



# Introduction to the special Issue, insights on carbonatites and their mineral exploration approach: A challenge towards resourcing critical metals

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## ABSTRACT

Population growth and technological progress in the last 50 years have resulted in the global demand for mineral resources increasing by 400% since 1970, and it is further expected to almost double by 2050. This context forecasts a never-seen-before market for some specific mineral commodities, termed critical metals. The resource and supply flow of critical metals would be decisive for the economic well-being of economies in near future. Carbonatites are the most prospective host rocks for Rare Earth Elements (REEs), which constitute some of the most important critical elements. This special issue aims to contribute to the debate on understanding the genesis of carbonatites and their prospectivity for REEs (including exploration strategies), by presenting a wide variety of studies on carbonatites from around the globe.

## 1. Introduction

### 1.1. Global overview of the driving forces of critical metal demand

In the last 50 years, the global population has grown from 3.6 billion to 7.7 billion, and it is estimated that in 2050, it will be ~10 billion (UN, 2020). During the same period, the global GDP has risen from ~3 trillion US dollars in 1970 to ~90 trillion US dollars in 2019 (World Bank, 2020). Globally, the population residing in cities has risen from ~750 million in 1950 to ~4.2 billion in 2018 (UN DESA, 2018). The increasing urbanisation has been accompanied by increasing dependency on technology in day-to-day life. For example, the estimated global production of mobile phones in the year 2020 is 900 million units (e.g., Chen et al., 2018).

The exponential increase in GDP has been accompanied by rising global demand for mineral resources, which increased ~400% from ~25 billion tonnes in 1970 to ~100 billion tonnes in 2017, and is further expected to almost double to ~185 billion tonnes by 2050 (IRP, 2017; PACE, 2020). The rising mineral resource demand is expected to be met through advances in two main avenues of supply: increased mineral production from new mines, and recycling technologies (e.g., Haque et al., 2014; Punkkinen et al., 2017; Australian Government, 2019;

Balaram, 2020; European Commission, 2020).

However, conflicting views on political, social and economic models of sustainable development have resulted in varying responses of nations to meet the challenge of sustainable supply of mineral resources. These responses highlight the uncertainty in the mineral resources supply chains (e.g., Bartekova and Kemp, 2016). The strategy of European Union (EU) is focussed on developing dialogue with countries with surplus resources, that of Japan and the United States is focussed on research and finding substitutes for REEs; while Australia's and China's policies efforts are on enhancing domestic mineral exploration and production and also on conservation and protection of resources (Bartekova and Kemp, 2016). However, trends keep changing, since Japan has supported the Mt Weld mine opening in Australia and processing plant in Malaysia. Also, the USA is helping companies develop USA REE mining and processing.

Based on the socio-economic developmental goals of different countries and availability of mineral resources, each country has classified some mineral commodities as "critical metals/minerals/commodities, a term which has rapidly become a fundamental part of mineral economics and policy (e.g., Skirrow et al., 2013; Hatayama and Tahara, 2015; Mudd et al., 2018; Kalantzakos, 2019; PDM, 2020; Wang, 2020; European Commission, 2020).

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In general terms, critical minerals are metals, non-metals and minerals that are considered vital for the present and future economic well-being of a country, and their supply may be at risk due to geological scarcity, geopolitical differences or trade policies (Skirrow et al., 2013). The European Commission (2014) defined critical raw materials as those materials for which “the risks of supply shortage and their impact on the economy are higher than for most of the other raw materials”. In contrast, the Japanese definition of critical metals/minerals is: “those which are economically or technologically difficult to extract in pure form and for which a substantial industrial demand exists both now and in future driven by technological innovation” (Resource Security Strategies, 2012; Hatayama and Tahara, 2015 and references therein).

