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# Europe's rare earth element resource potential: An overview of REE metallogenetic provinces and their geodynamic setting

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ABSTRACT

Security of supply of a number of raw materials is of concern for the European Union; foremost among these are the rare earth elements (REE), which are used in a range of modern technologies. A number of research projects, including the EURARE and ASTER projects, have been funded in Europe to investigate various steps along the REE supply chain. This paper addresses the initial part of that supply chain, namely the potential geological resources of the REE in Europe. Although the REE are not currently mined in Europe, potential resources are known to be widespread, and many are being explored. The most important European resources are associated with alkaline igneous rocks and carbonatites, although REE deposits are also known from a range of other settings. Within Europe, a number of REE metallogenetic belts can be identified on the basis of age, tectonic setting, lithological association and known REE enrichments. This paper reviews those metallogenetic belts and sets them in their geodynamic context. The most well-known of the REE belts are of Precambrian to Palaeozoic age and occur in Greenland and the Fennoscandian Shield. Of particular importance for their REE potential are the Gardar Province of SW Greenland, the Svecofennian Belt and subsequent Mesoproterozoic rifts in Sweden, and the carbonatites of the Central Iapetus Magmatic Province. However, several zones with significant potential for REE deposits are also identified in central, southern and eastern Europe, including examples in the Bohemian Massif, the Iberian Massif, and the Carpathians.
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## 1. Introduction

The rare earth elements (REE) are a group of 17 chemically similar elements (the lanthanides, scandium (Sc), and yttrium (Y)). Here we focus on the lanthanides and Y, which behave in similar ways in most environments in the Earth's crust. They are typically divided into light rare earth elements (LREE) and heavy rare earth elements (HREE). LREE and HREE are variably defined: we follow the EU definition of the LREE (EC, 2014) as lanthanum to samarium, and the HREE as europium to lutetium plus yttrium. Some members of this group are vital components in much modern technology, from neodymium (Nd), dysprosium (Dy), and praseodymium (Pr) for high-strength magnets used in wind turbines, hard disk drives and engines in electric cars, to europium (Eu), yttrium (Y), terbium (Tb), lanthanum (La), and cerium (Ce) for phosphor-based fluorescent lighting, smartphone screens and batteries (Guyonnet et al., 2015). Demand for these elements is thought to be growing at a rate of approximately 5–10% per year (Hatch, 2012; Massari and Ruberti, 2013) although rapid technological development means that accurate prediction is difficult. Recycling of scrap consumer electronics and technical industrial components will increasingly contribute to REE supply in the future (Binnemans et al., 2013), but is unlikely to be able to meet increasing demand (Du and Graedel, 2011), and thus mining of natural deposits is expected to continue as the major source for REE. At the time of writing, almost 90% of all REE entering the global market are produced in China (Wübbeke, 2013), and the EU has to import virtually all its REE, either as raw materials or as products such as batteries and magnets (Wall, 2014; Guyonnet et al., 2015). For this reason, the European Commission has recently identified the REE, particularly the HREE, as critical materials with a significant risk to supply (EC, 2014). Detailed recent research highlights Nd, Eu, Dy, Tb, and Y as the most critical of all of the REE, because of their use in the important magnet and phosphor markets (Du and Graedel, 2013), although the criticality of Eu, Tb, and Y is likely to change as LEDs increasingly replace phosphors (Guyonnet et al., 2015).

