Global Deposits of Rare Earth Elements and Prospects in the Democratic Republic of Congo

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Abstract

Rare earth elements (REE) are not as rare as their name indicate, but the deposits in which they are found at an economic interest are not very common. They are enriched in carbonatites, pegmatites, alkaline and peralkaline igneous rocks, placers, laterites, veins, bauxites and iron adsorption clays. Economic deposits of REE are mined from 3 main minerals, which are bastnaesite, monazite and xenotime. REE have been widely used in many high-tech and green technology gadgets, including batteries, computer memories, permanent magnets, smartphones, solar panels, wind turbines, speakers, air conditioners and many other applications. Due to these applications, REE are sought after by many developed and developing economies.

The Democratic Republic of Congo (DRC) is endowed with mineral potentials. Studies have speculated REE concentration in areas with carbonatite complexes such as Lueshe, Bingo and Kirumba. Other regions with REE potentials include pegmatites. A high weathering rate contributes to metals and REE deposition in lateritic profiles of pegmatites and other alkaline rocks. Additionally, there are placers in many locations of riverbanks. For example, the alluvial placers of Kabengelwa, Mashabuto and Obaye are enriched in monazite and contain significant quantities of rare earth oxides. We believe that, with more research and explorations, the DRC could be a potential target for future REE projects.

1. Introduction

The International Union of Pure and Applied Chemistry define rare earth elements (REE) as a collection of seventeen chemical elements called lanthanides, plus Scandium and yttrium (Connelly et al. 2005). Lanthanides are a group of 15 chemical elements (Table 1). There are two main groups of REE: Heavy and Light REE (Table 1). Another group that is not always mentioned is Medium REE (Table 1). Promethium is a radioactive element without a stable isotope (May and Thoennessen 2012; Voncken 2016; Zhou et al. 2017; Charles et al. 2021), and Scandium does not necessarily occur with other REE due to its unique properties (Golev et al. 2014; Charles et al. 2021). This sometimes leads to their exclusion from the REE classification (Hoatson et al. 2011; Golev et al. 2014; Machacek and Kalvig 2016; Charles et al. 2021). REE share similar geochemical and physical characteristics in nature. They are soft, silver, silvery-white or grey and have a high melting point, high conductivity, high density, high thermal conductivity and high electrical conductivity (Zepf 2013; Wall 2014; Voncken 2016; Balaram 2019; Dushyantha et al. 2020). REE chemical and physical properties can change gradually through the lanthanide series. The most crucial characteristic of REE chemical behaviour is the size decrease of lanthanide atomic and ionic radii with the increase of atomic numbers. This phenomenon is called lanthanide-contraction (Wall 2014; Hoshino et al. 2016).
### Table 1
The rare earth elements, their chemical properties and classification after (Jha 2014; Harmer and Nex 2016)

| Rare Earth Elements | Symbol | Atomic number | Atomic weight | Valence | Chemical classification | Metallurgical classification |
|---------------------|--------|---------------|---------------|---------|-------------------------|----------------------------|
| Scandium            | Sc     | 21            | 45            | 3       | Light Rare Earth Elements (LREE) | Light REE |
| Lanthanum           | La     | 57            | 139           | 3       | Light Rare Earth Elements (LREE) | Light REE |
| Cerium              | Ce     | 58            | 140           | 3 and 4 | Middle REE               | Middle REE |
| Praseodymium        | Pr     | 59            | 141           | 3       |                         |                            |
| Neodymium           | Nd     | 60            | 144           | 3       |                         |                            |
| Promethium          | Pm     | 61            | 145           | 3       |                         |                            |
| Samarium            | Sm     | 62            | 150           | 2 and 3 | Heavy Rare Earth Elements (HREE)   | Heavy Rare Earth Elements (HREE) |
| Europium            | Eu     | 63            | 152           | 2 and 3 |                         |                            |
| Gadolinium          | Gd     | 64            | 157           | 3       |                         |                            |
| Terbium             | Tb     | 65            | 159           | 3       |                         |                            |
| Dysprosium          | Dy     | 66            | 162           | 3       |                         |                            |
| Holmium             | Ho     | 67            | 164.9         | 3       |                         |                            |
| Erbium              | Er     | 68            | 167           | 3       |                         |                            |
| Thulium             | Tm     | 69            | 169           | 3       |                         |                            |
| Ytterbium           | Yb     | 70            | 173           | 2 and 3 |                         |                            |
| Lutetium            | Lu     | 71            | 175           | 3       |                         |                            |
| Yttrium             | Y      | 39            | 88.9          | 3       |                         |                            |

REE are crucial in the understanding of petrogenetic processes (Zepf 2013). They usually occur in a $3^+$ oxidation state (Table 1), allowing them to form oxides of the $\text{REE}_2\text{O}_3$ formula with some exceptions where some REE can have $2^+$ or $4^+$ oxidation state (Table 1). They form compounds with strong electronegative elements like oxygen and fluorine (Voncken 2016).