Based on the above definitions, the list of critical metals/minerals vary with country, time, and economic significance. For example, the current critical materials (metals/minerals) list of the EU contains 30 essential commodities. In contrast, the EU list contained 14 commodities in 2011, 20 in 2014 and 27 in 2017 (European Union, 2020). However, irrespective of the year and country, Rare Earth Elements (REEs) are always in the list (e.g., Hatayama and Tahara, 2015; Australia’s Critical Minerals Strategy, 2019; ERGI, 2020; European Commission, 2014; PDM, 2020). Rare earth elements comprise 15 lanthanide elements (La, Ce, Pr, Nd, Pm (with no stable isotope), Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, and Lu). Depending on definitions and approaches, and due to their chemical similarities, Y and Sc are often included as REEs (e.g., Commonwealth of Australia, 2020).

### 1.2. Global reserves of REEs: Demand and supply

The global economic reserves of REEs have been estimated at 120,000 kt (US Geological Services, 2020). The largest reserves of REEs are located in China (37%), Vietnam (18%), Brazil (18%), Russia (10%), India (6%), and Australia (3%). Whereas the actual production is dominated by China (63%), USA (12%), Myanmar (10%) and Australia (9%; USGS, 2020). The EU market predicts that the demand for REEs could increase ten-fold by 2050 (e.g., for electric vehicles, digital technologies and wind turbines; European Union, 2020). Canada and the USA aim to secure the supply chains for critical minerals through the Energy Resource Governance Initiative (ERGI, 2020). The demand for Dy and Nd is projected to increase by >2600% and >700%, respectively, within the next 25 years (Alonso et al., 2012). Since 1943 the USA has been the main hub for research on REEs. This moved to Japan in the 1980s and in 2000s shifted to China (Adachi et al., 2010, and references therein).

### 1.3. REEs and carbonatites

Rare earth elements have a variety of geological sources: (1) magmatic (e.g., carbonatite and alkaline rocks, pegmatite, etc.); (2) sedimentary deposits (basins, e.g., heavy-mineral sands); (3) regolith (e.g., clay minerals ion-adsorption deposits); and (4) metamorphic (calc-silicate; e.g., Jones et al., 1995; Hoatson et al., 2011; Chakhmouradian and Wall, 2012; Goodenough et al., 2016; Jowitt et al., 2017; Wang et al., 2018; Estrade et al., 2019; Borst et al., 2020). Carbonatites are one of the most prospective host rocks for REEs.

Many carbonatites have significant concentrations of LREEs. However, most of REEs deposits associated with carbonatites do not have significant quantities of HREEs (Gosen et al., 2019). Carbonatites are the main source of Nb as well as REEs (e.g., Simandl et al., 2018; Simandl and Paradis, 2018 and references therein). For example, the Seis Lagos Nb carbonatitic deposit has an estimated resource of ~ 2,900 Mt at 2.81 wt% Nb<sub>2</sub>O<sub>5</sub> and is associated with laterite regolith units (Giovannini et al., 2017). Today, Araxa and Catalao in Brazil supply most of the World’s Nb (Mackay and Simandl, 2014).

The carbonatite term has evolved significantly in time (e.g., Stoppa, 2021). According to IUGS, carbonatites are rocks with >50% modal carbonate content and <20 wt% SiO<sub>2</sub> content (Le Maitre, 2002). Other

authors support a different definition: “carbonatites (sensu lato) are defined as any rock containing greater than an arbitrary 30 vol% primary igneous carbonate regardless of silica content” (Mitchell, 2005).

There are ~530 carbonatites reported world-wide (Woolley and Kjarsgaard, 2008a). Two-thirds of carbonatites are Phanerozoic, and their abundance increases exponentially with decreasing age (Woolley and Kjarsgaard, 2008a); however, ~90% of known carbonatites are associated with Precambrian cratonic areas, strongly suggesting the tendency of carbonatites to be emplaced in a Precambrian host even if carbonatites are younger in age (Fig. 1; Woolley and Bailey, 2012). Around 80% of carbonatites occurrences are associated with a diverse suite of alkaline rocks (most abundantly with nephelinite-ijolite, phonolite – feldspathoidal syenite and trachyte-syenite; Woolley and Kjarsgaard, 2008b; Humphreys-Williams and Woolley, 2019 and references therein). Carbonatites are typically associated with extensional tectonic settings (e.g., Ernst and Bell, 2010; Pirajno et al., 2014; Pirajno, 2015 and references therein). Some studies suggest that carbonatites could be associated to mantle melting related to the subduction systems associated with penetration of the mantle transition-zone by sinking oceanic plates (e.g., Duke et al., 2014).

