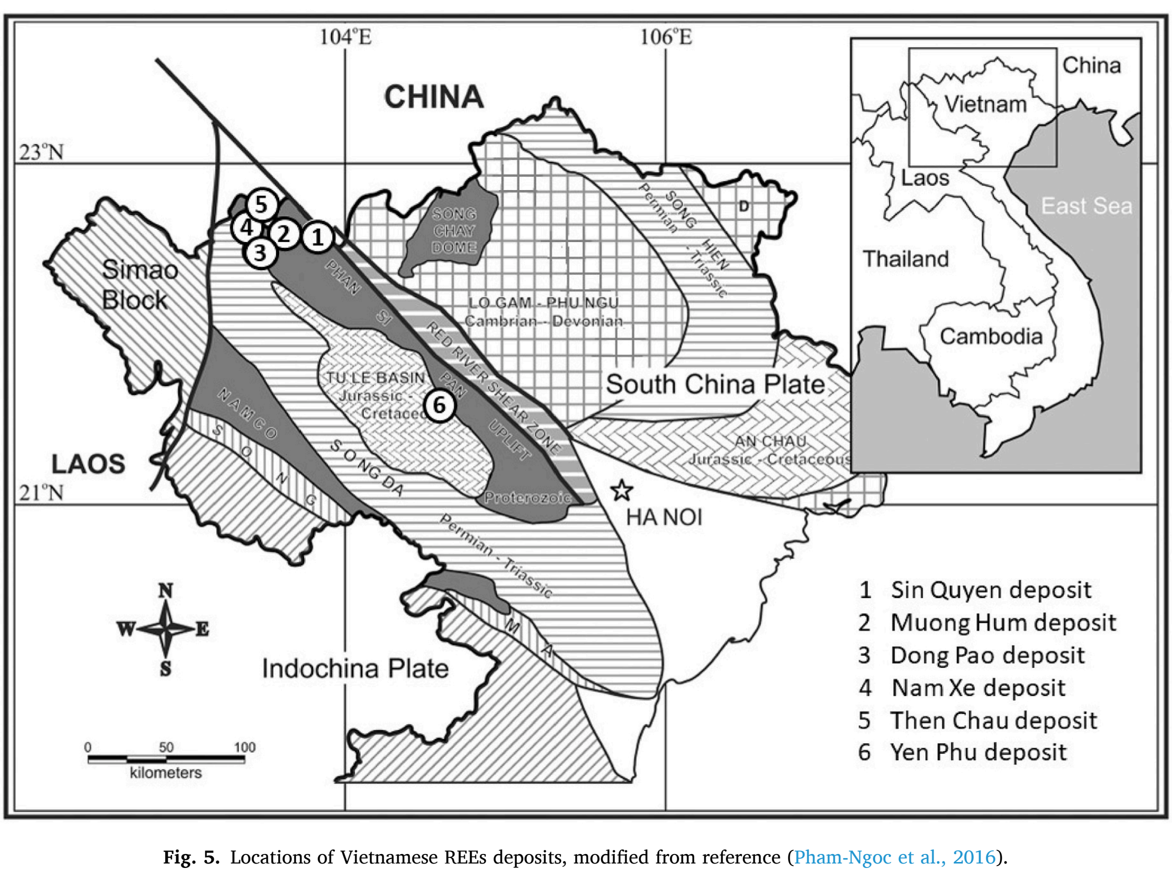

Fig. 5. Locations of Vietnamese REEs deposits, modified from reference (Pham-Ngoc et al., 2016).

4.2.3. Iron oxide-copper-gold deposit

The well-known deposit of this type is the Sin Quyen IOCG-REE deposit, considered one of the largest IOCG deposits in the north of Vietnam (Lao Cai province) (Li and Zhou, 2018). It is situated in the Phan Si Pan uplift, in close proximity to the Red River shear zone (Duong et al., 2021). The ore body primarily occurs within the Proterozoic metamorphic and sedimentary rocks of the Sin Quyen formation, particularly in contact with granite-gneiss and amphibolites (Ta, 1975). Recent studies (Ngo et al., 2020; Duong et al., 2021) have reported two stages of mineralization at approximately 880 Ma and 840 Ma, respectively. The first mineralization stage lead to the REE-rich allanite formation, whereas the main IOCG ores were formed during the second mineralization stage, leading to extensive alteration of the primary allanite, see Fig. 6a and b. A zipper tectonic model has been proposed to explain the mineralization process (Fig. 6c). In this model, the clockwise rotation of the Indochina block led to the emergence of three distinct tectonic stress regimes: one characterized by a compressive regime, another by a pure strike-slip regime, and the remaining one by an extensional regime. The Sin Quyen IOCG deposits are situated within the Red River shear zone of the pure strike-slip zone (Duong et al., 2021). The REE-bearing minerals are enriched in LREEs such as La, Ce, Pr and Nd, including bastnäsite-(Ce), monazite-(Ce), allanite-(Ce), chevkinite-(Ce), columbite-(Fe), aeschynite-(Ce), and ilmenite (Li and Zhou, 2017; Pieczonka et al., 2019). The proven reserves of the Sin Quyen deposit amount to 52.8 Mt of ore, containing 0.7% LREE (La, Ce, and Nd), as well as 14% Fe, 0.91% Cu, and 0.44 g/t Au (McLean, 2002).

4.3. Brazil

REE deposits in Brazil are associated with various geological features such as carbonatites, alkaline granitic rocks, residual weathering, and marine placers. Brazil possesses the world's third largest REE resource; however, the production of REEs in 2022 was only 80 tons (Table 2). This limited production could be attributed to the relatively smaller size of the deposits and the mining techniques employed. Currently, three primary REE projects are in progress: the Araxá project in Araxá alkaline carbonatite, Minas Gerais State; the Serra Verde Project (an IAD) in the Serra Dourada biotite granite, Goiás State; and the Pitinga Project in the Madeira alkali granite, Amazonas State (Takehara et al., 2016).

4.3.1. Carbonatite-related REE deposits and their weathered residuals

The alkaline-carbonatite complexes are mainly distributed in the margins of the Amazonas, Paraná, and Paranaíba basins and are associated with fracture zones (Dardenne and Schobbenhaus, 2001; Biondi, 2003). These complexes typically exhibit circular structures and form radial drainage patterns (Biondi, 2003). Extensive tropical weathering has resulted in the development of thick weathering profiles, reaching depths of over 250 m. Monazite, apatite, zircon, pyrochlore, and calcite are the primary minerals associated with REE mineralization, while in the residual weathered material, monazite becomes the dominant REE-bearing mineral, accompanied by minor secondary apatite and aluminum phosphates (Morteani and Preinfalk, 1996; de Oliveira and Imbernon, 1998; Takehara et al., 2016).

Araxá REE deposit. The Araxá REE deposit consists of deeply weathered residual overlaying the Barrairo do Araxá carbonatite complex, with REEs mainly occurring within monazite and goyazite. The Araxá carbonatite circular intrusion is located in the Barreiro area, with a diameter of roughly 4.5 km, and around 16 km^2 in area (Traversa et al., 2001). Evidence suggests that the Araxá carbonatite has been there since the late Precambrian, while significant amounts of magma types and igneous forms were intruded during the Mesozoic era (Traversa et al., 2001). Additionally, studies by Gibson et al. indicate that the alkaline magmatism in this region happened between 80 and 90 million years ago (Gibson et al., 1995). In carbonatite rocks, REE mineralization is primarily found in minerals like apatite, pyrochlore, zircon, monazite, and calcite (Morteani and Preinfalk, 1996), whereas in the residual weathered material, monazite, aluminum phosphates, and secondary apatite are the main REE-bearing minerals (Morteani and Preinfalk, 1996; de Oliveira and Imbernon, 1998; Toledo, 1999).

4.3.2. Alkaline granitic rocks and their weathered residuals

Alkaline granitic rocks related REE-bearing deposits are the second primary source in Brazil, and are enriched in HREEs. These deposits are typically found within multiphase anorogenic granite complexes. During the later stages of magma fractional crystallization, incompatible elements, including REEs, become highly enriched (Hannah and Stein, 1990). In the case of alkaline granitic deposits, in contrast to carbonatite deposits, HREEs tend to concentrate in the lower part of the weathered residuals, forming ion-adsorption clay deposits. HREEs are mainly associated with minerals such as xenotime, fergusonite, samarskite, and gagarinite. One renowned deposit of this type is the Pitinga deposit (Pollard, 1995; Wu et al., 1995; Long et al., 2012).

