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Rare Earth Elements in Europe and Greenland: A geological potential? An overview

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Abstract. Recently, rare earth elements (REE) have occupied a centre-stage owing to the large volatility of prices and stress occasioned on global markets by limitations of Chinese export quotas. Thus, numerous industries which depend on secured and diversified rare earths sources, now consider REE as critical for new technologies. In response, countries are developing and diversifying their supply sources, with new mining projects located outside China and efforts in the REE recycling domain.

Based on a global geological and metallogenic synthesis, a first review map representing more than 270 REE occurrences and deposits classified by typology in Europe and Greenland is proposed. At first glance, the Baltic Shield and South Greenland constitute the main areas with a strong potential. Indeed, northern Europe is characterised by numerous occurrences linked to alkaline intrusions, carbonatites and pegmatites. In southern Greenland, the Ilimaussaq alkaline complex contains the future world-class Kvanefjeld U-REE-Zn deposit.

While REE are relatively ubiquitous in Europe and Greenland and occur in a variety of geological settings, only the two previously mentioned regions appear to have economic potential. However, progress in the understanding of the REE ore forming processes is required to help better guide exploration and make new discoveries. While recycling technologies should be developed, reliance on extracted sources will continue to be indispensable, especially considering annual growth rates for REE demand, which are around 5%.

Keywords: REE, occurrence, deposit, Europe, Greenland, potential.

1 Rare earths: strategic and critical

Recent years have seen unprecedented volatility concerning prices and the dynamics in the global market of the rare earth elements (REE). Nowadays, numerous industries depend on secured and diversified rare earth sources, which are increasingly considered as critical to a wide range of new technologies (i.e. permanent magnets, energy storage, phosphors *etc.*) and as strategic by numerous states, including among the EU-27. As China is practically a monopoly producer, its recent limitations on export quotas have had a severe economic impact. To overcome this, REE consuming countries are developing and diversifying their supply sources, based on both extracted and recycled sources. With respect to the former, new mining projects in the USA and Australia (e.g. Mountain Pass, Mount Weld) provide welcome alternatives to import from China. Regarding Europe and taking into account Greenland, several new projects are currently being developed in Scandinavia and Greenland (e.g. Norra Kärr, Kvanefjeld). A reliable

assessment of current European REE resources and reserves and of future potentials should rely on a better understanding of REE ore-forming processes, taking into account the considerable diversity of deposits and associated geological settings within continental Europe. Relying on a global geological and metallogenic synthesis, notably from the European ProMine Project database, a first review map representing over 270 REE occurrences and deposits, classified by typology in Europe and Greenland, is proposed. Such a synthesis provides a basis for identifying preferential areas for future REE exploration (Figure 1).

2 Typology of rare earths deposits

The term REE is often considered as a misnomer since these elements are quite common in the Earth's crust. The REE can occur in a broad range of geological settings and their concentration and distribution in minerals depend on rock forming, hydrothermal, weathering and other surface processes. REE deposits are broadly divided into two main categories: primary deposits associated with magmatic and hydrothermal processes and secondary deposits concentrated by sedimentary processes and weathering (Kanazawa and Kamitani 2006; Walters et al. 2011; Chakhmouradian and Wall 2012).

2.1 Primary deposits

Primary REE deposits - which represent the bulk of REE production since 1960s - are broadly associated with alkaline-peralkaline igneous rocks and carbonatites. However, REE minerals may be also associated with pegmatites, skarns, Fe oxide-phosphates and quartz-fluorine-bearing veins.

In carbonatites, REE are mainly represented by light-group rare earth elements (LREE, from ^{57}La to ^{64}Gd) occurring in minerals such as bastnäsite, allanite, apatite and monazite (Gupta and Krishnamurthy, 2005). REE deposits associated with alkaline-peralkaline rocks are relatively low-grade (<5 % rare earth oxides REO) although they are commonly enriched in heavy-group rare earth elements (HREE, from ^{65}Tb to ^{71}Lu and also ^{39}Y ; Chakhmouradian and Zaitsev 2012). Typical minerals are apatite, bastnäsite, eudialyte, gadolinite and loparite, which are often associated with "exotic" rock names such as ijolite, lujavrite, urtite or melteigite.