A significant amount of scientific literature, including a large number of special issues, has been published on carbonatites in the last ~30 years (e.g., Bell et al., 1998; Rosatelli and Stoppa, 2003; Groves and Gwalani, 2004; Wall et al., 2005; Mitchell et al., 2008; Gwalani et al., 2010; Downes et al., 2012; Stoppa and Gwalani, 2014; Vrublevskii, 2021; Zozulya, 2021; Jones, 2000).

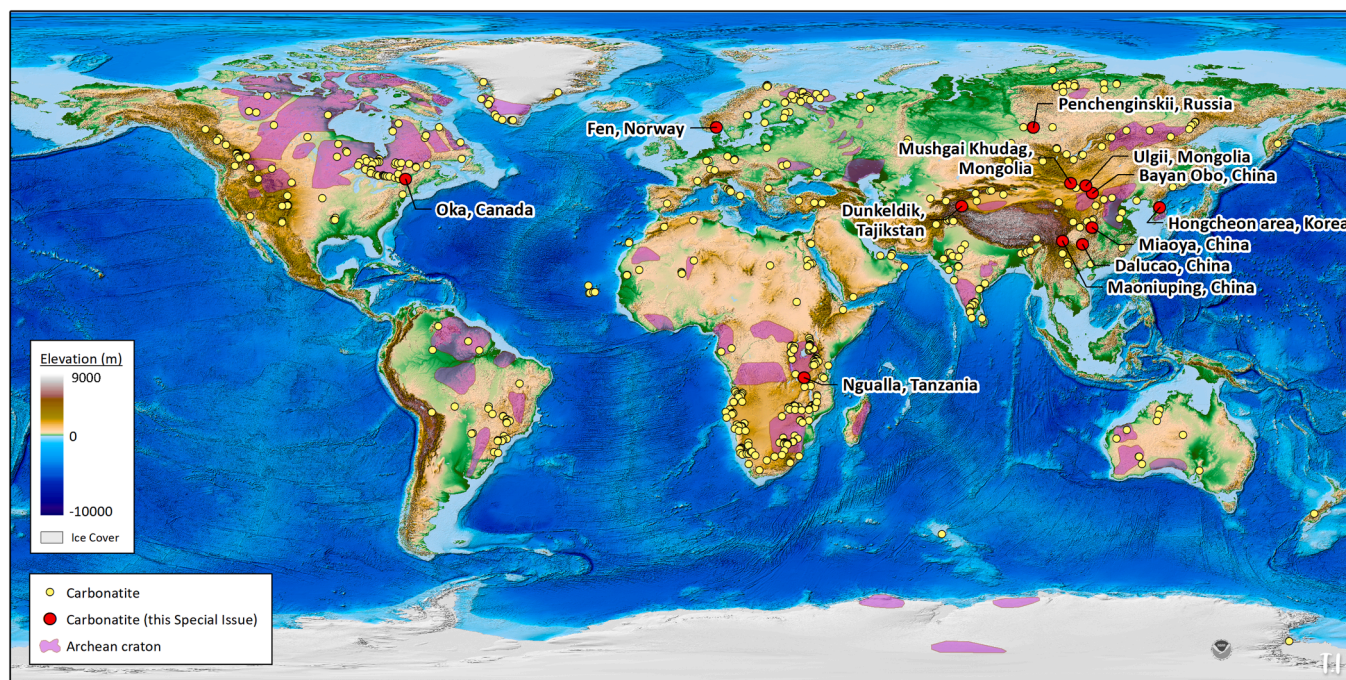
There is an on-going open and intense debate on how carbonatitic magma are generated, what is their genetic relation with other silicate rocks, and what are their associated magmas and fluids (e.g., Fitton and Upton, 1987; Bell, 1989; Stoppa and Woolley, 1997; Bell et al., 1998; Harmer et al., 1998; Harmer and Gittins, 1998; Mitchell, 2005; Wall et al., 2005; Woolley and Kjarsgaard, 2008b; Stoppa et al., 2009, 2019; Yang et al., 2009, 2017; Jones et al., 2013; Kynicky et al., 2019). Their relation with some specific rock types such as kimberlites and lamprophytes is also far from clear (e.g., Mitchell, 2005; Wall et al., 2005; Jones et al., 2013). The study of extrusive carbonatites has progressed our understanding significantly about the associations of carbonatite rock and their emplacement mechanisms (Woolley and Church, 2005).