This paper is a product of the EURARE project, which is funded by the European Commission under the Seventh Framework programme to set the basis for development of a European REE industry; and the ASTER project granted by the French national research agency (ANR) to understand REE flows and stocks in Europe. The EURARE project aims to assess the potential for REE resources in Europe, and to develop new, efficient and sustainable methods for processing of potential European REE ores. Such raw material processing is complex, comprising a beneficiation step to concentrate REE minerals from the ore, extraction of the rare earth oxides from their host minerals to produce a mixed rare earth concentrate, and subsequent metallurgical separation into individual rare earth metals. Once a rare earth deposit is identified, its geology and mineralogy must be fully characterised as beneficiation methods have to be tailor-made for each deposit, and are dependent on properties such as mineralogy, textures, and grain size of the ore (Jordens et al., 2013). The first step for the EURARE and ASTER projects has thus been a review of all potential European REE resources and an assessment of which REE deposits deserve further research and characterisation. This review paper presents an overview of the main natural REE occurrences and prospects in Europe, and identifies the areas with most potential for future exploration and development, on the basis of their geological suitability. 'Europe' in this context is considered to include EU countries and candidate countries, plus Norway, Switzerland, and Greenland. Russia and Ukraine are not included in this work.

Although the majority of the rare earth elements were originally discovered in European samples, chiefly from the Bastnäs and Ytterby mines in Sweden (Gadolin, 1794; Hisinger and Berzelius, 1804; Williams-Jones et al., 2012) there is no recent history of REE mining in Europe. Exploration over the last decade has identified some major REE deposits, particularly in Greenland and the Fennoscandian shield, but it is likely that more extensive primary resources of the REE remain to be identified.

The partners in the EURARE and ASTER projects (including the geological surveys of Denmark and Greenland, Sweden, Norway, Finland, France, Greece and the United Kingdom) have critically reviewed both published and unpublished data to develop the overview provided here. Due to the limited extent of REE exploration, only a small number of Europe's deposits have been investigated to the stage of a full REE resource estimate that is compliant with the JORC or NI-43–101 codes of practise for reporting of mineral resources and reserves. Where such resource estimates are available, they are included in this overview. However, our understanding of Europe's potential is still largely based on knowledge of the most suitable geological environments for enrichment of the REE in the crust, and on data derived from academic studies. It is very likely that some of the metallogenetic belts described here contain other REE-enriched localities that have not yet been described.

Where individual localities are recognised as being of interest, they are classified by the EURARE project as an REE 'resource', 'deposit', 'occurrence' or 'by-product' (Table 1). Resources have a formal resource estimate that has been published at the time of writing, although it should be noted that these vary widely in grade and tonnage across Europe. Deposits have typically been the subject of some previous exploration, and on the basis of the available evidence it is considered that an economic resource may be identified by future exploration. Individual REE occurrences have REE enrichments above normal crustal abundances, but are typically very low-grade or small in size and therefore unlikely to be economic; however, they are of significant scientific interest. By-product localities are those where the REE could be economic as by-products of the extraction of other minerals in large volumes. These classifications are based on review of the evidence available to the authors at the time of writing, and may be subject to change on the basis of new or unpublished evidence.

## 2. Overview of the geological setting of REE mineralisation in Europe

Despite their name, the rare earth elements are not all particularly rare in the earth's crust; the name reflects the difficulty of separating them into the native metals, and the fact that some members of the group are indeed rare (Chakhmouradian and Wall, 2012). They occur in small amounts in all parts of the Earth's crust in a wide range of tectonic settings, and are widely used for petrogenetic studies. The total concentration of REE in average bulk continental crust is c. 125 ppm; (Rudnick and Gao, 2004). Development of a potentially economic rare earth element resource requires that they are concentrated significantly above these background levels, typically to percentage concentrations of total REE. Enrichment of the REE may occur through primary processes such as magmatic processes and hydrothermal fluid mobilisation and precipitation, or through secondary processes that move REE minerals from where they originally formed, such as sedimentary concentration

**Table 1**
Significant localities or groups of localities described in this paper, classified as resource (those with a formal REE resource estimate compliant with the JORC or NI-43–101 reporting codes); deposit (those for which an economic resource is likely to be present and may be identified by future exploration); occurrence (those in which the REE are enriched but which are unlikely to be economic); and by-product (those in which the REE could be economic as a by-product of another commodity).