In nature, there are more than 200 REE-bearing minerals in a variety of chemical compounds, including phosphates, fluorcarbonates, oxides, silicates and fluorides (Table 2) (Kanazawa and Kamitani 2006; Balaram 2019; Dushyantha et al. 2020). Table 2 summarises some rare-earth minerals. Monazite, xenotime and bastnaesite are the principal and common economic minerals widely mined worldwide (Jordens et al. 2013; Haque et al. 2014; Wall 2014; Verplanck et al. 2016; Voncken 2016; Balaram 2019). Bastnaesite is the most abundant and frequent among these three minerals; monazite is the second most abundant, and xenotime comes at the third position. Some other REE minerals which are mined in some deposits include loparite and apatite (Golev et al. 2014; Wall 2014), eudialyte (Voncken 2016) as well as REE-bearing ion-
adsorption clays (Kanazawa and Kamitani 2006). Loparite is mined in Russia (Vereschagin et al. 2006; Charles et al. 2021), eudialyte is sourced from alkaline rocks in Sweden and Russia (Atanasova et al. 2013; Kogarko 2020), and ion-adsorption clays are exploited for HREE in China (Yang et al. 2013). Bastnaesite, monazite, loparite and apatite are primarily mined for their concentrations in LREE, while xenotime and ion-adsorption clays have high HREE concentration (Golev et al. 2014; Dushyantha et al. 2020). LREE are hosted in carbonates and phosphates, whereas HREE are hosted and expected in oxides and a portion of phosphates (Kanazawa and Kamitani 2006). At Songwe Hill in Malawi, LREE is hosted in synchisite, florencite and parasite, whereas HREE is in apatite (Al-Ali 2016; Broom-Fendley et al. 2017).
Table 2
Rare Earth Elements-bearing minerals in REE deposits (after Verplanck et al., 2016)

| Mineral       | Formula                                                                 |
|---------------|--------------------------------------------------------------------------|
| Allanite (Ce) | $(\text{Ce,Ca,Y})_2(\text{Al,Fe}_{2+},\text{Fe}_{3+})_3(\text{SiO}_4)_3(\text{OH})$ |
| Ancylite (Ce) | $\text{SrCe(CO}_3)_2\text{OH-H}_2\text{O}$                              |
| Bastnäsite (Ce) | $(\text{Ce,La})(\text{CO}_3)\text{F}$                               |
| Britholite (Ce) | $(\text{Ce,Ca})_5(\text{SiO}_4\text{PO}_4)_3(\text{OH,F})$            |
| Brockite      | $(\text{Ca,Th,Ce})(\text{PO}_4)_2\text{H}_2\text{O}$                 |
| Burbankite    | $(\text{Na,Ca})_3(\text{Sr,Ba,Ca,REE})_3(\text{CO}_3)_5$              |
| Carbocernaite | $(\text{Ca,Na})(\text{Sr,REE})(\text{CO}_3)_2$                       |
| Cerianite (Ce) | $(\text{Ce}_{4+},\text{Th})\text{O}_2$                               |
| Cerite (Ce)   | $\text{Ce}_9\text{Fe}_{3+}(\text{SiO}_2)_6[(\text{SiO}_2)(\text{OH})]\text{(OH)}_3$ |
| Cheralite     | $(\text{Ca,Ce,Th})(\text{PSi})\text{O}_4$                            |
| Chevkinite    | $(\text{Ca,Ce,Th})_4(\text{Fe}_{2+},\text{Mg})_2(\text{Ti,Fe}_{3+})_3\text{Si}_4\text{O}_{22}$ |
| Churchite (Y) | $\text{YPO}_4\cdot\text{H}_2\text{O}$                                |
| Florencite (Ce) | $\text{CeAl}_3(\text{PO}_4)_2(\text{OH})_6$                         |
| Florencite (La) | $(\text{La,Ce})\text{Al}_3(\text{PO}_4)_2(\text{OH})_6$          |
| Fluocerite (Ce) | $(\text{Ce,La})\text{F}_3$                                     |
| Fluorapatite  | $(\text{Ca,Ce})_5(\text{PO}_4)_3\text{F}$                           |
| Fluorite      | $(\text{Ca,REE})\text{F}$                                           |
| Gorceixite    | $(\text{Ba,REE})\text{Al}_3[(\text{PO}_4)_2(\text{OH})_5]\cdot\text{H}_2\text{O}$ |
| Khanneshite   | $(\text{Na,Ca})_3(\text{Ba,Sr,Ce,Ca})_3(\text{CO}_3)_5$             |
| Loparite      | $(\text{Na}_{0.5}\text{Ce}_{0.5})\text{TiO}_3$                      |
| Monazite (Ce) | $(\text{Ce,La,Nd,Th})\text{PO}_4$                                 |
| Parisite (Ce) | $\text{Ca( Ce,La)}_2(\text{CO}_3)_3\text{F}_2$                     |
| Perovskite    | $(\text{Ca,REE})\text{TiO}_3$                                      |

The compound minerals associated with the respective REE are in bold.
### Mineral Formulas

| Mineral                | Formula                                                   |
|------------------------|-----------------------------------------------------------|
| Pyrochlore (Ca,Na,REE) | (Ca,Na,REE)$_2$Nb$_2$O$_6$(OH,F)                         |
| Rhabdophane (Ce)       | (Ce,La)PO$_4$.H$_2$O                                      |
| Rhabdophane (La)       | (La,Ce)PO$_4$.H$_2$O                                      |
| Sahamalite             | (Mg,Fe)(Ce,La,Nd,Pr)$_2$(CO$_3$)$_4$                      |
| Samarskite             | (REE,Fe$_{2+}$,Fe$_{3+}$,U,TH,Ca)(Nb,Ta,Ti)O$_4$         |
| Synchysite (Ce)        | Ca(Ce,La)(CO$_3$)$_2$F                                    |
| Xenotime (Y)           | (HREE,Y)PO$_4$                                           |

The compound minerals associated with the respective REE are in bold.