This special issue aims to contribute to the existing knowledge about carbonatites and their mineral potential as sources of critical metals through a wide variety of studies on carbonatites/carbonatite complexes in Tanzania, China, Canada, Korea, Norway, Mongolia, Russia, Tajikistan and Norway (Table 1 and Fig. 1; see the section below).

## 2. Novel studies of carbonatites: Contributing to the debate

The papers presented in this special issue contribute to the debate and a better understanding of REEs enrichment in carbonatites. This enrichment can have its primary origin during the magmatic processes. However, REEs magmatic enrichment is not the critical factor in many carbonatites to make them economically viable for their REEs content. Hydrothermal events associated with the carbonatite emplacement as well as the mixing of meteoric fluids, or to post-depositional processes such as weathering can play essential roles resulting in the REEs enrichment of carbonatites (this issue). The collection of papers in this special issue consider a diversity of aspects and processes that have impact in the REEs budget associated to carbonatites (Table 1).

Witt et al. (2019, this issue) present the first published information since the 60s on the Mesoproterozoic Ngualla carbonatite complex, Tanzania. The Ngualla carbonatite was emplaced exploiting lithospheric-scale structures separating the Tanzania Craton from the West African, Congo and Kalahari cratons. They report that weathering was a critical factor in the formation of REEs ore at Ngualla. However, the primary proto-ore resulted mainly from in situ igneous processes. Concentrations of total Rare Earth Oxides (TREO) vary from fresh rock at 1–2% REEs ore to 3–6% TREO, resulting from weathering (generating



**Fig. 1.** Simplified global map of carbonatite occurrences, highlighting the location of carbonatites discussed in this Special Issue. Carbonatite locations are from Woolley and Kjarsgaard (2008a), and Archean cratons from Furnes et al. (2015). The relief model is modified from NOAA-National Geophysical Data Center (2009). The distribution of carbonatites displays a geographical correlation with several cratonic areas, and high-relief areas associated with erosional landscape regimes. Light grey color represents ice whereas white color is for elevations  $>6,200$  m. The green coloured areas represent a narrow bracket of elevation values close to zero.

a resource of 21.3 Mt at 4.75% REO and 37.7% barite). Witt et al. (2019, this issue) conclude that weathering is a critical component in the formation of carbonatites with economic REEs mineralization. They proposed that mineral exploration in Africa should target those carbonatite intrusions that have experienced an extended history of weathering and not exposed to erosion.

Chen et al. (2019, this issue) present a study on the chemical compositions of magnetite, from four carbonatite complexes namely Oka, Mushgai Khudag, Hongcheon and Bayan Obo in Canada, Mongolia, Korea, and China, respectively. Their study reports that High Field Strength Elements (HFSE; Zr, Hf, Nb, Ta, U, Th) are generally depleted, that a consistent concentration of 2–5 ppm is observed for Ge, and that V and Zn display significant variations that span from 10 s to 1000 s of ppm. Based on the results of this study, Chen et al. (2019, this issue) conclude that the correlation between Ti vs. Zr + Hf, Ti vs. Nb + Ta and Ni/Cr vs. Ti can be used to discriminate magmatic and hydrothermal magnetite in carbonatite-related environments. Besides, Zn/Co vs. Cu/Mo and Cu vs. Zr + Hf ratios can be used to distinguish carbonatite-related magnetite from magnetite that formed in other settings (Fe-Ti-P deposit, andesite, IOCG, porphyry, BIF, Fe-skarn, albitized granitoid and carbonate alteration complexes). Taking into account that magnetite is one of the most common accessory minerals in magmatic rocks, the outputs of this study strongly support that magnetite can be used as an indicator mineral to locate carbonatites.