| Locality | Country | Type | Deposit classification |
|---|---|---|---|
| Aksu Diamas | Turkey | Placer | Resource |
| Alnö | Sweden | Carbonatite | Occurrence |
| Arran, Skye, Mourne Mountains | UK | Granite & pegmatite | Occurrence |
| Biggejavri | Norway | Hydrothermal | Occurrence |
| Delitzsch (Storkwitz) | Germany | Carbonatite | Resource |
| Ditrău | Romania | Alkaline igneous rock | Deposit |
| Fen | Norway | Carbonatite | Resource |
| Galiñeiro | Spain | Alkaline igneous rock | Deposit |
| Gardiner Complex | Greenland | Alkaline igneous rock | Occurrence |
| Grønnedal-Ika | Greenland | Carbonatite | Occurrence |
| Grängesberg-Blötberget | Sweden | Iron oxide–apatite | By-product (iron ore) |
| Halpanen | Finland | Carbonatite | Occurrence |
| Høgtuva | Norway | Hydrothermal | Occurrence |
| Iivaara | Finland | Alkaline igneous rock | Occurrence |
| Ivigtut | Greenland | Alkaline igneous rock | Occurrence |
| Jämtland | Sweden | Alkaline igneous rock | Occurrence |
| Kaiserstuhl | Germany | Carbonatite | Occurrence |
| Katajakangas | Finland | Alkaline igneous rock | Deposit |
| Kiruna-Malmberget | Sweden | Iron oxide–apatite | By-product (iron ore) |
| Kizilcaören | Turkey | Hydrothermal | Deposit |
| Kodal | Norway | Alkaline igneous rock | By-product (apatite) |
| Korsnäs | Finland | Carbonatite | Deposit |
| Kringlerne | Greenland | Alkaline igneous rock | Resource |
| Krušné hory | Czech Republic | Alkaline igneous rock | Occurrence |
| Kvanefjeld | Greenland | Alkaline igneous rock | Resource |
| Lamujärvi | Finland | Alkaline igneous rock | Occurrence |
| Loch Loyal | UK | Alkaline igneous rock | Occurrence |
| Mediterranean bauxites | Italy, Greece, Turkey | Bauxite | By-product (aluminium) |
| Milne Land | Greenland | Placer | Occurrence |
| Misværdal | Norway | Alkaline igneous rock | Deposit |
| Motzfeldt | Greenland | Alkaline igneous rock | Resource |
| Naantali | Finland | Carbonatite | Occurrence |
| Nea Peramos, Strymonikos Gulf | Greece | Placer | Occurrence |
| Nettuno | Italy | Placer | Occurrence |
| Norberg | Sweden | Hydrothermal | Deposit |
| Norra Kärr | Sweden | Alkaline igneous rock | Resource |
| North Qôroq | Greenland | Alkaline igneous rock | Deposit |
| Olserum | Sweden | Hydrothermal | Resource |
| Palaeozoic nodular monazites | UK, Belgium, France, Portugal | Diagenetic | Occurrence |
| Petäiskoski/Juuka | Finland | Carbonatite | Occurrence |
| Qaqarssuk | Greenland | Carbonatite | Deposit |
| Riddarhyttan-Bastnäs | Sweden | Hydrothermal | Deposit |
| Sæteråsen | Norway | Alkaline igneous rock | Occurrence |
| San Venanzo, Polino, Cupaello and Monte Vulture | Italy | Carbonatite | Occurrence |
| Sarfartoq | Greenland | Carbonatite | Resource |
| Siilinjärvi | Finland | Carbonatite | By-product (apatite) |
| Skjoldungen | Greenland | Alkaline igneous rock | Occurrence |
| Sofular | Turkey | Carbonatite | Deposit |
| Sokli | Finland | Carbonatite | Deposit |
| Svecofennian pegmatites | Sweden, Finland | Granite & pegmatite | Occurrence |
| Sveconorwegian pegmatites | Norway, Sweden | Granite & pegmatite | Occurrence |
| Tajno | Poland | Carbonatite | Occurrence |
| Tikiusaaq | Greenland | Carbonatite | Deposit |
| Třebíč | Czech Republic | Alkaline igneous rock | Occurrence |
| Tupertalik | Greenland | Carbonatite | Occurrence |
| Tysfjord | Norway | Alkaline igneous rock | Occurrence |
| Västervik | Sweden | Placer | Occurrence |

and weathering. Natural rare earth element deposits and occurrences may thus be divided into primary (high-temperature) and secondary (low-temperature) deposit types.