REE and their alloys are useful in many products used for communication and other important domains of our daily lives (Fig. 1). Their industrial and technological applications include devices such as batteries, computer memories, DVDs, permanent magnets, smartphones, LED screens for televisions and lighting, solar panels, wind turbines, magnetic resonance, speakers, microphones, air conditioners and other many applications (Voncken 2016; Balaram 2019). REE are useful in magnets, metal alloys, catalysts, polishing, batteries, glass, phosphors and pigments, ceramics and others (Fig. 1) (Zepf 2013; Jha 2014; Wall 2014; Roskill 2016). REE find applications in many energy-efficient tools, military applications and agriculture.

REE are classified among critical and strategic metals by developed countries (Buchert et al. 2009; Long et al. 2010; Moss et al. 2011; Wall 2014; Schulz et al. 2017; Goodenough et al. 2018), owing to their importance in recent technologies, their market dominance hold by China (Xie et al. 2016; Shen et al. 2020) and their direct interaction with business and policy interventions of governments (Mancheri et al. 2019).

Due to their increasing demand, REE are growing interest among exploration and mining geologists and technology companies worldwide for their essential green technology role (Dent 2012; Zepf 2013; Habib and Wenzel 2014). This will bring to government and industries solutions to meet emission standards and fight against climate change and global warming (Goodenough et al. 2018). REE demand is growing by 5% per year since 2016 (Dutta et al. 2016); and particularly, neodymium-iron-boron (NdFeB) magnets which are crucial in hybrid and electric vehicles, wind turbines, military and defence industry (Habib and Wenzel 2014; Smith Stegen 2015; Goodenough et al. 2018; Dushyantha et al. 2020).

Several exploration campaigns for new deposits have been launched worldwide to mitigate the Chinese dominance over REE (Shen et al. 2020), and an extensive focus is given to carbonatites and alkaline rocks. The trend is also noticeable in developing countries where exploration works have been geared towards unravelling REE resource potentials in African petrological units (Harmer and Nex 2016; Goodenough et al. 2018; Nthiharirizwa et al. 2018; Buyse et al. 2020). In this idea, the Democratic Republic of Congo (DRC) is an excellent target for REE because it has favourable geologic settings and extensive mining history. Being in
central Africa, DRC has occurrences and favourable lithologies that can host REE, including carbonatites, pegmatites and placers. In this paper, we critically review and compare REE resources and reserves in the world, and their target localisation and potential in Africa as well as in DRC.

2. Rare Earth Element Deposits And Their Spatial Distribution

2.1. Main types of REE Deposits

2.1.1. Carbonatite deposits

Carbonatites are providers of many mineral commodities, including Nb, REE, apatite, Cu, Th and vermiculite. Carbonatites are an essential target and repository of REE globally (Anenburg et al. 2020; Dushyantha et al. 2020; Wang et al. 2020). They contain a high content of LREE, which are enriched in minerals like bastnaesite, monazite, allanite and apatite (Chakhmouradian and Zaitsev 2012). Some REE deposits are associated with fresh carbonatite and others with weathered lateritic profiles. Examples include fresh and weathered carbonatites of the famous and most significant mines in the world located in Bayan Obo, Dulucao and Maoniuping in China and Mountain Pass in the USA (Yang and Woolley 2006; Wall 2014; Verplanck et al. 2016) (Fig. 2). The Bayan Obo is the world largest REE deposit and has been producing most of the world supply since the 1980s from bastnaesite (Xu et al. 2010; Smith et al. 2015; Xie et al. 2016; Smith et al. 2016; Wang et al. 2020). Most REE-bearing minerals exploited in these deposits are bastnaesite and monazite (Simandl 2014).

2.1.2. Laterite deposits

Lateritic deposits are associated with weathering of primary carbonatite and alkaline rocks deposits. Weathering of carbonatite is a necessary process that can upgrade REE content to an economic level (Hoshino et al. 2016). In many tropical regions, carbonatites are covered by thick lateritic soils which have a huge concentration of economic minerals such as Nb in Araxá (Brazil), in Bingo and Lueshe (DR Congo) (Wall et al. 1996; Williams et al. 1997; Kasay 2018), phosphates in Dorowa (Barber 1991) and REE at Mount Weld (Australia) (Jaireth et al. 2014). Other laterites have proven interests in being REE repositories at Mrima Hill (Kenya), Panda and Ngualla Hills (Tanzania), Araxá (Brazil) (Harmer and Nex 2016; Verplanck et al. 2016) (Fig. 2). These secondary deposits concentrate remobilised REE resources into secondary minerals in a specific layer of the lateritic profile (Berger et al. 2014). Other Nb-bearing laterites have to be further investigated and assessed to determine their REE economic content.