Shu and Liu (2019, this issue) study the role of hydrothermal fluids in the transport and precipitation of REEs, by analysing the fluid inclusions in the Cenozoic Dalucao carbonatite REEs deposit, Sichuan, China. They study four different processes affecting the Dalucao carbonatite: magmatic, pegmatitic, hydrothermal, and supergene processes. The presence of melt and melt–fluid inclusions in the pegmatite stage is interpreted as a magmatic origin for the ore-forming fluids. In contrast, the cooling of the fluids and the inflow of meteoric waters are envisioned as the factors resulting in hydrothermal REEs precipitation. Shu and Liu (2019, this issue) conclude that from an exploration perspective, cratonic margins enriched in Sr, Ba, and REEs, in combination with the

occurrence of pegmatite, fenitization, and mineral assemblages comprising fluorite–barite–calcite and containing  $\text{CO}_2$ -bearing and high-salinity inclusion assemblages, are vectors towards carbonatites enriched in REEs.

Vrublevskii et al. (2019, this issue) study the Penchenga Neoproterozoic fenite-carbonatite complex in the Yenisei Ridge, Siberia, Russia. They describe high-temperature primary mineral phases, late-magmatic accessories, and secondary phases of hydrothermal and supergene minerals. Vrublevskii et al. (2019, this issue) interpret that the degassing of juvenile alkali-dolomite melts and its interaction with meteoric waters led to fenitization and hydrothermal fluids. Rare earth element-bearing mineral phases precipitate from these REEs-rich fluids. The oxygen isotope system of the carbonate, apatite, magnetite, and pyrochlore minerals was closed at  $\sim 250$  to  $480$  °C. This study presents significant novel insights on the chemical evolution of Penchenga-like carbonatite system, and the conditions at which the carbonatite became enriched in Nb–Ta and REEs.

Hong et al. (2019, this issue) report a recently discovered carbonatite–syenite complex in the Dunkeldik area of Pamir, Tajikistan. They present a petrological and geochemical study, coupled with zircon U–Pb ages and Hf isotope compositions for the carbonatite and the associated alkaline-carbonatite belt. They suggest that the carbonatite parental magmas were derived from thickened lower crust enriched with material and fluids from an ancient subducted oceanic slab. They interpret that the carbonatite and syenitic porphyries formed in a Miocene post-collisional setting. The upwelling of an asthenospheric mantle diapir during the Cenozoic induced the partial melting of metasomatized lithospheric mantle and lower crust beneath the western margin of the Indian–Asian collision zone. Carbonatitic magmas ascended through the Karakorum strike-slip fault. This study points out the crucial importance of major crustal structures for the carbonatitic intrusion emplacement.

Feng et al. (2020, this issue) address the mechanisms that concentrate REEs during carbonatitic magmatic processes by studying apatite-hosted melt inclusions from the Ulgii Khiid carbonatites, Mongolia. They report within melt inclusions a phosphate glass significantly enriched in

**Table 1**

Summary of the carbonatite occurrences studies presented in this Special Issue and their exploration proxies cross-referenced to Fig. 1.