4.3.3. Placers

Placer deposits in Brazil are known for heavy minerals including ilmenite, zircon, rutile, and monazite, especially monazite (Möller, 1986; Dardenne and Schobbenhaus, 2001; Pires and Miano, 2014). These heavy minerals are the weathered products of continental igneous

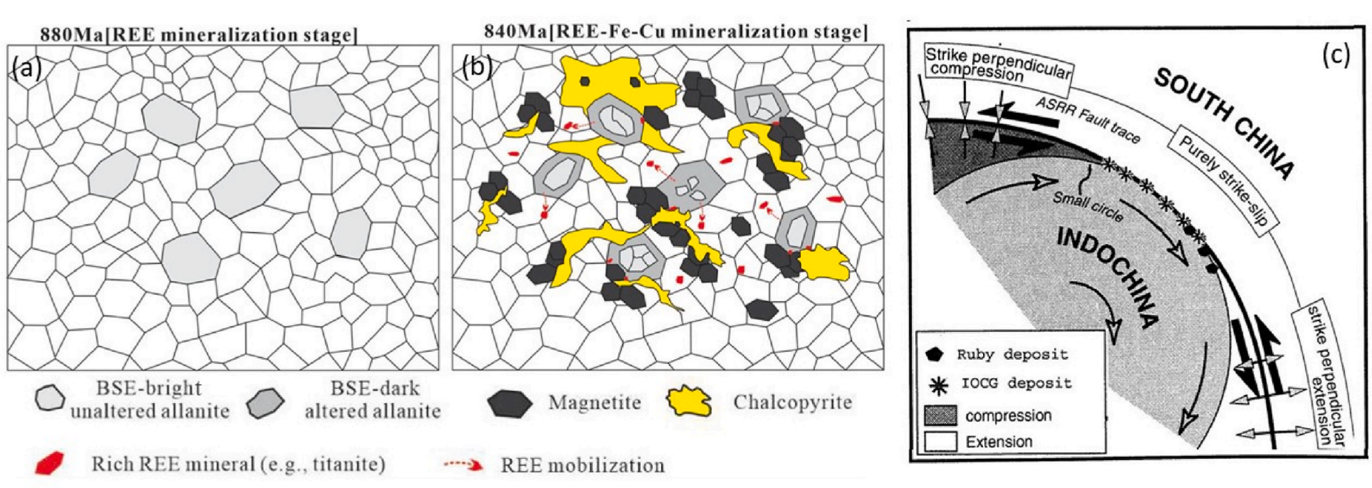

Fig. 6. Two metallogenic episodes showing REE mineralization of early stage (a) and remobilization of later stage (b). A proposed zipper tectonic model for the Sin Quyen IOCG-REE mineralization (c). Data from references (Ngo et al., 2020; Duong et al., 2021).

rocks which formed during orogenic events, and mainly concentrated in the Tertiary-aged units, for example, a lot of shoreline deposits are hosted in the Barreira group (Sengupta and Van Gosen, 2016; Takehara et al., 2016). REEs that occur within these heavy minerals are scattered along the Brazilian coast, ranging from Pará to Rio Grande do Sul (Cavalcanti, 2011). Placer deposits were historically the first deposits that were mined for REEs in Brazil and were critical resources until the mid-1960s (Serra, 2011).

4.4. Australia, India, USA, and other countries

These countries possess numerous medium to small REE deposits; however, the individual REE reserves of each country do not exceed 3 wt % of the global total (Table 2). Australia's rare earth mines are primarily extracted from placers, carbonatites and their weathering residuals, and IOCG (Mudd, 2008; Jaireth et al., 2014; Subasinghe et al., 2022). Additionally, Australia used to be the world's largest monazite supplier because of the widespread distribution of heavy mineral sand placer deposits containing REE minerals along its coastline. This dominance continued from the early years up to the mid-1990s (Mudd, 2008; Jaireth et al., 2014; Subasinghe et al., 2022). Today, Mount Weld is Australia's leading rare earth ore producing area (Zhukova et al., 2021). The main sources of REE deposits in India are predominantly carbonatites and placers (Krishnamurthy, 2020; Verplanck, 2020). A notable potential for REE resources in beach placers has been identified along the southern coast of Odisha, India, stretching from Garampeta to Markandi beach (Ghosal et al., 2020). While carbonatites constitute the major REE deposits in the USA, there are also small amounts of hydrothermal REE deposits, placers, and alkaline igneous rocks associated deposits. Also, there have been proposals suggesting marine phosphorites and coals as potential sources of REE (Castor, 2008; Long et al., 2012). Currently, carbonatite-related REE are mined in the USA from Mountain Pass, but REEs are also produced as a byproduct of mining Ti and Zr in beach placers (Bailey, 2021), such as Georgia coastal region (Oladeni, 2022). Studies have also indicated a high concentration of REE in the mined kaolin ore, kaolin mine tailings, and the kaolin-associated sands, resulting from the weathering of granitic parent rocks in the upper coastal plain of central Georgia (Cheshire et al., 2018; Boxleiter and Elliott, 2023). In regions of the Russian Far East, coal deposits have high concentrations of REEs (ranging from 300 to 1000 ppm) (Seredin, 1996). Furthermore, some European countries are formulating strategies to extract REEs as by-products of phosphate mining, particularly from apatite. Recent reports have indicated the sub-economic potential of REE resources in iron ore deposits, such as the Per Geijer deposit (Sweden), in association with phosphate mining, this deposit is the biggest reported REE deposit in Europe (Decrée et al., 2023). There are numerous reviews examining the REE resources in other various countries or districts, including Africa (Harmer and Nex, 2016; Buccione et al., 2021), Greenland (Thrane et al., 2014), Europe (Charles et al., 2013; Decrée et al., 2023), Russia (Kalashnikov et al., 2016), Sri Lanka (Batapola et al., 2020), the Democratic Republic of Congo (Kasay et al., 2022), Philippines (Gibaga et al., 2022), and Mongolia (Dostal and Gerel, 2023). Some notable REE deposits are summarized below.

Mount Weld REE deposit, Australia. This deposit is close to Laverton, Western Australia, about 35 km to the southeast. and represents a weathering residual associated with carbonatites, with a thickness of up to 90 m (Willett et al., 1986). The carbonatite is situated within the Laverton Tectonic Zone and is surrounded by late Archean volcanic-sedimentary sequences (Henson et al., 2010). The primary carbonatite complex is dominated by coarse calcite-carbonatite, with small amounts of dolomite- and ferro-carbonatite, as well as phoscorite. A glimmerite alteration zone, approximately 0.5 km wide, developed around the central deposit. Studies indicate that this carbonatite complex formed around 2025 Ma (Nelson et al., 1988; Graham et al., 2004; Czarnota et al., 2010). The weathering of the carbonatite has resulted in the decomposition of primary carbonatite, leading to the formation of apatite-rich residual zones (Lottermoser, 1990). This process has contributed to Mount Weld being one of the highest-grade REE deposits globally, with 23.8 million tonnes of ore grading at 7.9%. Additionally, minor amounts of Nb, Ta, and P_2O_5, are present as by-products. REEs are found in various minerals, including monazite, churchite, plumbogummite-group minerals, and rhabdophane (Lottermoser, 1990).

Mountain Pass REE deposit, USA. This deposit is located in the central Mojave Desert of California, USA, and is known for owning the world's second largest REE deposit. The REEs are enriched in the Sulphide Queen Carbonatite, a special carbonatite that differs from others in the world. Unlike most carbonatites that are associated with alkaline rocks, this carbonatite is associated to the ultrapotassic alkaline rocks, by intruding into the latter as a tabular intrusion (Castor, 2008). However, the Th–Pb dates of monazite indicate this carbonatite has an age of 1375 ± 7 Ma, younger than that of the ultrapotassic rocks (1400 ± 7 Ma) (DeWitt et al., 1987). Studies have suggested that the carbonatite magma shares a common origin with the ultrapotassic rocks, likely derived from mantle sources enriched through metasomatism or contamination by subducted crustal rocks (Castor, 2008). But the origin of the carbonatite in the Mountain Pass deposit still remains highly controversial (Haxel, 2005; Poletti et al., 2016). For example, carbonatites are surrounded by a fenitisation alteration zone, or existed fluorite veins suggesting a hypothesis of alkali metasomatism (Smith et al., 2016). The major and trace elements analysis of the carbonatite and ultrapotassic rocks imply that these two rocks originated from separate mantle melts (Poletti et al., 2016). Bastnaesite-(Ce) is the major REE-bearing mineral with minor monazite-(Ce) and parisite-(Ce) (Smith et al., 2016). This deposit is extremely enriched in LREEs with an ore grade of 8.5% total REOs but Nb depleted (Castor, 2008; Smith et al., 2016; Zhou et al., 2016), and it used to be the largest LREE mining project from the 1960s to the mid-1990s in the world (Castor, 2008). The mining of this deposit was stopped several times for various reasons but was reopened again in the first quarter of 2018 to meet the domestic high REE demand (Koltun and Tharumarajah, 2014; Ash, 2019).

5. Conclusions

REEs are crucial for various high-technological industrial applications, given their special physicochemical properties. They find extensive use in metallurgy, energy, military, and agriculture sectors, leading to a steady growth in demand. However, the production of REEs is limited by geographical constraints, mining and smelting technologies, and policies, among other factors. As a result, the global supply of REEs remains unstable and uncertain. Currently, many countries are actively seeking to acquire additional REE resources to meet their domestic needs. In light of these circumstances, we aimed to provide a timely and in-depth review of REE mineralogy, occurrences, distributions, and the genesis of major REE deposits. The goal was to enhance our understanding of REE resources worldwide and aid in the exploration of new REE mineral deposits. Although we have classified REE deposits based on their occurrences, the majority cannot be attributed to a single mineralization process. This is because mineralization resulting from geological activities is often a complex process involving multiple periods, stages, and interrelated constraints. At present, carbonatite-related REE deposits and their weathered residuals, and IADs stand out as the most prominent REE deposits being actively exploited globally. But REE-enriched phosphate deposits and coal mines have the potential to serve as a substantial resource for REE. China remains the world's largest producer of REEs, but countries worldwide are expanding their domestic REE production capacity to alleviate concerns about the supply of rare earths due to geopolitical policies.

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CRediT authorship contribution statement

Ping Chen: Writing – review & editing, Writing – original draft, Investigation, Conceptualization. **Eugene S. Ilton:** Writing – review & editing. **Zheming Wang:** Writing – review & editing. **Kevin M. Rosso:** Writing – review & editing, Funding acquisition, Conceptualization. **Xin Zhang:** Writing – review & editing, Writing – original draft, Supervision, Investigation, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare no competing financial interest.

Data availability

The data that has been used is confidential.