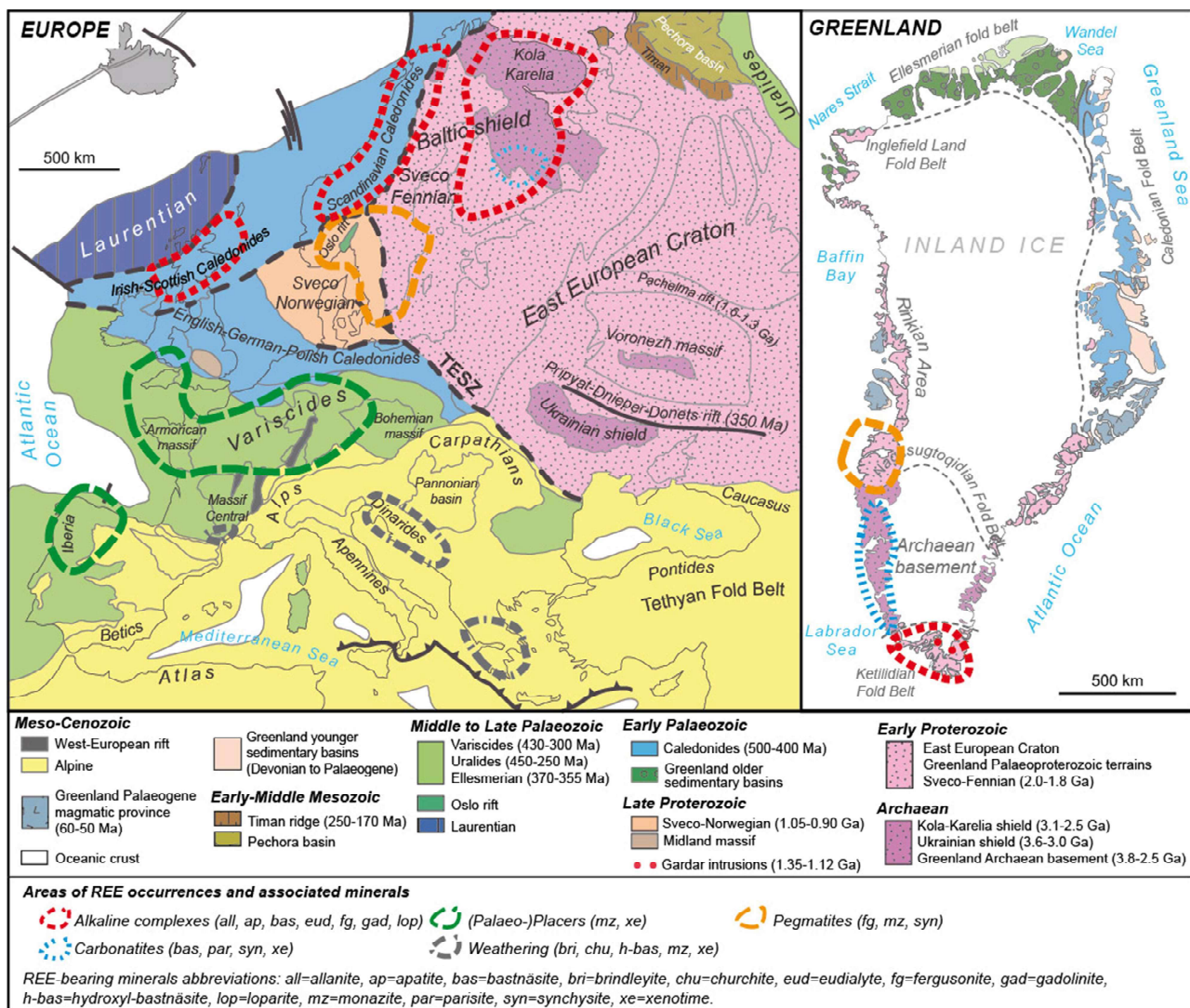


Figure 1. Simplified geotectonic map of Europe and Greenland (modified after Artemieva et al. 2006; Gee and Stephenson 2006; Henriksen 2008) and their potential areas for REE occurrences and deposits. Also indicated are REE-bearing minerals associated with each deposit type.

In addition to alkaline-peralkaline igneous rock deposits, pegmatites containing significant amounts of LREE (allanite, monazite) or HREE (gadolinite) mineralisation can occur.

Moreover, notable REE concentrations are observed within a few iron-oxide-copper-gold (IOCG) deposits or in the magnetite-apatite deposit of the Kiruna district in northern Sweden (Harlov et al. 2002). Such deposits are hosted by a variety of rocks ranging from intrusive igneous to volcanic and sedimentary rocks, with REE-bearing minerals such as apatite or allanite.