Carbonatite complex	Country	Authors (this issue)	Proxies and processes for REEs enrichment in carbonatites
1 Ngualla	Tanzania	Witt et al.	Africa should target those carbonatite intrusions that have experienced an extended history of weathering and which have not been exposed to erosion.
2 Oka	Canada	Chen et al.	Magnetite geochemistry as an indicator mineral to discriminate magmatic and hydrothermal magnetite in carbonatite, and to distinguish carbonatite-related magnetite from magnetite that formed in other settings.
3 Mushgai Khudag	Mongolia	Chen et al.	Magnetite geochemistry as an indicator mineral to discriminate magmatic and hydrothermal magnetite in carbonatite, and to distinguish carbonatite-related magnetite from magnetite that formed in other settings.
4 Hongcheon	South Korea	Chen et al.	Magnetite geochemistry as an indicator mineral to discriminate magmatic and hydrothermal magnetite in carbonatite, and to distinguish carbonatite-related magnetite from magnetite that formed in other settings.
5 Bayan Obo	P.R.C. China	Chen et al.	Magnetite geochemistry as an indicator mineral to discriminate magmatic and hydrothermal magnetite in carbonatite, and to distinguish carbonatite-related magnetite from magnetite that formed in other settings.
6 Dalucao	P.R.C. China	Shu and Liu	Cratonic margins enriched in Sr, Ba, and REEs, in combination with the occurrence of pegmatite, fenitization, and mineral assemblages comprising fluorite–barite–calcite and containing CO <sub>2</sub> -bearing and high-salinity inclusion assemblages, are vectors towards carbonatites enriched in REEs.
7 Penchenga	Russia	Vrublevskii et al.	Interaction with meteoric waters led to fenitization and hydrothermal fluids. Rare earth element-bearing mineral phases precipitate from these REEs-rich fluids.
8 Dunkeldik	Tajikistan	Hong et al.	Major crustal structures for the carbonatitic intrusion emplacement.
9 Ulgii Khiid	Mongolia	Feng et al.	Apatite-poor and barite/celestine/fluorine-rich carbonatites are more prospective targets for REEs mineral exploration.
10 Bayan Obo	P.R.C. China	Ren et al.	The primary REEs were derived from a carbonatite magmatic source, and later

**Table 1 (continued)**

Carbonatite complex	Country	Authors (this issue)	Proxies and processes for REEs enrichment in carbonatites
11 Maoniuping	P.R.C. China	Zheng and Liu	fluid flowed into the deposit and resulted in REEs remobilisation. High concentrations of Na, K, Sr, Ba, and REEs, the occurrence of pegmatite, intense fenitization, the presence of stable mineral assemblages of fluorite, barite, and calcite.
12 Miaoya	P.R.C. China	Zhang et al.	High tectonic deformation in the area and high hydrothermal activity as key processes for REE enrichment.
13 Fen	Norway	Dietzel et al.	Enrichment of REEs was originated by large amounts of carbonatite-derived REE-rich fluids penetrating the earlier crystallized carbonatites along permeable zones.

REEs, which have a homogenization temperature above 1,200 °C. They suggest that large amounts of magmatic apatite in carbonatite rocks could be an indicator of the P saturation in the melt. This could explain why some carbonatites are economic resources based on their apatite content, and have less REEs content than other carbonatites. Therefore, they conclude that P plays a significant role in controlling the REEs budget in the evolution of the carbonatites. Feng et al. (2020, this issue) suggest that apatite-poor and barite/celestine/fluorine-rich carbonatites are more prospective targets for REEs mineral exploration.

Ren et al. (2019, this issue) report a mineralogical and geochemical study of apatite and dolomite from the Bayan Obo Fe-REEs-Nb deposit, which is the world's largest resource of REEs. They identified three types of fluorapatite. Type I and Type II fluorapatite have high REEs content (17470–77090 ppm), whereas Type III fluorapatite has much lower REE content (2452–7496 ppm) and differs in Y, Na and Sr content significantly. Type I and Type II fluorapatite is interpreted as the result of remobilization during fluid-induced dissolution-reprecipitation processes during a late-stage of REEs rich hydrothermal event, whereas Type II is the result of a REE-poor stage. Ren et al. (2019, this issue) conclude that Bayan Obo deposit experienced multistage hydrothermal metasomatism. They conclude that the primary REEs were derived from a carbonatite magmatic source, and later fluid flowed into the deposit and resulted in REEs remobilisation.