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References

Ahmed, A., Aseri, A., Ali, K., 2022. Geological and geochemical evaluation of phosphorite deposits in northwestern Saudi Arabia as a possible source of trace and rare-earth elements. Ore Geol. Rev. 144, 104854.
Amalan, K., Ratnayake, A.S., Ratnayake, N.P., Weththasinghe, S.M., Dushyantha, N., Lakmali, N., Premasiri, R., 2018. Influence of nearshore sediment dynamics on the distribution of heavy mineral placer deposits in Sri Lanka. Environ. Earth Sci. 77, 1–13.
Andersen, A.K., Clark, J.G., Larson, P.B., Donovan, J.J., 2017. REE fractionation, mineral speciation, and supergene enrichment of the Bear Lodge carbonatites, Wyoming, USA. Ore Geol. Rev. 89, 780–807.
Andersen, A.K., Clark, J.G., Larson, P.B., Neill, O.K., 2016. Mineral chemistry and petrogenesis of a HFSE (+ HREE) occurrence, peripheral to carbonatites of the Bear Lodge alkaline complex, Wyoming. Am. Mineral. 101, 1604–1623.
Andreoli, M., Smith, C., Watkeys, M., Moore, J., Ashwal, L., Hart, R., 1994. The geology of the Steenkampskraal monazite deposit, South Africa; implications for REE-Th-Cu mineralization in charnockite-granulite terranes. Econ. Geol. 89, 994–1016.
Anenburg, M., Broom-Fendley, S., Chen, W., 2021. Formation of rare earth deposits in carbonatites. Elements: An International Magazine of Mineralogy, Geochemistry, and Petrology 17, 327–332.
Anenburg, M., Mavrogenes, J.A., Frigo, C., Wall, F., 2020. Rare earth element mobility in and around carbonatites controlled by sodium, potassium, and silica. Sci. Adv. 6, eabb6570.
Anh, T.T., Hoa, T.T., Lan, C., Chung, S., Lo, C., Wang, P., Merzman, S., 2004. Mesozoic bimodal alkaline magmatism in the Tu Le basin, North Vietnam: constraints from geochemical and isotopic significances. J. Geol. 24, 1–9.
Ash, S., 2019. Mineral Commodity Summaries 2019. US Geological Survey, Reston, VA.
Atwood, D.A., 2013. The Rare Earth Elements: Fundamentals and Applications. John Wiley & Sons.
Auer, G., Reuter, M., Hauzenberger, C.A., Piller, W.E., 2017. The impact of transport processes on rare earth element patterns in marine authigenic and biogenic phosphates. Geochem. Cosmochim. Acta 203, 140–156.
Bagdonas, D., Enriquez, A., Coddington, K., Finnoff, D., McLaughlin, J., Bazilian, M., Phillips, E., McLing, T., 2022. Rare earth element resource evaluation of coal byproducts: a case study from the Powder River Basin, Wyoming. Renew. Sustain. Energy Rev. 158, 112148.
Bailey, M.P., 2021. US-European rare earth production initiative launched. Chem. Eng. News. March 8, 2021. (Accessed 10 December 2021).
Baker, M.B., Wyllie, P.J., 1990. Liquid immiscibility in a nephelinite–carbonate system at 25 kbar and implications for carbonatite origin. Nature 346, 168–170.
Balaram, V., 2019. Rare earth elements: a review of applications, occurrence, exploration, analysis, recycling, and environmental impact. Geosci. Front. 10, 1285–1303.
Bao, Z., Zhao, Z., 2008. Geochemistry of mineralization with exchangeable REY in the weathering crusts of granitic rocks in South China. Ore Geol. Rev. 33, 519–535.
Batapola, N., Dushyantha, N., Premasiri, H., Abeysinghe, A., Rohitha, L., Ratnayake, N., Dissanayake, D., Ilankoon, I., Dharmaratne, P., 2020. A comparison of global rare earth element (REE) resources and their mineralogy with REE prospects in Sri Lanka. J. Asian Earth Sci. 200, 104475.
Beard, C.D., Goodenough, K.M., Borst, A.M., Wall, F., Siegfried, P.R., Deady, E.A., Pohl, C., Hutchison, W., Finch, A.A., Walter, B.F., 2023. Alkaline-silicate REE-HFSE systems. Econ. Geol. 118, 177–208.
Beland, C.M., Williams-Jones, A.E., 2021. The mineralogical distribution of the REE in carbonatites: a quantitative evaluation. Chem. Geol. 585, 120558.
Bide, T., Brown, T., Gunn, A., Deady, E., 2022. Development of decision-making tools to create a harmonised UK national mineral resource inventory using the United Nations Framework Classification. Resour. Pol. 76, 102558.
Binnemans, K., Jones, P.T., Blanpain, B., Van Gerven, T., Yang, Y., Walton, A., Buchert, M., 2013. Recycling of rare earths: a critical review. J. Clean. Prod. 51, 1–22.
Biondi, J.C., 2003. Processos metalogenéticos e os depósitos minerais brasileiros. Oficina de Textos.
Boxleiter, A., Elliott, W.C., 2023. Rare-earth minerals in kaolin ore, mine tailings, and sands–Central Georgia, upper coastal plain. Clay Clay Miner. 1–35.
Broom-Fendley, S., Brady, A.E., Wall, F., Gunn, G., Dawes, W., 2017. REE minerals at the Songwe Hill carbonatite, Malawi: HREE-enrichment in late-stage apatite. Ore Geol. Rev. 81, 23–41.
Buccione, R., Kechiched, R., Mongelli, G., Sinisi, R., 2021. REEs in the North Africa P-Bearing deposits, paleoenvironments, and economic perspectives: a review. Minerals 11, 214.
Cangelosi, D., Smith, M., Banks, D., Yardley, B., 2020. The role of sulfate-rich fluids in heavy rare earth enrichment at the Dashigou carbonatite deposit, Huanglongpu, China. Mineral. Mag. 84, 65–80.
Cardenas-Vera, A., Hesse, M., Möckel, R., Merker, R.G., Heinig, T., Van Phan, Q., 2022. Investigation of Sensor-Based sorting and selective comminution for pre-concentration of an unusual parisite-rich REE ore, South Namxe, Vietnam. Miner. Eng. 177, 107371.
Castor, S.B., 2008. Rare earth deposits of North America. Resour. Geol. 58, 337–347.
Castor, S.B., Hedrick, J.B., 2006. Rare earth elements. In: Kogel, J.E., Trivedi, N.C., Barker, J.M., Krukowski, S.T. (Eds.), Industrial Minerals and Rocks: Commodities, Markets, and Uses, vol. 7. Society for Mining Mineralogy, United States, pp. 769–792.
Cavalcanti, V.M.M., 2011. Plataforma Continental: A Última Fronteira da Mineração Brasileira, vol. 104. DNPM, Brasília.
Chakhmouradian, A.R., Zaitsev, A.N., 2012. Rare earth mineralization in igneous rocks: sources and processes. Elements 8, 347–353.
Chao, E., Back, J., Minkin, J., Yinchen, R., 1992. Host-rock controlled epigenetic, hydrothermal metasomatic origin of the Bayan Obo REEFe-Nb ore deposit, Inner Mongolia, PRC. Appl. Geochem. 7, 443–458.
Charles, N., Tuduri, J., Guyonnet, D., Melleton, J., Pourret, O., 2013. Rare earth elements in Europe and Greenland: a geological potential? An overview. 12th meeting of the Society of Geology Applied to Mineral Deposits (SGA) 1698–1701.
Cheshire, M.C., Bish, D.L., Cahill, J.F., Kertesz, V., Stack, A.G., 2018. Geochemical evidence for rare-earth element mobilization during kaolin diagenesis. ACS Earth Space Chem. 2, 506–520.
Chi, N., Flower Martin, J., Hung, D., 2008. Carbonatites in phong Tho, Lai Chau province, north–west Vietnam: their petrogenesis and relationship with cenozoic potassic alkaline magmatism. The 33rd international geological congress in Oslo (Norway) 1–45.
Chi, N.T., 2003. Petrology and metallogeny of alkaline formations of North Vietnam. Rep. Proj. Research Institute of Geology and Mineral Resources.
Chu, G., Chen, H., Feng, Y., Wu, C., Li, S., Zhang, Y., Lai, C.-K., 2024. Are South China granites special in forming ion-adsorption REE deposits? Gondwana Res. 125, 82–90.
Ciacci, L., Vassura, I., Cao, Z., Liu, G., Passarini, F., 2019. Recovering the "new twin": analysis of secondary neodymium sources and recycling potentials in Europe. Resour. Conserv. Recycl. 142, 143–152.
Conrad, R., 2017. Report on Rare Earth Elements from Coal and Coal Byproducts. US Department of Energy, Washington, DC.
Cronan, D.S., 1999. In: Handbook of Marine Mineral Deposits. CRC Marine Science Series, vol. 17. CRC Press, Boca Raton. ISBN 0-8493-8429-X.
Czarnota, K., Champion, D., Goscombe, B., Blewett, R., Cassidy, K., Henson, P., Groenewald, P., 2010. Geodynamics of the eastern yilgarn craton. Precambrian Res. 183, 175–202.
Dai, S., Graham, I.T., Ward, C.R., 2016. A review of anomalous rare earth elements and yttrium in coal. Int. J. Coal Geol. 159, 82–95.
Dai, S., Li, D., Chou, C.-L., Zhao, L., Zhang, Y., Ren, D., Ma, Y., Sun, Y., 2008. Mineralogy and geochemistry of boehmite-rich coals: new insights from the haerwusu surface mine, jungar coalfield, inner Mongolia, China. Int. J. Coal Geol. 74, 185–202.
Damhus, T., Hartshorn, R., Hutton, A., 2005. Nomenclature of Inorganic Chemistry: IUPAC Recommendations 2005. Royal Society of Chemistry, Cambridge, UK.