It is worth to mention some other REE deposits associated with sedimentary rocks, e.g. fluorite-baryte mineralisations (disseminated in veins and breccia, with synchysite and parisite) or U-deposits.

2.2 Secondary deposits

Secondary deposits represented the bulk of REE production prior to the 1950s (100 kt), especially from monazite-bearing placers (Orris and Grauch 2002).

Secondary deposits are mainly the result of sedimentary remobilization and weathering processes: placers, REE-bearing clays and laterites including ion-adsorption type

REE deposits. The latter are currently only mined in southern China for HREE.

Placer deposits are accumulations of heavy minerals in sands and gravels by gravity separation during sedimentary processes. Placers are generally Tertiary and Quaternary in age, although a few are dated as Precambrian. Main REE-bearing minerals are monazite (with or without xenotime), fergusonite, euxenite, allanite and loparite (Donnot et al. 1973; Morteani 1991; Mohanty et al. 2003; Elsner 2007).

Weathering processes lead to the breakdown of many rock-forming minerals, the leaching of certain elements (Mg, Ca) and the residual enrichment of less mobile elements (Fe, Al). Thus weathering of initially REE-enriched rocks (e.g. carbonatite) can provide residual weathering REE deposits (e.g. laterites, bauxite; Lottermoser 1990) with new supergene minerals (e.g. phosphates such as monazite) and high-grades (10-25% REO).

Another type of residual REE deposit has been described: REE-bearing clays, termed ion-adsorption clays (Chi and Tian 2008). These low-grade deposits

(0.03-0.35% REO) are HREE-rich and often associated with weathered REE-enriched granites, where REE are adsorbed by clay minerals such as kaolin or halloysite.

3 Geological potential: an overview

3.1 Rare Earths in Europe

In Europe, primary deposits or occurrences are mainly represented by alkaline complexes and carbonatites, located in northern Europe. Indeed, at first glance, the Baltic shield and Kola Peninsula constitute the main areas with strong geologic potentials. Alkaline intrusions such as Norra Kärr (Sweden) can constitute new projects for REE mining in Europe. This intrusion, represented by a nepheline syenite, contains an inferred REE mineral resource of 60.5 Mt @ 0.54% REO (Tasman Metals, 2013). Other potential deposits linked to alkaline intrusions are Tasjö (Sweden), Katajakangas and Otänmaki (Finland), Kodal and Saeterasen (Norway). Moreover, the Kola Peninsula exhibits the both well-known Khibina and Lovozero alkaline complexes (Sørensen 1997; Arzamastsev et al. 2006) with reserves estimated at 1,000 Mt @ 0.8-1.5% REO (Kogarko 1995 in Orris and Grauch 2002). In the north-west of Scotland, several occurrences associated with British Caledonian alkaline intrusions are mentioned close to Loch Borralan, Loch Ailsh and Ben Loyal (Shaw and Gunn 1993; Young et al. 1994). To the latter can be added occurrences related to British Tertiary igneous rocks, such as Skye and St-Kilda. With respect to carbonatites, examples are the Fen Nb-Ta deposit (Norway), with several REE-bearing minerals (monazite, bastnäsite, synchysite), and also the Sokli carbonatite in Finland. Close to the Permian Oslo rift, the Larvik-Langesundfjord region exhibits numerous pegmatites with REE-bearing minerals. Note that anecdotic concentrations of REE-bearing minerals have been reported in pegmatites in the Italian Alps. In northern Sweden, the Kiruna apatite-iron ore deposit has REE resources roughly estimated to ~5.6 Mt @ 0.5% REO (Parák 1973). It is also worth noting the occurrence of REE observed within Zn-Pb-F-Ba deposits in the North Pennine ore field (England; Bau et al. 2003).

Secondary deposits or occurrences in Europe are mainly represented by grey monazite palaeoplacers, associated with Ordovician sediments of Palaeozoic basins (i.e. western France, Wales, Belgium, Czech Republic) and linked to the Variscan orogeny. Current to recent placers that might constitute interesting targets are found in Denmark (Hanstholm), Germany (Cuxhaven) or Poland (Slupsk), and would deserve to be better explored and qualified. Potential occurrences related to weathering processes should not be overlooked, e.g. REEs related to bauxite deposits in the Balkans and Greece (Grebnik, Vlasenica, Marmara; i.e. hydroxyl-bastnäsite, brindleyite, goyazite), or in the south of France. Investigations could be carried out on clays from Permian-Triassic terrains, phosphorous levels within certain Palaeozoic sediments (e.g. southern France) and on F-Ba deposits of the French Massif Central.