2.1.3. Alkaline and per-alkaline igneous rocks

Deposits associated with these rocks are commonly hosted in nepheline syenites and pegmatites (peralkaline granites). Their REE concentration is related to magmatic processes and fractional crystallisation. The main REE-bearing minerals are loparite and eudialyte, with a low content of bastnaesite, monazite, zircon, gittinsite and fergusononite (Dostal 2017). Only one successful project is recognised and located in Lovozero massif (Russia), where REO are exploited from loparite as a by-product of Nb and eudialyte (Zaitsev and Kogarko 2012; Kogarko 2020; Charles et al. 2021). Several exploration projects
worldwide are focussed on REE deposits of alkaline and per-alkaline rocks because they concentrate higher concentration of HREE and Y than LREE (Hoshino et al. 2016; Goodenough et al. 2018). However, these deposits are associated with U and Th high content, making them a source of environmental concerns for their exploitation. These deposits are large in size and low grade.

2.1.4. Veins of monazite and apatite

This REE deposit type forms after the country rock emplacement. Phosphate minerals concentrate in hydrothermal veins. In these veins, REE minerals such as monazite and xenotime solutions precipitate. Apatite is the phosphate mineral found in veins associated with monazite, as the main REE-bearing mineral (Hoshino et al. 2016). A notable example of this deposit type is in Steenkampskaal in South Africa (Harmer and Nex 2016) and the structurally controlled REE deposit at Gakara in Burundi (Decrée et al. 2015). These deposits are high grade but low tonnage.

2.1.5. Placer deposits

These deposits result from the mechanical desegregation of parental rocks enriched in REE. The ore-bearing minerals are monazite and xenotime. They are chemically strong and heavy to sustain the transportation from their formation to their deposition locations (Wall 2014; Sengupta and Gosen 2016). They concentrate near river and ocean banks (Fig. 2) in Eneabba, Western Australia (Hoatson et al. 2011; Jaireth et al. 2014), in Orissa and Kerala, Southern India (Singh 2020) and at Richards Bay, South Africa (Wall 2014). Although REE placer deposits have shown interest in their easy and well-developed processing recovery, they are highly enriched in radioactive minerals such as Th and U (Goodenough et al. 2018). This has led to their restricted exploitation due to the problem associated with safety and radioactive wastes in the environment (Chakhmouradian and Wall 2012; Weng et al. 2014).

2.1.6. Bauxite deposits

Apart from aluminium, bauxites have proven to contain a by-product of REE minerals at low grade in some world places (Wang et al. 2010; Deady et al. 2016). Bauxites develop lateritic soils on their top weathered geologic formations. They tend to concentrate crandallite and florencite in which REE are concentrated. The main REE-bearing minerals found in bauxite ores are parasite and churchite (Wang et al. 2010). Rare earths can be produced as an alumina by-product from a red mud residue (Wang et al. 2019). Red mud is produced during the extraction of alumina from bauxite. An example of this REE production process is implemented in Quebec, Canada (Hoshino et al. 2016).

2.1.7. Ion adsorption clay deposits

These deposit types are located in Xinxiu, Heling, Jiangxi, Huashan and Guposhan in South China, where they are exploited for their highly dominant HREE (Bao and Zhao 2008; Sanematsu and Watanabe 2016; Xu et al. 2017) (Fig. 2). They are associated with weathering processes that affect the granites of the Mesozoic age. The country rocks are mostly granites and, to a small extent, lamprophyres. Weathering of granites, which are initially enriched in REE, contribute to clay formation, on which REE minerals are adsorbed (Bao and Zhao 2008). The concentration of REE minerals is generally correlated to the parental rock mineralogical composition. REE high contents are mostly on clay profiles developed above granitic rocks,
where they are accumulated in parasite. The high oxidation of the deposits leads to Ce depletion (Xu et al. 2017). Minerals of these deposit types are not so radioactive, and as they accumulate in clay, they are easily exploited and processed with minor energy consumption and low radioactivity (Sanematsu and Watanabe 2016). These facts make ion adsorption clay deposits economically valuable. Ion-adsorption clay deposits have been discovered outside of China, such as in Serra Nevada in Brazil. Madagascar is one of the African countries, which has shown REE potentials (Harmer and Nex 2016; Hoshino et al. 2016; Borst et al. 2020). Further explorations should focus on kaolinite in other places of the world which have shown prospective interests for this kind of deposits (Borst et al. 2020).

2.1.8. Iron Oxide Copper-Gold deposits (IOCG)

The term IOCG was introduced since the discovery of the giant Olympic Dam deposit in Australia. It is mined mainly for uranium, copper, gold as well as silver. IOCG deposits are a potential for iron-oxide minerals and an economical REE source (Groves et al. 2010; Wall 2014) (Fig. 2). These deposits are classified into five subclasses: the iron oxide copper-gold deposits at Olympic Dam; the apatite-magnetite deposit at Kiruna; the iron-oxide alkaline or carbonatite intrusion at Vergenoeg; the porphyry copper-gold deposits at Yerington; and the magnetite-replacement gold-copper deposits at Tennant Creek (Groves et al. 2010). They are associated with large batholithic granitoid and are distributed in all continents; their age range from Late Archean to the present (Williams et al. 2005). Most of the IOCG deposits contain economic sources of LREE whose mineralogy depends heavily on the host rock composition. The apatite of the Kiruna apatite-magnetite deposit in Sweden contains between 2000 and 7000 ppm of REE with negative Eu anomalies (Frietsch and Perdahl 1995).