Dardenne, M.A., Schobbenhaus, C.S., 2001. Metalogênese Do Brasil. Editora Universidade de Brasília/CNPq, Brasília.
de Oliveira, S.M.B., Imbernon, R.A.L., 1998. Weathering alteration and related REE concentration in the Catalão I carbonatite complex, central Brazil. J. S. Am. Earth Sci. 11, 379–388.
Deady, E., 2021. Global rare earth element (REE) mines, deposits and occurences (May 2021). British Geological Survey.
Decrée, S., Coint, N., Debaille, V., Hagen-Peter, G., Leduc, T., Schiellerup, H., 2023. The potential for REEs in igneous-related apatite deposits in Europe. Geol. Soc. Lon. Spec. PubL. 526, 251–265.
Deng, Z.X., Qin, L., Wang, G.S., Luo, S.H., Peng, C.L., Li, Q., 2019. Metallogenic process of ion adsorption REE ore based on the occurrence regularity of La in kaolin. Ore Geol. Rev. 112, 103022.
DeWitt, E., Kwak, L., Zartman, R., 1987. U-Th-Pb and 40Ar/39Ar Dating of the Mountain Pass Carbonatite and Alkalic Igneous Rocks, Southeastern California, 1987 Annual Meeting of the Geological Society of America. Society of Economic Geologists, Phoenix, Arizona.
Dostal, J., 2017. Rare earth element deposits of alkaline igneous rocks. Resources 6, 34.
Dostal, J., Gerel, O., 2023. Rare earth element deposits in Mongolia. Minerals 13, 129.
Drobniak, A., Mastalerz, M., 2022. Rare earth elements: a brief overview. Ind. j. earth sci. 4.
Duong, V.H., Trinh, P.T., Nguyen, T.D., Piestrzyski, A., Nguyen, D.C., Pieczonka, J., Ngo, X.D., Van, P.T., Pham, B.T., Nguyen-Van, H., 2021. Cu-Au mineralization of the Sin Quyen deposit in north Vietnam: a product of Cenozoic left-lateral movement along the Red River shear zone. Ore Geol. Rev. 132, 104065.
Dushyantha, N., Batapola, N., Ilankoon, I., Rohitha, S., Premasiri, R., Abeysinghe, B., Ratnayake, N., Dissanayake, K., 2020. The story of rare earth elements (REEs): occurrences, global distribution, genesis, geology, mineralogy and global production. Ore Geol. Rev. 122, 103521.
Emsbo, P., McLaughlin, P.I., Breit, G.N., du Bray, E.A., Koenig, A.E., 2015. Rare earth elements in sedimentary phosphate deposits: solution to the global REE crisis? Gondwana Res. 27, 776–785.
Estrade, G., Marquis, E., Smith, M., Goodenough, K., Nason, P., 2019. REE concentration processes in ion adsorption deposits: evidence from the Ambohimirahavavy alkaline complex in Madagascar. Ore Geol. Rev. 112, 103027.
Fan, H.R., Hu, F.F., Yang, K.F., Pirajno, F., Liu, X., Wang, K.Y., 2014. Integrated U–Pb and Sm–Nd geochronology for a REE-rich carbonatite dyke at the giant Bayan Obo REE deposit, Northern China. Ore Geol. Rev. 63, 510–519.
Fan, H.R., Yang, K.F., Hu, F.F., Liu, S., Wang, K.Y., 2016. The giant Bayan Obo REE-Nb-Fe deposit, China: controversy and ore genesis. Geosci. Front. 7, 335–344.
Filho, W.L., Kotter, R., Özuyar, P.G., Abubakar, I.R., Eustachio, J.H.P.P., Matandirotya, N.R., 2023. Understanding rare earth elements as critical raw materials. Sustainability 15, 1919.
Finkelman, R.B., 1993. Trace and Minor Elements in Coal, Organic Geochemistry: Principles and Applications. Springer, pp. 593–607.
Finkelman, R.B., Palmer, C.A., Wang, P., 2018. Quantification of the modes of occurrence of 42 elements in coal. Int. J. Coal Geol. 185, 138–160.
Foley, S., Yaxley, G., Rosenthal, A., Buhre, S., Kiseeva, E., Rapp, R., Jacob, D., 2009. The composition of near-solidus melts of peridotite in the presence of CO2 and H2O between 40 and 60 kbar. Lithos 112, 274–283.
Folkedahl, B., Nyberg, C., Biswas, S., Zhang, X., 2023. Round-robin interlaboratory study on rare-earth elements in US-based geologic materials. Minerals 13, 944.
Fu, B., Hower, J.C., Zhang, W., Luo, G., Hu, H., Yao, H., 2022. A review of rare earth elements and yttrium in coal ash: content, modes of occurrences, combustion behavior, and extraction methods. Prog. Energy Combust. Sci. 88, 100954.
Geng, Y., Sarkis, J., Bleischwitz, R., 2023. How to build a circular economy for rare-earth elements. Nature 619, 248–251.
Ghosal, S., Agrahari, S., Banerjee, S., Chakrabarti, R., Sengupta, D., 2020. Geochemistry of the heavy mineral sands from the Garampeta to the Markandi beach, southern coast of Odisha, India: implications of high contents of REE and radioelements attributed to placer monazite. J. Earth Syst. Sci. 129, 1–12.
Gibaga, C.R.L., Samaniego, J.O., Tanciongco, A.M., Quierrez, R.N.M., Montano, M.O., Gervasio, J.H.C., Reyes, R.C.G., Peralta, M.J.V., 2022. The rare earth element (REE) potential of the Philippines. J. Geochem. Explor., 107082
Gibson, S., Thompson, R., Leonardos, O., Dickin, A., Mitchell, J., 1995. The Late Cretaceous impact of the Trindade mantle plume: evidence from large-volume, mafic, potassic magmatism in SE Brazil. J. Petrol. 36, 189–229.
Gittins, J., 1988. The origin of carbonatites. Nature 335, 295–296.
Goodenough, K.M., Wall, F., Merriman, D., 2018. The rare earth elements: demand, global resources, and challenges for resourcing future generations. Nat. Resour. Res. 27, 201–216.
Graham, S., Lambert, D., Shee, S., 2004. The petrogenesis of carbonatite, melnoite and kimberlite from the eastern goldfields province, yilgarn craton. Lithos 76, 519–533.
Green, C., Simandl, G.J., Paradis, S., Katay, F., Hoshino, M., Kon, Y., Kodama, S., Graf, C., 2017. Geological setting of the rock Canyon Creek REE-fluorite deposit, British Columbia, Canada. In: Geological Fieldwork 2016, 2017-1. British Columbia Ministry of Energy and Mines. British Columbia Geological Survey, Canada, pp. 195–203.
Groves, D.I., Bierlein, F.P., Meinert, L.D., Hitzman, M.W., 2010. Iron oxide copper-gold (IOCG) deposits through Earth history: implications for origin, lithospheric setting, and distinction from other epigenetic iron oxide deposits. Econ. Geol. 105, 641–654.
Hamilton, D., Freestone, I.C., Dawson, J.B., Donaldson, C.H., 1979. Origin of carbonatites by liquid immiscibility. Nature 279, 52–54.