Zheng and Liu (2019, this issue) present a study of the Cenozoic Maoniuping REEs deposit, located in the eastern Tibetan Plateau, which is the second-largest carbonatite-REEs deposit in China. Based on geological observations and the petrography of fluid inclusions, Zheng and Liu (2019, this issue) interpreted that the mineralisation processes at the Maoniuping REEs deposit happened in four stages: magmatic, pegmatitic, hydrothermal, and REEs enrichment stage. They interpret that  $\delta D$  and  $\delta^{18}O_{\text{fluid}}$  values and the high N<sub>2</sub>/Ar ratios indicate that the ore fluids originated from carbonatitic magma. In contrast, magmatic and meteoric water co-existed during the second hydrothermal event and the REEs stage. During the REEs stage, magmatic fluid cooling and mixing with meteoric water played a fundamental role in the mineralisation stage, which is interpreted to have happened at 160–240 °C and <0.5 kbar. Zheng and Liu (2019, this issue) propose that high concentrations of Na, K, Sr, Ba, and REEs, the occurrence of pegmatite, intense fenitization, the presence of stable mineral assemblages of fluorite, barite, and calcite are exploration proxies for carbonatite REEs deposits.

Zhang et al. (2019, this issue) present an isotopic and mineralogical study on the Miaoya REEs prospect, Qinling orogenic Belt, China. They

use this case study to consider different processes needed to form a carbonatite REEs deposit. Zhang et al. (2019, this issue) report that LA-ICP-MS analyses reveal that apatite and calcite in carbonatite concentrate the REEs content. They interpret that the REEs content at the Miaoya prospect is derived from the associated carbonatite-syenite complex. They conclude that the low REE of the Miaoya prospect is the result of two main factors: low tectonic deformation in the area resulting in restricted hydrothermal activity, and the lack of scavenging fluids to remobilise and concentrate the REEs.

Dietzel et al. (2019, this issue) present a mineralogical and chemical study of the largest carbonatite-related REEs and Th deposit in Europe: the hydrothermal REEs-Th-Nb-mineralization in the Fen complex, Norway. They report that the Fen complex underwent three intense post-magmatic-hydrothermal alteration events, resulting in two distinct phases of mineralization. Dietzel et al. (2019, this issue) interpret that the mixing of the carbonatite-derived fluid and meteoric fluid resulted in the formation of distinct zones of REEs. The highest HREEs-enrichment corresponds to the most intense hydrothermal alteration. Thorium-rich minerals were precipitated in close association with HREEs-rich minerals. During a second (pene-contemporaneous) alteration phase, a REEs-rich fluid led to remobilization and redistribution of Fe and Al and the formation of REEs-F-carbonates. The metasomatic silicification redistributed P and remobilized LREEs. Dietzel et al. (2019, this issue) suggest that the enrichment of REEs was initiated by large amounts of carbonatite-derived REE-rich fluids penetrating the earlier crystallized carbonatites along permeable zones.

### 3. Implications for exploration targeting of carbonatite-hosted REEs

In the words of Prof Robert Kerrich (1948–2013), “Rare earth elements are not rare and are not from Earth” (since REEs form by supernova nucleosynthesis). Rare earth elements concentration in the upper continental crust (UCC), Post-Archean Australian Shale (PAAS) and North American Archean Shale (NASC) (excluding Y and Sc) average values are ~150, ~185, and ~175 ppm, respectively (Nance and Taylor, 1976; Gromet et al., 1984; Rudnick and Gao, 2003). The above average concentrations, even if very low as background, indicate that the sedimentary packages in basins have the potential to provide vast resources of REEs with a technology that could concentrate and “farm” these elements out of the sedimentary units. The problem is not about finding REEs enrichments, but about their extraction and concentration with acceptable cost and environmental impact.