2.2. Global REE Resources

Among explored and recognised deposits worldwide, carbonatites remain the primary provider of REE, followed by peralkaline granites or pegmatite and nepheline syenites and then IOCG deposits (Dostal 2017) (Fig. 2). Available global resources of REE are estimated to around 478 Mt of rare earth oxides, of which the most significant production is constrained in countries such as China which is the largest REE producer and followed by Brazil and Australia (Fig. 3) (Zhou et al. 2017; Spandler et al. 2020). Other countries like Greenland, Russia, Canada, the USA and Vietnam provide the rest of the production (Fig. 3). The world distribution of REE reserves is estimated at 120 Mt, while the production in 2020 was 240,000 tonnes (USGS 2021) (Table 3).
Table 3
World distribution of REE reserves and mine production in 2020 (USGS 2021)

| Country                 | Mine production in tonnes | Reserves of REE in tonnes | World share in % |
|-------------------------|---------------------------|---------------------------|------------------|
| United States of America| 38,000                    | 1,500,000                 | 1.25             |
| Australia               | 17,000                    | 4,100,000                 | 3.41             |
| Brazil                  | 1,000                     | 21,000,000                | 17.5             |
| Burma                   | 30,000                    | -                         | -                |
| Burundi                 | 500                       | -                         | -                |
| Canada                  | -                         | 830,000                   | 0.69             |
| China                   | 140,000                   | 44,000,000                | 36.6             |
| Greenland               | -                         | 1,500,000                 | 1.25             |
| India                   | 3,000                     | 6,900,000                 | 5.75             |
| Madagascar              | 8,000                     | -                         | -                |
| Russia                  | 2,700                     | 12,000,000                | 10               |
| South Africa            | -                         | 790,000                   | 0.65             |
| Tanzania                | -                         | 890,000                   | 0.74             |
| Thailand                | 2,000                     | -                         | -                |
| Vietnam                 | 1,000                     | 22,000,000                | 18.33            |
| Other countries         | 100                       | 310,000                   | 0.25             |
| World total (rounded)   | 240,000                   | 120,000,000               |                  |

2.3. Rare Earth Elements Deposits in Africa

There are several REE deposits in Africa (Table 4), and some are either at an exploration or development stage. Only a few of them at an exploitation phase (Fig. 4). However, REE resources in Africa are relatively under-explored, and Africa would be on the hunt for these deposits in the future. Many REE deposits of the continent are around Alkaline Igneous Provinces and Archean cratons surrounded by Proterozoic mobile belts. This is why the Congo, Tanzania and West African cratons would have potential REE deposits (Goodenough et al. 2016). Recent research has proven new deposits in North Africa such as the Twihinat area in South Morocco (Benaouda et al. 2020), and more exploration would reveal several others in other parts of the continent. Table 4 gives a summary of the geology, mineralisation and owner company of selected REE deposits in Africa, more information is in Harmer and Nex (2016) and references therein.
### Table 4
REE deposits in Africa: their host rock, minerals, mineralization type and ownership

| REE deposit Country | Host rock | REE-bearing minerals | Mineralization type | Ownership | References |
|---------------------|-----------|----------------------|---------------------|-----------|------------|
| Songwe Hill (Malawi) | Carbonatite and fenite | Apatite and synchysite-Ce | Magmatic-hydrothermal | Mkango Resources Ltd. | (Broom-Fendley 2015; Broom-Fendley et al. 2016; Broom-Fendley et al. 2017b; Broom-Fendley et al. 2017a) |
| Kangankunde (Malawi) | Carbonatite | Monazite with minor bastnaesite, synchysite and florencite | Magmatic-Hydrothermal | Lynas Corporation | (Wall and Mariano 1996) |
| Nkombwa Hill Zambia | Iron-rich Carbonatite | Bastnaesite and diqingshanite-Ce | Magmatic-Hydrothermal | - | (Appleton et al. 1992; Harmer and Nex 2016) |
| Wigu Hill (Tanzania) | Carbonatite | Bastnaesite | Magmatic-Hydrothermal | Montero Mining and Exploration | (Harmer and Nex 2016) |
| Ngualla Hill (Tanzania) | Carbonatite | Synchysite, bastnaesite and minor monazite | Epigenetic and secondary laterites | Peak Resources | (Harmer and Nex 2016; Witt et al. 2018) |
| Mrima Hill (Kenya) | Carbonatite | - | Epigenetic and secondary laterites | - | (Patel and Mangala 1994; Harmer and Nex 2016) |
| Gakara (Burundi) | Carbonatite | Bastnaesite and monazite | Hydrothermal veins | Rainbow Rare Earths | (Decrée et al. 2015; Ntiharirizwa et al. 2018; Buyse et al. 2020) |
| Zandkopsdrift (South Africa) | Mica-carbonatite breccia | Late-stage and supergene monazite and apatite-derived minerals | Epigenetic and residual soil deposit | Frontier Rare Earths Ltd. | (Harmer and Nex 2016) |
| REE deposit | Host rock | REE-bearing minerals | Mineralization type | Ownership | References |
|-------------|-----------|---------------------|---------------------|-----------|------------|
| Xiluvo      | Carbonatite | Monazite | Epigenetic and residual deposit | Promac lda | (Harmer and Nex 2016) |
| (Mozambique)|           |         |                     |           |            |
| Steenkampskaal | granitoid gneiss covered by shales and quartzites | Monazite | Hydrothermal veins | Steenkampskaal Monazite Mine Ltd. | (Harmer and Nex 2016) |
| (South Africa) |           |         |                     |           |            |
| Glenover | Carbonatite and pyroxenite | Monazite and REE carbonates | Epigenetic Karst-solution breccias. | Glenover Pty Ltd and Galileo Resources plc. | (Harmer and Nex 2016) |
| (South Africa) |           |         |                     |           |            |
| Tantalus | Syenite and skarns | Eudialyte, chevkinite, monazite, zircon and pyrochlore are in granite, and bastnaesite, synchysite and parasite in skarns | Ion-adsorption clays | Tantalus Rare Earths AG | (Harmer and Nex 2016) |
| (Mozambique) |           |         |                     |           |            |