Han, A.P., Ge, J.P., Lei, Y.L., 2015. An adjustment in regulation policies and its effects on market supply: game analysis for China's rare earths. Resour. Pol. 46, 30–42.
Hannah, J.L., Stein, H.J., 1990. Magmatic and hydrothermal processes in ore-bearing systems. In: Stein, H.J., Hannah, J.L. (Eds.), Ore-bearing Granite Systems; Petrogenesis and Mineralizing Processes, vol. 246. Geol. Soc. Am, pp. 1–10. Special Paper.
Harben, P., 2002. In: The Industrial Mineral Handy Book-A Guide to Markets, Specifications and Prices, fourth ed., vol. 412. Industrial Mineral Information, Worcester Park.
Harlov, D.E., Meighan, C.J., Kerr, I.D., Samson, I.M., 2016. Mineralogy, chemistry, and fluid-aided evolution of the Pea Ridge Fe oxide-(Y+ REE) deposit, southeast Missouri, USA. Econ. Geol. 111, 1963–1984.
Harmer, R., Gittins, J., 1998. The case for primary, mantle-derived carbonatite magma. J. Petrol. 39, 1895–1903.
Harmer, R., Nex, P., 2016. Rare earth deposits of Africa. Episodes J. Int. Geosci. 39, 381–406.
Haxel, G., 2005. Ultrapotassic Mafic Dikes and Rare Earth Elements-And Barium-Rich Carbonatite at Mountain Pass, Mojave Desert, Southern California: Summary and Field Trip Localities. US Geological Survey.
Haxel, G.B., Hedrick, J.B., Orris, G.J., 2002. Rare Earth Elements: Critical Resources for High Technology, vols. 087–02. USGS Fact Sheet.
Hayes-Labruto, L., Schillebeeckx, S.J., Workman, M., Shah, N., 2013. Contrasting perspectives on China's rare earths policies: reframing the debate through a stakeholder lens. Energy Pol. 63, 55–68.
He, Y.L., Ma, L.Y., Li, X.R., Wang, H., Liang, X.L., Zhu, J.X., He, H.P., 2023. Mobilization and fractionation of rare earth elements during experimental bio-weathering of granites. Geochem. Cosmochim. Acta.
Henson, P., Blewett, R., Roy, I., Miller, J.M., Czarnota, K., 2010. 4D architecture and tectonic evolution of the Laverton region, eastern Yilgarn Craton, Western Australia. Precambrian Res. 183, 338–355.
Holtstam, D., Andersson, U.B., Broman, C., Mansfeld, J., 2014. Origin of REE mineralization in the bastnäs-type Fe-REE-(Cu-Mo-Bi-Au) deposits, bergslagen, Sweden. Miner. Deposita 49, 933–966.
Hu, X., Sun, B., Wang, C., Lim, M.K., Wang, P., Geng, X., Yao, C., Chen, W.-Q., 2023a. Impacts of China's exports decline in rare earth primary materials from a trade network-based perspective. Resour. Pol. 81, 103321.
Hu, X.Q., Sun, B.X., Wang, C., Lim, M.K., Wang, P., Geng, X.Y., Yao, C.Y., Chen, W.Q., 2023b. Impacts of China's exports decline in rare earth primary materials from a trade network-based perspective. Resour. Pol. 81, 103321.
Huang, J., Tan, W., Liang, X., He, H., Ma, L., Bao, Z., Zhu, J., 2021a. REE fractionation controlled by REE speciation during formation of the Renju regolith-hosted REE deposits in Guangdong Province, South China. Ore Geol. Rev. 134, 104172.
Huang, S., Fu, Y., 2023. Enrichment characteristics and mechanisms of critical metals in marine Fe-Mn crusts and nodules: a review. Minerals 13, 1532.
Huang, Y., He, H., Liang, X., Bao, Z., Tan, W., Ma, L., Zhu, J., Huang, J., Wang, H., 2021b. Characteristics and genesis of ion adsorption type REE deposits in the weathering crusts of metamorphic rocks in Ningdu, Ganzhou, China. Ore Geol. Rev. 135, 104173.
Humphries, M., 2019. Critical Minerals and US Public Policy, Report No. R45810. Congressional Research Service.
Huong, N., 1994. Concluded Report of Project:"standard Sample Suites of Geological Formations. Viet Nam". Documented in Institute of Geological. Informations–Archives and Museum, Hanoi (in Vietnamese).
Hussain, A., Zhao, K.-D., Arif, M., Palmer, M.R., Chen, W., Zhang, Q., Li, Q., Jiang, S.-Y., Girei, M.B., 2020. Geochronology, mineral chemistry and genesis of REE mineralization in alkaline rocks from the Kohistan Island Arc, Pakistan. Ore Geol. Rev. 126, 103749.
Iia, V., IuD, E., Son, N., Doc, N., 1961. Concluded Report of Exploring Project on Nam Xe Rare Earth–Ore Deposite (1958–1960 Stage). Documented in Institute of Geological Informations–Archives and Museum, Hanoi (in Vietnamese). 169pp.
Jaireth, S., Hoatson, D.M., Miezitis, Y., 2014. Geological setting and resources of the major rare-earth-element deposits in Australia. Ore Geol. Rev. 62, 72–128.
Jha, M.K., Kumari, A., Panda, R., Kumar, J.R., Yoo, K., Lee, J.Y., 2016. Review on hydrometallurgical recovery of rare earth metals. Hydrometallurgy 165, 2–26.
Jordens, A., Cheng, Y.P., Waters, K.E., 2013. A review of the beneficiation of rare earth element bearing minerals. Miner. Eng. 41, 97–114.
Kalantzakos, S., 2020. The race for critical minerals in an era of geopolitical realignments. Int. Spect. 55, 1–16.
Kalashnikov, A., Konopleva, N., Pakhomovsky, Y.A., Ivanyuk, G.Y., 2016. Rare earth deposits of the Murmansk region, Russia—a review. Econ. Geol. 111, 1529–1559.
Kanazawa, Y., Kamitani, M., 2006. Rare earth minerals and resources in the world. J. Alloys Compd. 408, 1339–1343.
Kasay, G.M., Bolarinwa, A.T., Aromolaran, O.K., Nzolang, C., Kivava, A.S., 2022. Rare earth element deposits and their prospects in the democratic republic of Congo. Min. Metall. Explor. 39, 625–642.
Ketris, M.á., Yudovich, Y.E., 2009. Estimations of Clarkes for Carbonaceous biolithes: world averages for trace element contents in black shales and coals. Int. J. Coal Geol. 78, 135–148.
Kjarsgaard, B., Hamilton, D., 1989. Carbonatite origin and diversity. Nature 338, 547–548.
Koltun, P., Tharumarajah, A., 2014. Life Cycle Impact of Rare Earth Elements. ISRn Metallurgy 2014.
Komar, P.D., 2007. The entrainment, transport and sorting of heavy minerals by waves and currents. Dev. Sedimentol. 58, 3–48.
Krakatoa, R.L., 2020. MT CLERE RARE EARTH PROJECT: 9 OCTOBER 2020.
Krishnamurthy, P., 2020. Rare metal (RM) and rare earth element (REE) resources: world scenario with special reference to India. J. Geol. Soc. India 95, 465–474.