3.2 Rare Earths in Greenland

In view of current proposed projects, it has been suggested that Greenland may represent a REE potential capable of meeting 25% of global demand.

Primary deposits or occurrences mainly consist of the Gardar alkaline complexes. Located in South Greenland, the Gardar Province (1.35-1.12 Ga) contains alkaline complexes that exhibit main occurrences with potentially future world-class REE deposits, such as Kvanefjeld in the Ilímaussaq intrusion (6.6 Mt total REO (TREO) coupled with U resources), and the Kringlerne (20 Mt TREO) or Motzfeldt intrusions (Sørensen et al. 2011; Steinfeldt 2012). The Gardar Province contains other alkaline intrusions that can be interesting for REE potential, such as Grønnedal-Ika, Igaliko, Nunarssuit or Tugtutôg. Those alkaline complexes mainly consist of nepheline syenite, locally associated with carbonatite, and are intruded into the Julianehab batholith in relation with the Ketilidian fold belt. Alkaline intrusions also occur to the eastern part of Greenland: the Gardiner complex (50 Ma) and Kap Simpson. In the western part of Greenland, in the Archaean craton and Rinkian Palaeoproterozoic mobile belt, many promising occurrences of carbonatites and pegmatites are described. For example the Sarfartoq carbonatite, dated at 565 Ma, contains ~14 Mt @ 1.51% REO (Secher and Larsen 1980). Besides, the Jurassic Qaqqarsuk (156 Ma) and Tikiusaaq (158 Ma) carbonatites show REO contents of 2.4 and 9.6%, respectively. South of the Rinkian Palaeoproterozoic mobile belt, pegmatites dated at 1.8 Ga, largely occur in the Nassuttutata Tasia area. Main REE-bearing minerals are monazite, allanite and apatite.

There are currently few descriptions of secondary deposits or occurrences in Greenland. One occurrence is Milne Land, located in eastern Greenland, which is a Cretaceous monazite-bearing palaeoplacer.

4 Economic considerations

Parallel to current efforts to find alternative extracted sources of REEs, a significant effort is devoted developing technologies for recycling REEs in products. Binnemans et al. (2013) provide a review of current technologies for the three market sectors that appear to provide the most potential in terms of recycling: permanent magnets, NiMH batteries and phosphors. A global perspective of REE flows and stocks in the world economy is provided by Du and Graedel (2011a), using material flow analysis. The diagrams for several REEs illustrate the orders of magnitude of flows between various compartments of the economy (manufacture, use, etc.) but also stocks accumulated in the use compartment (Du and Graedel 2011b). These data suggest accumulated (and hence potentially recyclable) stocks in the economy on the order of 440,000 t REE in 2007. According to Lynas (2010), world rare earth demand in 2010 was on the order of 136,100 t (i.e. approx. 115,000 t REE). Even assuming significant progress in REE recycling technologies, given the annual rate of growth of REE demand (on the order of 5%; Alonso et al. 2012), recycling of accumulated

stocks in the economy cannot be expected to satisfy demand. In a growth based economy, there is a gap between demand and the “offer” provided by the waste stream, due to the lifetime of products in the economy (see e.g. Grosse 2010). Therefore, REEs will need to be extracted in the future, in order to satisfy in particular the demand for clean technologies. Recycling, however, especially of certain HREEs (Dy, Tb, etc.) but also Nd, is essential to reduce the so-called “balance problem” (Binnemans et al. 2013), which generates an excess of the more abundant elements (La, Ce) as a result of mineral extraction. The potential from recycling can be compared to that of mining projects cited previously. For three European projects alone (Kringlerne, Kvanefjeld and Norra Kärr) the potential (resources + reserves) is on the order of 30 Mt REO.

5 Perspectives for exploration?

The review of rare earth occurrences in Europe and Greenland illustrates the relative ubiquity of REEs in various geological settings. Currently, however, the most promising potential is only concentrated in southern Greenland and in the Baltic shield, with a few very large deposits. Further work on REE ore-forming processes applied to specific European geological settings could help guide exploration and allow new discoveries (e.g. Permian-Triassic clays in western Europe, F-Ba deposits in the French Massif Central, phosphorous levels of Palaeozoic sedimentary series, alkaline intrusions of the Gardar complex in Greenland, etc.).

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