3. Potential Ree Deposits In DRC

3.1. Monazite targets

Monazite is one of the most common REE-bearing minerals of economic interest. It is concentrated in several types of deposits where it can be the main mineral or associated with others. In DRC, several detrital deposits of monazite were discovered in Kivu, Katanga and Kasai during exploration campaigns of Au and Sn alluvial placers. From 1951 to 1966, 71 tonnes of monazite (Ce) were produced from Mashabuto alluvial mines (Gupta and Krishnamurthy 1992). In 1968, economic feasibility studies revealed that tin tailings and alluvial ores of Kabengelwa and Obaye in North Kivu province could contain cerite and europium-rich monazite (Morgan et al. 1985; Gupta and Krishnamurthy 1992). The cerite production was 178 tonnes, in 1969 and raised to 225 tonnes, in 1972. The Kabengelwa ore reserves contain up to 1,100 Mt of monazite, while the Mashabuto ore reserves are 45 Mt (Morgan et al. 1985).

Monazite is associated with zircon in magmatic ores of the Bingo carbonatite in North Kivu province (Gupta and Krishnamurthy 1992). This carbonatite also has a high content of $\text{Nb}_2\text{O}_5$ and phosphate minerals (Woolley et al. 1995; Williams et al. 1997; Carlotta et al. 2002; Kasay 2018).

Monazite is also highly-enriched in Nb-Ta pegmatites of Kampene and Kasese in Maniema. These deposits and their associated weathering products are good future targets for rare metals. Hydrothermal veins of Sulia and Kailo in Maniema contain a significant monazite concentration in association with tin and
wolframite. Monazite is also hosted in metamorphic ore of Luputa charnockite in Kasai province. In the same region, Sandoa gneisses contain monazite.

### 3.2. Carbonatite targets

There are four documented carbonatite complexes in DRC. These are located in the East African Rift System (EARS) in Lueshe, Bingo, Mombadio and Kirumba (Fig. 5). The Bingo and Lueshe complexes have been mentioned in many articles and reports as prospective REE sources, and their potential should be evaluated (Van Wambbeke 1971; Nasraoui et al. 2000; Berger et al. 2009; Goodenough et al. 2018; Kasay 2018; Kasay et al. 2021). The economic feasibility of these deposits has shown that they are endowed in Nb$_2$O$_3$ and phosphate minerals (Maravic and Morteani 1980; Maravic et al. 1989; Woolley et al. 1995; Williams et al. 1997; Carlotta et al. 2002; Kasay 2018; Kasay et al. 2021). However, a more detailed study involving geochemical and petrological aspects would reveal many other rare metal potentials, including REE.

#### 3.2.1. The Lueshe carbonatite

This carbonatite complex is located in North Kivu province in the western branch of the EARS (Fig. 5). The complex is intrusive in quartzite and schists of the Precambrian age. The geology of Lueshe is dominated by different rock types, including carbonatites, syenites, pyroxenites, micaschists and quartzites. Lueshe REE-bearing minerals in calciocarbonatite hydrothermal nodules are synchysite and parasite (Nasraoui 1996; Nasraoui et al. 2000). These two minerals are. Nevertheless, ancylite is in calciocarbonatite hydrothermal veins (Nasraoui et al. 2000; Nasraoui and Bilal 2000). Latentite profiles have a minor amount of REE hosted in fluorcarbonates, monazite, parasite, ancylite, and rhabdophane (Nasraoui et al. 2000). Geochemical data showing REE from calciocarbonatite samples from Lueshe is presented in Table 5. Chondrite-normalized REE patterns of Lueshe and Bingo show higher LREE and lower HREE (Fig. 6). The Lueshe geochemical chondrite-normalised REE patterns show that the calciocarbonatite is less enriched in LREE than average calciocarbonatite, but the two have similar HREE behaviour with some element exceptions (Fig. 6).
Table 5
Average REE values of the Lueshe (Nasraoui et al. 2000) and Bingo calciocarbonatites (Woolley et al. 1995) compared to average calciocarbonatite values (Woolley and Kempe 1989).