Kynicky, J., Smith, M.P., Xu, C., 2012. Diversity of rare earth deposits: the key example of China. Elements 8, 361–367.
Lai, X., Yang, X., Santosh, M., Liu, Y., Ling, M., 2015. New data of the Bayan Obo Fe–REE–Nb deposit, Inner Mongolia: implications for ore genesis. Precambrian Res. 263, 108–122.
Lee, Y., Dacass, T., 2022. Reducing the United States' risks of dependency on China in the rare earth market. Resour. Pol. 77, 102702.
Lei, S., Na, W., Shuai, Z., Li, G., 2017. Overview on China's rare earth industry restructuring and regulation reforms. J. Resour. Ecol. 8, 213–222.
Lewicka, E., Guzik, K., Galos, K., 2021. On the possibilities of critical raw materials production from the EU's primary sources. Resources 10, 50.
Li, H.T., Yang, K.F., Gao, Y.P., Zhao, J., Yuan, X.Y., Li, X.C., Fan, H.R., 2022. Age and origin of the H9 member from the bayan Obo group: implications for the genesis of the giant bayan Obo Fe-Nb-REE deposit, China. Ore Geol. Rev. 146, 104927.
Li, X.C., Zhou, M.F., 2017. Hydrothermal alteration of monazite-(Ce) and chevkinite-(Ce) from the Sin Quyen Fe-Cu-LREE-Au deposit, northwestern Vietnam. Am. Mineral. 102, 1525–1541.
Li, X.C., Zhou, M.F., 2018. The nature and origin of hydrothermal REE mineralization in the Sin Quyen deposit, northwestern Vietnam. Econ. Geol. 113, 645–673.
Li, Y.H.M., Zhao, W.W., Zhou, M.F., 2017. Nature of parent rocks, mineralization styles and ore genesis of regolith-hosted REE deposits in South China: an integrated genetic model. J. Asian Earth Sci. 148, 65–95.
Liang, T., Li, K., Wang, L., 2014. State of rare earth elements in different environmental components in mining areas of China. Environ. Monit. Assess. 186, 1499–1513.
Lin, R., Soong, Y., Granite, E.J., 2018. Evaluation of trace elements in US coals using the USGS COALQUAL database version 3.0. Part I: rare earth elements and yttrium (REY). Int. J. Coal Geol. 192, 1–13.
Linares, E., Velasquez, G., Manrique, J., Monsalve, J., Mónaco, S.L., Shumlyanskyy, L., 2023. REE+ Y signatures of the Navay phosphate deposit, SW Venezuela: seawater paleoredox conditions and diagenetic implications. J. S. Am. Earth Sci. 129, 104532.
Linnen, R., Samson, I., Williams-Jones, A., Chakhmouradian, A., 2013. Geochemistry of the rare-earth element, Nb, Ta, Hf, and Zr deposits. In: Treatise on Geochemistry, second ed., pp. 543–568.
Liu, S., Fan, H.R., Groves, D.I., Yang, K.F., Yang, Z.F., Wang, Q.W., 2020. Multiphase carbonatite-related magmatic and metasomatic processes in the genesis of the ore-hosting dolomite in the giant Bayan Obo REE-Nb-Fe deposit. Lithos 354, 105359.
Liu, S.L., Fan, H.R., Liu, X., Meng, J., Butcher, A.R., Yann, L., Yang, K.F., Li, X.C., 2023. Global rare earth elements projects: new developments and supply chains. Ore Geol. Rev., 105428
Liu, Y., Hou, Z.Q., Tian, S.H., Zhang, Q.C., Zhu, Z.M., Liu, J.H., 2015. Zircon U-Pb ages of the Mianning-Dechang syenites, Sichuan Province, southwestern China: constraints on the giant REE mineralization belt and its regional geological setting. Ore Geol. Rev. 64, 554–568.
Long, K.R., Van Gosen, B.S., Foley, N.K., Cordier, D., 2012. The principal rare earth elements deposits of the United States: a summary of domestic deposits and a global perspective. In: Non-Renewable Resource Issues. Springer, pp. 131–155.
Lottermoser, B., 1990. Rare-earth element mineralisation within the Mt. Weld carbonatite laterite, Western Australia. Lithos 24, 151–167.
Luong, T.D., 1988. Geological Map of Vietnam: Scale 1: 500000. Institute of Information and Documentation.
Mancheri, N.A., 2012. Chinese monopoly in rare earth elements: supply–demand and industrial applications. China Rep. 48, 449–468.
Mancheri, N.A., Sprecher, B., Bailey, G., Ge, J., Tukker, A., 2019. Effect of Chinese policies on rare earth supply chain resilience. Resour. Conserv. Recycl. 142, 101–112.
Marks, M.A., Markl, G., 2017. A global review on agpaitic rocks. Earth Sci. Rev. 173, 229–258.
Martin, L.H., Schmidt, M.W., Mattsson, H.B., Guenther, D., 2013. Element partitioning between immiscible carbonatite and silicate melts for dry and H2O-bearing systems at 1–3 GPa. J. Petrol. 54, 2301–2338.
McKinney, S.T., Cottle, J.M., Lederer, G.W., 2015. Evaluating rare earth element (REE) mineralization mechanisms in Proterozoic gneiss, Music Valley, California. Bulletin 127, 1135–1152.
McLean, R.N., 2002. The Sin Quyen iron oxide-copper-gold-rare earth oxide mineralization of North Vietnam. In: Porter, T.M. (Ed.), Hydrothermal Iron Oxide Copper-Gold & Related Deposits: A Global Perspective 2. PGC Publishing, Adelaide, pp. 293–301.
Meshram, P., Pandey, B., 2019. Perspective of availability and sustainable recycling prospects of metals in rechargeable batteries–a resource overview. Resour. Pol. 60, 9–22.
Möckel, R., Heinig, T., Vera, A.F.C., Gutzmer, J., Merker, G., 2019. Beneficiation of parisite-rich rare earth ore from the Nam Xe South deposit, Vietnam. Proceedings of the 15th SGA Biennial Meeting, pp. 1508–1511.
Moldoveanu, G., Papangelakis, V., 2016. An overview of rare-earth recovery by ion-exchange leaching from ion-adsorption clays of various origins. Mineral. Mag. 80, 63–76.
Möller, P., 1986. Rare earth mineral deposits and their industrial importance. In: Möller, P., Cerny, P., Saupe, F. (Eds.), Lanthanides, Tantalum and Niobium: Mineralogy, Geochemistry, Characteristics of Primary Ore Deposits, Prospecting, Processing and Applications. Springer-Verlag, Berlin, pp. 171–188.
Moody, M.D., 2013. Mother lode: the untapped rare earth mineral resources of Vietnam. Department of Joint Military Operations. Thesis.
Morteani, G., Preinfalk, C., 1996. REE distribution and REE carriers in laterites formed on the alkaline complexes of Araxá and Catalão (Brazil). In: Jones, A.P., Wall, F., Williams, C.T. (Eds.), Rare Earth Minerals: Chemistry, Origin and Ore Deposits, Mineralogical Society Series, vol. 7. Chapman & Hall, London, pp. 227–255.
Mudd, G.M., 2008. Radon sources and impacts: a review of mining and non-mining issues. Rev. Environ. Sci. Biotechnol. 7, 325–353.
Nabyl, Z., Massuyeau, M., Gaillard, F., Tuduri, J., Iacono-Marziano, G., Rogerie, G., Le Trong, E., Di Carlo, I., Melleton, J., Bailly, L., 2020. A window in the course of alkaline magma differentiation conducive to immiscible REE-rich carbonatites. Geochem. Cosmochim. Acta 282, 297–323.
Nelson, D., Chivas, A., Chappell, B., McCulloch, M., 1988. Geochemical and isotopic systematics in carbonatites and implications for the evolution of ocean-island sources. Geochem. Cosmochim. Acta 52, 1–17.
Ngo, X.D., Zhao, X.F., Tran, T.H., Deng, X.D., Li, J.W., 2020. Two episodes of REEs mineralization at the Sin quyen IOCG deposit, NW Vietnam. Ore Geol. Rev. 125, 103676.
Nguyen Thi, T., Wada, H., Ishikawa, T., Shimano, T., 2014. Geochemistry and petrogenesis of carbonatites from South Nam Xe, Lai Chau area, northwest Vietnam. Mineral. Petrol. 108, 371–390.
Oh, M., Hildebrand, J., Lee, H.W., 2021. Enhancing US-Japan Cooperation on Global Supply Chains. Atlantic Council.
Oladeni, I.A., 2022. Rare-earth Element Occurrences in Heavy Mineral Sand, Southeast Georgia. Georgia State University, Atalanta, GA, USA. Master Thesis.
Orris, G.J., Grauch, R.I., 2002. Rare earth element mines, deposits, and occurrences. US Geological Survey Open File Report 02-189.
Ou, X., Chen, Z., Chen, X., Li, X., Wang, J., Ren, T., Chen, H., Feng, L., Wang, Y., Chen, Z., 2022. Redistribution and chemical speciation of rare earth elements in an ion–adsorption rare earth tailing, Southern China. Sci. Total Environ. 821, 153369.
Patil, A.B., Paetzel, V., Struis, R.P., Ludwig, C., 2022. Separation and recycling potential of rare earth elements from energy systems: feed and economic viability review. Separations 9, 56.
Pham-Ngoc, C., Ishiyama, D., Tran, T.A., Hoshino, M., Taguchi, S., 2016. Characteristic features of REE and Pb–Zn–Ag mineralizations in the Na son deposit, northeastern Vietnam. Resour. Geol. 66, 404–418.
Pham, T.T., Shellnutt, J.G., Tran, T.A., Lee, H.Y., 2020. Petrogenesis of Eocene to early Oligocene granitic rocks in Phan Si Pan uplift area, northwestern Vietnam: geochemical implications for the Cenozoic crustal evolution of the South China Block. Lithos 372, 105640.
Phan, Q.V., Dao, T.T., Nguyen, P., Trinh, D.H., Heinig, T., 2019. An assessment of natural radioactivity in the Namxe rare earth deposit, Laichau Province, Vietnam. Minerals 9, 602.
Pieczonka, J., Nguyen, C.D., Piestrzyński, A., Le, P.K., 2019. Timing of ore mineralization using ore mineralogy and U-Pb dating, iron oxide copper gold Sin quyen deposit, north Vietnam. Geol. Q. 63.
Pilet, S., Baker, M.B., Stolper, E.M., 2008. Metasomatized lithosphere and the origin of alkaline lavas. Science 320, 916–919.
Pirajno, F., Yu, H.C., 2022. The carbonatite story once more and associated REE mineral systems. Gondwana Res. 107, 281–295.
Pires, F., Miano, S., 2014. REE in Brazil–Condition of formation and types of deposits. IAEA-CN-216 Abstact 203.
Poletti, J.E., Cottle, J.M., Hagen-Peter, G.A., Lackey, J.S., 2016. Petrochronological constraints on the origin of the Mountain Pass ultrapotassic and carbonatite intrusive suite, California. J. Petrol. 57, 1555–1598.
Pollard, P.J., 1995. A special issue devoted to the geology of rare metal deposits; geology of rare metal deposits; an introduction and overview. Econ. Geol. 90, 489–494.
Pufahl, P.K., Groat, L.A., 2017. Sedimentary and igneous phosphate deposits: formation and exploration: an invited paper. Econ. Geol. 112, 483–516.
Rankin, A., Le Bas, M., 1974. Liquid immiscibility between silicate and carbonate melts in naturally occurring ijolite magma. Nature 250, 206–209.
Reich, M., Simon, A.C., Barra, F., Palma, G., Hou, T., Bilenker, L.D., 2022. Formation of iron oxide–apatite deposits. Nat. Rev. Earth Environ. 3, 758–775.
Roberts, D., Hudson, G., 1983. The olympic Dam copper-uranium-gold deposit, roxby downs, South Australia. Econ. Geol. 78, 799–822.
Rout, S., Abhilash, Meshram, P., Zhang, P., 2023. A comprehensive review on occurrence and processing of phosphate rock based resources-focus on REEs. Miner. Process. Extr. Metall. Rev. 1–21.
Rudnick, R.L., Gao, S., 2003. Composition of the continental crust. In: Rudnick, R.L. (Ed.), The Crust. In: Holland, H.D., Turekian, K.K. (Eds.), Treatise on Geochemistry, vol. 3. Elsevier-Pergamon, Oxford, pp. 1–64.
Schulz, K.J., DeYoung, Jr.J.H., Seal II, R.R., Bradley, D.C., 2017. Critical Mineral Resources of the United States: Economic and Environmental Geology and Prospects for Future Supply, vol. 1802. U. S. Geological Survey Professional Paper, Reston, VA, p. 797.
Sengupta, D., Van Gosen, B.S., 2016. Placer-type rare earth element deposits. In: Verplanck, P.L., Hitzman, M.W. (Eds.), Rare Earth and Critical Elements in Ore Deposits. Society of Economic Geologists, USA.
Seredin, V., 1996. Rare earth element-bearing coals from the Russian Far East deposits. Int. J. Coal Geol. 30, 101–129.
Seredin, V.V., Dai, S., 2012. Coal deposits as potential alternative sources for lanthanides and yttrium. Int. J. Coal Geol. 94, 67–93.
Serra, O.A., 2011. Rare earths: Brazil x China. J. Braz. Chem. Soc. 22, 811–812.
She, H.D., Fan, H.R., Yang, K.F., Li, X.C., Wang, Q.W., Zhang, L.F., Liu, S., Li, X.H., Dai, Z. H., 2021. In situ trace elements of magnetite in the Bayan Obo REE-Nb-Fe deposit: implications for the genesis of mesoproterozoic iron mineralization. Ore Geol. Rev. 139, 104574.