Carbonatites are one of the most prospective host rocks for REEs resources but not all carbonatites are heavily enriched in REEs and therefore their REE content needs to be enriched through secondary processes. However, the geological processes that lead to critical metals enrichment in carbonatites are not well understood (e.g., Verplanck, 2020). A variety of processes have been reported to enrich REEs in carbonatites, namely, magmatic, hydrothermal or late weathered related processes. (Table 1; e.g., articles presented in this issue). However, there is considerable uncertainty about why some carbonatites are REEs enriched, and others are not. Reducing the uncertainty about where to look for mineralized carbonatites would be a significant step forward in the exploration of the carbonatitic REEs deposits.

Based on the distribution of the known carbonatite occurrences, cratons are the most favourable geological setting for carbonatite emplacement (Woolley and Bailey, 2012). However, the small size of the carbonatite outcrops and footprints of (~3 km<sup>2</sup>) makes them a difficult target (e.g., Simandl and Paradis, 2018). On the other hand, most of the carbonatites are associated with alkaline complexes (Woolley and Kjarsgaard, 2008b), which are larger in scale and, therefore, display larger lithological, geochemical and geophysical footprints. This has significant implications for mineral exploration, mostly if the carbonatite-associated footprints can be expressed as mappable proxies and be used as ore vectors in a mineral systems framework (e.g., Knox-

Robinson and Wyborn, 1997; McCuaig et al., 2010; McCuaig and Hronsky, 2014; Banks et al., 2019).

Many carbonatite complexes present a circular or semicircular geometry in plan view (e.g., Barber, 1991; Giovannini et al., 2017; Simandl and Paradis, 2018) that could be detectable in a wide variety of geoscience datasets, particularly remote sensing (e.g., panchromatic, multispectral, hyperspectral as well as microwave images, and digital elevation models) and geophysical (radiometrics, magnetic and gravity) data. Integration of geometrical, spectral and geophysical features in combination with geochemical footprints (e.g., REEs, PO<sub>4</sub>, F, Cl, etc enrichments) can provide useful exploration proxies for carbonatite. Recent advances in data science and analysis technology provide powerful and promising targeting tools for data integration at regional scales (e.g., Neave et al., 2016; Porwal and González-Álvarez, 2019 and references therein). However, limited availability of regional datasets with appropriate data density and small-scale of carbonatite outcrops/footprints make applications of data-analytical-techniques impracticable in many areas. Moreover, many extensional belts on the continents, particularly in cratonic areas, have thick cover (transported material and/or intensely and deeply weathered profiles), which makes the detection of carbonatites problematic.

The geographical distribution of discovered carbonatites displayed in Fig. 1 shows a geographical correlation with diverse cratonic areas in the Superior Craton in North America, Tanzania and Kapvaal in Africa, Amazonian in South America, Siberian in Russia and the Dharwar Craton in India. Furthermore, the distribution of carbonatites suggests a correlation with high-relief areas associated with erosional landscape regimes (Fig. 1). This geomorphological context may facilitate the detection of ore footprints. Similar geographical correlation with erosional landscape regimes has been reported in Western Australia for ore deposits and Au surface geochemical anomaly distribution in the Forrestania region, Yilgarn Craton (González-Álvarez et al., 2019).

At present, there are not many published prospectivity analysis studies that link conceptual models of carbonatite emplacement with diverse spatial proxies using mathematical/statistical or machine learning approaches (e.g., Porwal et al., 2010; Porwal and Krauzer, 2010; Aitken et al., 2014; Morgenstern et al., 2018). Such studies can help in delineating potential targets for locating new carbonatite occurrences, and also help in validating the conceptual models and their exploration proxies at different scales and in different geological environments. In particular, in areas of intensely weathered profiles and under cover where the detection of carbonatites is especially challenging (e.g., González-Álvarez et al., 2016, 2020 and references therein).

For effective targeting of carbonatites and carbonatite-hosted REEs deposits, it is going to be critical to combine data-driven approaches based on integration of remote sensing, regional geochemical, and geophysical (magnetics, radiometrics and gravity) datasets with improved understanding of the processes (magmatic, hydrothermal, or surficial) that control the emplacement of carbonatites and enrich carbonatites in REEs. This integrated approach can fundamentally impact the estimation of the REEs resource associated with this rare lithological rock type.

### Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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