| REE (in ppm) | Lueshe | Bingo | Average calciocarbonatite |
|--------------|--------|-------|--------------------------|
| La           | 158.81 | 322.3 | 608                      |
| Ce           | 374.72 | 637.3 | 687                      |
| Pr           | 36.75  | -     | 219                      |
| Nd           | 131.96 | 220   | 883                      |
| Sm           | 21.07  | 32.8  | 130                      |
| Eu           | 6.19   | 9.3   | 39                       |
| Gd           | 25.46  | 28.2  | 105                      |
| Tb           | 2.89   | -     | 9                        |
| Dy           | 13.25  | 13    | 34                       |
| Ho           | 2.48   | -     | 6                        |
| Er           | 7.01   | -     | 4                        |
| Tm           | 0.87   | -     | 1                        |
| Yb           | 5.61   | 1.5   | 5                        |
| Lu           | 0.81   | -     | 1                        |

3.2.2. The Bingo carbonatite

The bingo carbonatite is in the North Kivu province in the North of the Lueshe complex within the EARS (Fig. 5). The calciocarbonatite intruded orthogneisses of Precambrian age and is surrounded by nepheline syenites, ijolites and fenites (Woolley et al. 1995). Dolerite, gabbro and quartzite are country rocks (Woolley et al. 1995; Kasay 2018). The Bingo region tropical climate enhances weathering of outcrops in the study area, which produce laterites. The laterites are composed of iron oxides, brooksite, goethite, albite, chlorite, magnetite and ringwoodite (Philippo 1995). The carbonatite and lateritic soils have concentrations of La and Ce, and the REE patterns show a concentration of LREE (Fig. 6). REE-carbonates and fluorcarbonates are present in the Bingo calciocarbonatite hydrothermal veins (Van Wambeke 1971; Williams et al. 1997). Monazite is one of the REE-minerals in the Bingo carbonatite complex (Morgan et al. 1985; Gupta and Krishnamurthy 1992). Some geochemical data of the carbonatite have revealed REE in the carbonatite, as seen in Table 5. The Bingo has also been speculated and plotted in maps as one of REE potentials worldwide by many reports (Berger et al. 2009; Goodenough et al. 2018; Wang et al. 2020; Kasay et al. 2021). Further research is necessary to appraise this important deposit REE-content.
3.2.3. The Kirumba carbonatite

The Kirumba is one of the carbonatite complexes in the DRC. Located in North Kivu, DRC, it is not far from the North of the Lueshe carbonatite (Fig. 5). This alkaline province has carbonatite and syenite complexes which are intrusive into quartzite, mica schist and banded iron formations (Denaeyer 1958; Denaeyer 1959; Denaeyer 1966; Makutu 1990). The carbonatite has a huge concentration of iron and ankerite. It is called rauhaugite (Kasay et al. 2021). It is speculated to be a potential source of REE (Berger et al. 2009). Allanite, chevkinite and cerite are REE minerals of the Kirumba alkaline complex (Denaeyer 1966).

3.3. Placer targets

The hydrographic network of DRC is a source of many heavy minerals classified as placers. These placers are physically and chemically hard minerals to resist weathering and fragmentation. Alluvial placers are located along riverbanks and meanders. The common minerals in these locations include monazite, zircon, gold, tungsten, coltan and diamond. Among these minerals, monazite, xenotime, cerite, zircon and allanite are REE-bearings. These minerals are associated with a high radioactive risk which may hinder their exploitation.

Alluvial placers and stream sediments in many areas of the DRC are a potential source of many minerals, and exploitations using drags are implemented in many rivers in Haut-Uele, Ituri, Maniema, Katanga and North Kivu provinces. Stream sediments contain xenotime, cassiterite, ilmenite and other minerals near the Lugulu pegmatite and in flat areas of Maniema. However, they are still underexplored, and their literature is non-existent. This is why studies related to the appraisal of REE-minerals in placers and stream sediments are essential in the future.

Beach placers are not common in DRC but are located in the western part of the country at the Atlantic Ocean coastline in the Central Kongo province. Beach placers have enrichment of heavy and resistant sand minerals. These minerals include zircon, ilmenite, monazite and garnet. Other accessory minerals can also be found but in a low quantity. Boma has the largest coastline and beach placer deposit in DRC and could be considered a REE target. However, the quality and quantity of its minerals are yet to be studied to confirm their potentiality.

3.4. Pegmatite targets

Pegmatites are strongly enriched in incompatible elements, including Li, Cs, Ta, Be, Sn and W. Pegmatites and their lateritic soil profiles are the second major source of REE worldwide. Pegmatite occurrences are in many parts of the eastern of DRC, especially in Maniema, South Kivu, North Kivu and a small part of the North Katanga. These pegmatites are providers of rare metals, including niobium, tantalite, beryllium, uranium and others (Melcher et al. 2015; Melcher et al. 2017). Some of these pegmatites have been studied, and their literature is published articles and unpublished reports. However, their REE potential resources are not known. Famous pegmatites in DRC include the Numbi, Manono, Kitotolo, Kobokobo, Kampene, Lugulu and Kasese pegmatites (Melcher et al. 2015; Dewaele et al. 2016; Oyediran et al. 2020). Manono pegmatite is a crucial and large LCT pegmatite that hosts many critical metals necessary for green technology. It is endowed in lithium, tin, caesium, tantalum and other trace elements (Dewaele et al. 2016; Melcher et al.)
The REE chemical composition of the Numbi, Manono-Kitotolo are presented in table 6. This composition reflects that the pegmatites are rich in LREE relative to HREE. Pegmatites and their associated lateritic profiles are known as REE resources worldwide; this is why REE potential of pegmatites in DRC should be evaluated. These studies can be done either by research institutions and centres, geological survey of DRC or even private researchers.