Sidder, G.B., Day, W.C., Nuelle, L.M., Seeger, C., Kisvarsanyi, E., 1993. Mineralogic and fluid-inclusion studies of the Pea Ridge iron-rare-earth-element deposit, southeast Missouri. US Geol. Surv. Bull. 2039, 205–216.

Simandl, G.J., Paradis, S., 2018. Carbonatites: related ore deposits, resources, footprint, and exploration methods. B. Appl. Earth Sci. 127, 123–152.

Simandl, G.J., Paradis, S., Savard, J., Miller, D., D'Souza, R., Araoka, D., Akam, C., Hoshino, M., Kon, Y., 2021. Mineral control on the geochemistry of the rock Canyon Creek REE-F-Ba deposit, British Columbia, Canada. Geochem. Explor. Environ. Anal. 21 geochem2020-010.

Skirrow, R.G., 2022. Iron oxide copper-gold (IOCG) deposits–A review (part 1): settings, mineralogy, ore geochemistry and classification. Ore Geol. Rev. 140, 104569.

Slack, J.F., Corriveau, L., Hitzman, M.W., 2016. A special issue devoted to Proterozoic iron oxide-apatite (±REE) and iron oxide copper-gold and affiliated deposits of southeast Missouri, USA, and the Great Bear magmatic zone, Northwest Territories, Canada: preface. Econ. Geol. 111, 1803–1814.

Smith, M., Campbell, L., Kynicky, J., 2015. A review of the genesis of the world class Bayan Obo Fe–REE–Nb deposits, Inner Mongolia, China: multistage processes and outstanding questions. Ore Geol. Rev. 64, 459–476.

Smith, M., Kynicky, J., Xu, C., Song, W., Spratt, J., Jeffries, T., Brtnicky, M., Kopriva, A., Cangelosi, D., 2018. The origin of secondary heavy rare earth element enrichment in carbonatites: constraints from the evolution of the Huanglongpu district, China. Lithos 308, 65–82.

Smith, M., Moore, K., Kavecsánszki, D., Finch, A.A., Kynicky, J., Wall, F., 2016. From mantle to critical zone: a review of large and giant sized deposits of the rare earth elements. Geosci. Front. 7, 315–334.

Song, W., Xu, C., Qi, L., Zhou, L., Wang, L., Kynicky, J., 2015. Genesis of Si-rich carbonatites in Huanglongpu Mo deposit, Lesser Qinling orogen, China and significance for Mo mineralization. Ore Geol. Rev. 64, 756–765.

Spandler, C., Morris, C., 2016. Geology and genesis of the Toongi rare metal (Zr, Hf, Nb, Ta, Y and REE) deposit, NSW, Australia, and implications for rare metal mineralization in peralkaline igneous rocks. Contrib. Mineral. Petrol. 171, 1–24.

Spandler, C., Slezak, P., Nazari-Dehkordi, T., 2020. Tectonic significance of Australian rare earth element deposits. Earth Sci. Rev. 207, 103219.

Streckeisen, A., 1980. Classification and nomenclature of volcanic rocks, lamprophyres, carbonatites and melilitic rocks IUGS Subcommission on the Systematics of Igneous Rocks: recommendations and suggestions. Geol. Rundsch. 69, 194–207.

Su, J.-H., Zhao, X.-F., Li, X.-C., Su, Z.-K., Liu, R., Qin, Z.-J., Chen, M., 2021. Fingerprinting REE mineralization and hydrothermal remobilization history of the carbonatite-alkaline complexes, Central China: constraints from in situ elemental and isotopic analyses of phosphate minerals. Am. Mineral. 106, 1545–1558.

Su, W., 2009. Economic and Policy Analysis of China's Rare Earth Industry. China Financ. Econ. Publ. House, Beijing.

Subasinghe, C.S., Ratnayake, A.S., Roser, B., Sudesh, M., Wijewardhana, D.U., Attanayake, N., Pitawala, J., 2022. Global distribution, genesis, exploitation, applications, production, and demand of industrial heavy minerals. Arabian J. Geosci. 15, 1616.

Ta, V., 1975. Report of Geological Surveys and Their Results Performed at the IOCG Sin Quyen Deposit in Lao Cai, North Vietnam. Main Department of Geology of Vietnam 318.

Taggart, R.K., Hower, J.C., Dwyer, G.S., Hsu-Kim, H., 2016. Trends in the rare earth element content of US-based coal combustion fly ashes. Environ. Sci. Technol. 50, 5919–5926.

Takeda, O., Okabe, T.H., 2014. Current status on resource and recycling technology for rare earths. Metall. Mater. Trans. 1, 160–173.

Takehara, L., Silveira, F.V., Santos, R.V., 2016. Potentiality of rare earth elements in Brazil. In: Rare Earths Industry. Elsevier, pp. 57–72.

Tang, H., Liu, Y., Song, W., 2021. Igneous genesis of the Bayan Obo REE–Nb–Fe deposit: new petrographical and structural evidence from the H1–H9 cross-section and deep-drilling exploration. Ore Geol. Rev. 138, 104397.

Tao, Y., Shen, L., Feng, C., Yang, R., Qu, J., Ju, H., Zhang, Y., 2022. Distribution of rare earth elements (REEs) and their roles in plant growth: a review. Environ. Pollut. 298, 118540.

Tappert, M.C., Rivard, B., Giles, D., Tappert, R., Mauger, A., 2013. The mineral chemistry, near-infrared, and mid-infrared reflectance spectroscopy of phengite from the Olympic Dam IOCG deposit, South Australia. Ore Geol. Rev. 53, 26–38.

Thanh, P., Suc, N., Khang, L., 2002. Distribution of Rare Earth Elements in Nam Xe Carbonatites, Selected Reports of 15th Sciences Conference in Hanoi University of Mining and Geology, pp. 367–375.

Theodosopoulos, V., 2020. The Geopolitics of Supply: towards a New EU Approach to the Security of Supply of Critical Raw Materials? Institute for European Studies Policy Brief.

Thrane, K., Kalvig, P., Keulen, N., 2014. REE Deposits and Occurrences in Greenland, ERES2014: 1st European Rare Earth Resources Conference, Milos, Greece.

Toledo, M.C.M.d., 1999. Os fosfatos aluminosos da série da crandallita-uma revisão. Rev. Institut. Geol. 20, 49–63.

Traversa, G., Gomes, C.B., Brotzu, P., Buraglini, N., Morbidelli, L., Principato, M.S., Ronca, S., Ruberti, E., 2001. Petrography and mineral chemistry of carbonatites and mica-rich rocks from the Araxá complex (Alto Paranaíba Province, Brazil). An Acad. Bras Ciências 73, 71–98.

Twyman, J.D., Gittins, J., 1987. Alkalic Carbonatite Magmas: Parental or Derivative?, vol. 30. Geological Society, London, Special Publications, pp. 85–94.

U.S. Geological Survey, 2021. Mineral commodity summaries 2021. U.S. Geological Survey, 200 p.

U.S. Geological Survey, 2023. Mineral commodity summaries 2023. U.S. Geological Survey, 210 p.

Upton, B., Emeleus, C., Heaman, L., Goodenough, K., Finch, A., 2003. Magmatism of the mid-Proterozoic Gardar Province, South Greenland: chronology, petrogenesis and geological setting. Lithos 68, 43–65.

Usuki, T., Lan, C.Y., Tran, T.H., Pham, T.D., Wang, K.L., Shellnutt, G.J., Chung, S.L., 2015. Zircon U–Pb ages and Hf isotopic compositions of alkaline silicic magmatic rocks in the Phan Si Pan-Tu Le region, northern Vietnam: identification of a displaced western extension of the Emeishan Large Igneous Province. J. Asian Earth Sci. 97, 102–124.

Valetich, M., Zivak, D., Spandler, C., Degeling, H., Grigorescu, M., 2022. REE enrichment of phosphorites: an example of the Cambrian Georgina Basin of Australia. Chem. Geol. 588, 120654.

Van Gosen, B.S., Verplanck, P.L., Long, K.R., Gambogi, J., Seal II, R.R., 2014. The Rare-Earth Elements: Vital to Modern Technologies and Lifestyles, Fact Sheet. US Geological Survey, Reston, VA.

Van Gosen, B.S., Verplanck, P.L., Seal Ii, R.R., Long, K.R., Gambogi, J., 2017. Rare-earth elements. In: Critical Mineral Resources of the United States—Economic and Environmental Geology and Prospects for Future Supply, vol. 1802. U.S. Geological Survey Professional Paper, pp. O1–O31.

Veksler, I.V., Lentz, D., Webster, J., 2006. Parental magmas of plutonic carbonatites, carbonate-silicate immiscibility and decarbonation reactions: evidence from melt and fluid inclusions. Melt inclusions in plutonic rocks 36, 123–149.

Verplanck, P.L., 2020. Rare earth element resources: Indian context. Econ. Geol. 115, 1875–1876.

Vivoda, V., 2023. Friend-shoring and critical minerals: exploring the role of the minerals security partnership. Energy Res. Social Sci. 100, 103085.

Wall, F., 2014. Rare earth elements. In: Gunn, A.G. (Ed.), Critical Metals Handbook. John Wiley & Sons, pp. 312–339.

Wallace, M.E., Green, D.H., 1988. An experimental determination of primary carbonatite magma composition. Nature 335, 343–346.

Walter, A., Lusty, P., Chetmyn, C., Hill, A., 2010. Rare Earth Elements British Geological Survey. Natural Environment Research Council. Centre of Sustainable Mineral Development, UK.

Walter, B.F., Giebel, R.J., Steele-MacInnis, M., Marks, M.A., Kolb, J., Markl, G., 2021. Fluids associated with carbonatitic magmatism: a critical review and implications for carbonatite magma ascent. Earth Sci. Rev. 215, 103509.

Walter, M.J., Bulanova, G., Armstrong, L.S., Keshav, S., Blundy, J.D., Gudfinnsson, G., Lord, O.T., Lennie, A., Clark, S., Smith, C., 2008. Primary carbonatite melt from deeply subducted oceanic crust. Nature 454, 622–625.

Wang, D.H., Zhao, Z., Yu, Y., Dai, J.J., Deng, M.C., Zhao, T., Liu, L.J., 2018. Exploration and research progress on ion-adsorption type REE deposit in South China. China Geology 1, 415–424.

Wang, G.F., Xu, J., Ran, L.Y., Zhu, R.L., Ling, B.W., Liang, X.L., Kang, S.C., Wang, Y.Y., Wei, J.M., Ma, L.Y., Zhuang, Y., Zhu, J.X., He, H.P., 2023a. A green and efficient technology to recover rare earth elements from weathering crusts. Nat. Sustain. 6, 81–92.

Wang, Y., Liu, L., Sun, M., Huang, J., Huang, Y., Liang, X., Tan, W., He, H., Zhu, J., 2023b. Distribution and fractionation of rare earth elements (REE) in the ion adsorption-type REE deposit (IAD) at maofeng mountain, guangzhou, China. Clay Clay Miner. 71, 340–361.

Wang, Z., Hill, R., Williams, G., Dwyer, G.S., Hu, J., Schnug, E., Bol, R., Sun, Y., Coleman, D.S., Liu, X.-M., 2023c. Lead isotopes and rare earth elements geochemistry of global phosphate rocks: insights into depositional conditions and environmental tracing. Chem. Geol. 639, 121715.

Wang, Z.Y., Fan, H.R., Zhou, L.L., Yang, K.F., She, H.D., 2020. Carbonatite-related REE deposits: an overview. Minerals 10, 965.

Wei, C.W., Deng, M., Xu, C., Chakhmouradian, A.R., Smith, M.P., Kynicky, J., Song, W.L., Chen, W., Fu, B., 2022. Mineralization of the bayan Obo rare earth element deposit by recrystallization and decarbonation. Econ. Geol. 117, 1327–1338.

Weng, Q., Niu, H.C., Qu, P., Li, N.B., Shan, Q., Yang, W.B., 2022a. Controlling factors of prolonged REE mineralization in the Maoniuping REE deposit: constraints from alkaline granite in the syenite–carbonatite complex. Ore Geol. Rev. 142, 104705.

Weng, Q., Niu, H.C., Qu, P., Shan, Q., Li, N.B., Yang, W.B., 2022b. Mica compositional constraints on the petrogenesis and mineralization of the syenite–carbonatite complex in the Maoniuping REE deposit, SW China. Ore Geol. Rev. 145, 104917.

White, H., 2021. 100-Day Reviews under Executive Order 14017: Building Resilient Supply Chains, Revitalizing American Manufacturing, and Fostering Broad-Based Growth. White House, Washington DC.

Willett, G., Duncan, R., Rankin, R., 1986. Geology and economic evaluation of the Mt Weld carbonatite, Laverton, western Australia. International Kimberlite Conference. Extended Abstracts, pp. 97–99.

Witt, W., Hammond, D., Hughes, M., 2019. Geology of the ngualla carbonatite complex, Tanzania, and origin of the weathered bastnaesite zone REE ore. Ore Geol. Rev. 105, 28–54.

Woolley, A.R., Kjarsgaard, B.A., 2008. Paragenetic types of carbonatite as indicated by the diversity and relative abundances of associated silicate rocks: evidence from a global database. Can. Mineral. 46, 741–752.

Wu, C.Y., Yuan, Z.X., Bai, G., 1995. Rare earth deposits in China. In: Jone, A.P., Wall, F., Williams, C.T. (Eds.), Rare Earth Minerals–Chemistry, Origin and Ore Deposits, vol. 7. Chapman and Hall. The Mineralogical Society Series, New York, pp. 281–310.

Wu, G., Shi, N., Wang, T., Cheng, C.-M., Wang, J., Tian, C., Pan, W.-P., 2022. Enrichment and occurrence form of rare earth elements during coal and coal gangue combustion. Environ. Sci. Pollut. Res. 29, 44709–44722.

Wu, S., Wang, L., Zhao, L., Zhang, P., El-Shall, H., Moudgil, B., Huang, X., Zhang, L., 2018. Recovery of rare earth elements from phosphate rock by hydrometallurgical processes–A critical review. Chem. Eng. J. 335, 774–800.

Wübbeke, J., 2013. Rare earth elements in China: policies and narratives of reinventing an industry. Resour. Pol. 38, 384–394.
Wyllie, P.J., Lee, W.-J., 1998. Model system controls on conditions for formation of magnesiocarbonatite and calciocarbonatite magmas from the mantle. J. Petrol. 39, 1885–1893.
Xie, Y., Xia, J., Cui, K., Qu, Y., Liang, P., Zhong, R., 2020. Rare earth elements deposits in China: spatio-temporal distribution and ore-forming processes. Chin. Sci. Bull. 65, 3794–3808.
Xie, Y.L., Verplanck, P.L., Hou, Z.Q., Zhong, R.C., 2019. Rare earth element deposits in China: a review and new understandings. Soc. Econ. Geol. Spec. Publ. 22, 509–552.
Xu, C., Kynicky, J., Chakhmouradian, A.R., Campbell, I.H., Allen, C.M., 2010. Trace-element modeling of the magmatic evolution of rare-earth-rich carbonatite from the Miaoya deposit, Central China. Lithos 118, 145–155.
Xu, C., Taylor, R.N., Li, W., Kynicky, J., Chakhmouradian, A.R., Song, W., 2012. Comparison of fluorite geochemistry from REE deposits in the Panxi region and Bayan Obo, China. J. Asian Earth Sci. 57, 76–89.
Yamaguchi, A., Honda, T., Tanaka, M., Tanaka, K., Takahashi, Y., 2018. Discovery of ion-adsorption type deposits of rare earth elements (REE) in Southwest Japan with speciation of REE by extended X-ray absorption fine structure spectroscopy. Geochem. J. 52, 415–425.
Yan, S., Liu, W., 2022. Rare earth elements in the iron-oxide apatite (IOA) deposit: insights from apatite. Int. Geol. Rev. 64, 3230–3247.
Yang, K.F., Fan, H.R., Santosh, M., Hu, F.F., Wang, K.Y., 2011a. Mesoproterozoic carbonatitic magmatism in the Bayan Obo deposit, Inner Mongolia, North China: constraints for the mechanism of super accumulation of rare earth elements. Ore Geol. Rev. 40, 122–131.
Yang, K.F., Fan, H.R., Santosh, M., Hu, F.F., Wang, K.Y., 2011b. Mesoproterozoic mafic and carbonatitic dykes from the northern margin of the North China Craton: implications for the final breakup of Columbia supercontinent. Tectonophysics 498, 1–10.
Yang, X., Lai, X., Pirajno, F., Liu, Y., Mingxing, L., Sun, W., 2017. Genesis of the Bayan Obo Fe-REE-Nb formation in Inner Mongolia, north China craton: a perspective review. Precambrian Res. 288, 39–71.
Yang, X.J., Lin, A.J., Li, X.L., Wu, Y.D., Zhou, W.B., Chen, Z.H., 2013. China's ion-adsorption rare earth resources, mining consequences and preservation. Environ. Dev. 8, 131–136.
Yang, X.Y., Sun, W.D., Zhang, Y.X., Zheng, Y.F., 2009. Geochemical constraints on the genesis of the bayan Obo Fe–Nb–REE deposit in inner Mongolia, China. Geochem. Cosmochim. Acta 73, 1417–1435.
Yaroshevsky, A., 2006. Abundances of chemical elements in the Earth's crust. Geochem. Int. 44, 48–55.
Yin, J., Song, X., 2022. A review of major rare earth element and yttrium deposits in China. Aust. J. Earth Sci. 69, 1–25.
Yuan, Z., Shi, Z., Bai, G., Wu, C., Chi, R., Li, X., 1995. Rare Earth Element Deposit in Maoniuping Mianning, Sichuan Province. Geological Publishing House, Beijing.
Zhang, W., Honaker, R., Groppo, J., 2017. Concentration of rare earth minerals from coal by froth flotation. Miner. Metall. Process. 34, 132–137.
Zhang, W., Rezaee, M., Bhagavatula, A., Li, Y., Groppo, J., Honaker, R., 2015. A review of the occurrence and promising recovery methods of rare earth elements from coal and coal by-products. International Journal of Coal Preparation and Utilization 35, 295–330.
Zhao, L.-Y., Lan, T.-G., Fan, H.-R., Lan, J., Wang, H., Chen, W.T., Hu, H.-L., Li, D.-J., 2023. Origin and mineralization processes of REE during magmatic-hydrothermal evolution: insights from in-situ geochemistry of calcite from the Weishan REE deposit, eastern North China Craton. Ore Geol. Rev. 105676.
Zhao, Z., Wang, D., Bagas, L., Chen, Z., 2022. Geochemical and REE mineralogical characteristics of the Zhaibei Granite in Jiangxi Province, southern China, and a model for the genesis of ion-adsorption REE deposits. Ore Geol. Rev. 140, 104579.
Zheng, X., Liu, Y., 2019. Mechanisms of element precipitation in carbonatite-related rare-earth element deposits: evidence from fluid inclusions in the Maoniuping deposit, Sichuan Province, southwestern China. Ore Geol. Rev. 107, 218–238.
Zhou, B., Li, Z., Chen, C., 2017. Global potential of rare earth resources and rare earth demand from clean technologies. Minerals 7, 203.
Zhou, B., Li, Z., Zhao, Y., Zhang, C., Wei, Y., 2016. Rare Earth Elements supply vs. clean energy technologies: new problems to be solve. Gospod. Surowcami Miner. /Miner. Resour. Manag.
Zhu, X., Zhang, B., Ma, G., Pan, Z., Hu, Z., Zhang, B., 2022a. Mineralization of ion-adsorption type rare earth deposits in Western Yunnan, China. Ore Geol. Rev. 148, 104984.
Zhu, X.P., Zhang, B., Ma, G.T., Pan, Z.W., Hu, Z.G., Zhang, B.T., 2022b. Mineralization of ion-adsorption type rare earth deposits in Western Yunnan, China. Ore Geol. Rev. 148, 104984.
Zhukova, I.A., Stepanov, A.S., Jiang, S.-Y., Murphy, D., Mavrogenes, J., Allen, C., Chen, W., Bottrill, R., 2021. Complex REE systematics of carbonatites and weathering products from uniquely rich Mount Weld REE deposit, Western Australia. Ore Geol. Rev. 139, 104539.