4. Discussions

The importance of REE in many electronic gadgets and high-tech industries is obvious. The uses of REE have been widely important in small devices which power green technology and allow mitigating global warming (Wall 2014; Zhou et al. 2017; Balaram 2019; Dushyantha et al. 2020). The Chinese market control over the REE market, their available deposits and production (Mackay and Simandl 2014; Mancheri et al. 2019; Shen et al. 2020) have severe concerns to other developed economies. There is, therefore, a need to look for additional deposits outside China. Developed economies classify REE among critical and strategic elements (Golev et al. 2014; Goodenough et al. 2018). Demand for REE has increased and has led many countries to look into this opportunity to find available deposits. In this context, DRC, which is endowed with many natural resources, can also play a significant role in finding REE potentials within its settings.

DRC has carbonatite, pegmatite and placer occurrences which are crucial for REE exploration (Kasay et al. 2021). Although many information related to the geology, mineralogy and geochemistry of these potentials remain unknown, it is clear that extensive research of new resources would give positive results.

From the current state of knowledge, carbonatites have high potentials for providing feasible REE resources. World-class REE deposits are hosted in carbonatites, and examples include the Bayan Obo in China, Mountain Pass in the USA and the Mt Weld in Australia (Orris and Grauch 2002; Smith et al. 2015; Xie et al. 2016; Deady et al. 2016; Smith et al. 2016; Spandler et al. 2020). This is why, Bingo and Lueshe carbonatites, which show similar geological characteristics with the Mrima Hill in Kenya and Panda Hill in Tanzania (Jäger et al. 1959; Harris 1965; Van Wambcke 1971; Maravic et al. 1989; Witt et al. 2018), are great potential for REE in DRC (Kasay 2018; Kasay et al. 2021). Their high Nb₂O₅, in the laterites, vitalises this assumption (Goodenough et al. 2018).

Besides, DRC is in the tropical terrains where changing seasons intensify weathering. Therefore, there are lateritic profiles overlying many fields. Weathered profiles over pegmatites are good targets for REE exploration. Many pegmatitic terrains have cover terrains that can provide valuable information and data on the REE content. These terrains may provide high REE content, which is economically feasible. The Manono-Kitotolo, Kampene, Kasese and Numbi pegmatites are to be considered for future exploration campaigns (Dewaele et al. 2016; Oyediran et al. 2020).

The hydrography of the DRC is good to point while considering further exploration targets of REE. This is emphasised by the high weathering rate in the tropical region. Placers are along many riverbanks in the Congo. These are enriched in ilmenite, monazite, cerite, xenotime and other heavy and resistant minerals. Focussing on these potentials would provide valuable information and monazite enrichment within the
riverbanks. Kabengelwa, Mashabuto and Obaye are important locations which provided monazite in the 1968's and 1970's (Morgan et al. 1985; Gupta and Krishnamurthy 1992); they still have enough resources and a good target for REE explorations.

5. Conclusion

The role of REE in modern and green technologies is prominent. They play a critical role in many military and defence applications, making them attractive to many developed economies. Their huge demand has led many countries to look into their geological settings and find out how to provide and secure these resources. To face the dependency of several developed countries on China, which control the REE market fluctuations, it is essential to explore and establish the REE mining sector in other corners of the world. Many projects are being launched in many countries worldwide. In Africa, these countries include South Africa, Namibia, Angola, Malawi, Tanzania, Zambia, Kenya, Burundi, Morocco. In most of these countries, REE potentials are found associated with carbonatites. World-class REE deposits are found in carbonatites, and examples include Bayan Obbo in China, Mountain Pass in the USA. Other deposits are mainly included in laterites and are located in Mt Weld in Australia, and Araxá in Brazil. Ion adsorption clays provide the largest part of HREE from clay deposits in China. In the DRC context, potential LREE deposits are situated in some carbonatite complexes such as Bingo, Lueshe and Kirumba. Other potentials are found in places with pegmatite occurrences, and specifically the Kampene, Kasese, Numbi and Kobokobo are a good prospect for future projects of REE exploration. Placers are found along many riverbanks of which many show a high content of monazite. Placers of Kabengelwa, Mashabuto and Obaye constitute a good potential for monazite. However, all of these potential sources of REE are to be thoroughly studied to have a clear idea of their geological, mineralogical and geochemical characteristics, and to know they are economic feasibility. Additionally, many of these occurrences are only mentioned without good precision of their REE-bearing minerals, and we believe that this paper is vital for future explorations and research projects.

Declarations

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Disclosure statement

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**Figures**
Figure 1

Rare Earth Elements consumption by major applications in 2016 after (Roskill 2016; Zhou et al. 2017)
**Figure 2**

REE deposits main classification and global distribution of known and explored repositories after (Elliott et al. 2018). Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.
Figure 3

Global REE resources distribution and the significant deposits types after (Zhou et al. 2017)
Figure 4

Selected African Rare Earth Exploration and development projects after (Harmer and Nex 2016)
Figure 5

Carbonatite occurrences distribution in DRC and their localisation in the western branch of the EARS after (Kasay et al. 2021)
Figure 6

Chondrite-normalised REE patterns of the Lueshe, Bingo and average calciocarbonatites, normalisation values from (Taylor and McLennan 1985)