The most important primary deposits with high grade and tonnage are typically associated with alkaline–peralkaline igneous rocks and carbonatites formed in extensional intracontinental rifts (Chakhmouradian and Zaitsev, 2012; Wall, 2014). Primary REE concentrations can also be formed in a range of other geological settings, often associated with granites and pegmatites or with hydrothermal systems, and more rarely in metamorphic or diagenetic settings. Erosion or weathering of any of these primary enrichment types may produce secondary deposits such as placers and ion adsorption deposits (Wall, 2014). In a global context, the bulk of the world's REE are currently derived from carbonatites, notably Bayan Obo in China; these deposits are typically high-grade, but LREE-dominated (Chakhmouradian and Wall, 2012; Wall, 2014). REE deposits associated with alkaline igneous rocks are typically lower grade but with larger tonnage and a higher content of the most critical HREE (Wall, 2014).

Formation of REE deposits in alkaline to peralkaline igneous rocks and carbonatites is typically due to magmatic and/or hydrothermal processes (Wall and Mariano, 1996; Kogarko et al., 2002; Salvi and Williams-Jones, 2006; Schilling et al., 2011; Sheard et al., 2012; McCreath et al., 2012). Alkaline silicate and carbonatite magmatism are associated with small degrees of partial melting of enriched mantle,

**Table 2**
Table of all the main REE-bearing minerals and mineral groups found in the European deposits and occurrences described here. Note that many of these groups contain a range of individual mineral species (Wall, 2014), for example the monazite group includes monazite-(La), monazite-(Ce), monazite-(Nd), and monazite-(Sm). For simplicity, these variations are encompassed as REE (LREE/HREE) in the formulae given here. Mineral groups are marked with an asterisk.

| REE-bearing mineral or mineral group* | Formula | Typical deposit types | Examples from this study |
|---|---|---|---|
| Aeschynite* | $REE(Ti,Nb)_2(O,OH)_6$ | Hydrothermal deposits | Galiñeiro, Spain; Ditrău, Romania |
| Allanite* | $(REE,Ca)_2(Al,Fe)_3(SiO_4)\ (Si_2O_7)O(OH)$ | Miaskitic igneous rocks | Loch Loyal, Scotland; Misværdal, Norway; Třebíč, Czech Republic |
| Ancylite* | $LREE(Sr, Ca)(CO_3)_2(OH).H_2O$ | Carbonatite | Sokli, Finland; Qaqarssuk, Greenland |
| Apatite* | $Ca_5(PO_4)_3(F,Cl,OH)$ | Carbonatite; iron oxide–apatite deposits | Siilinjärvi, Finland; Kiruna, Sweden; Sokli, Finland; Kodal, Norway |
| Bastnäsite* | $REE(CO_3)F$ | Carbonatite; hydrothermal deposits | Bastnäs, Sweden; Fen, Norway; Sokli, Finland; |
| Britholite* | $(REE,Ca)_5(SiO_4)_3(OH,F)$ | Hydrothermal deposits | Norberg, Sweden; Korsnäs, Finland |
| Brockite | $(Ca,Th,Ce)(PO_4).H_2O$ | Hydrothermal deposits | Kizilcaören, Turkey |
| Burbankite | $(Na,Ca)_3(Sr,Ba,LREE)_3(CO_3)_5$ | Carbonatite | Qaqarssuk, Greenland |
| Cerite* | $(LREE,Ca)_9(Mg,Ca,Fe^{3+})\ (SiO_4)_3(SiO_3OH)_4(OH)_3$ | Hydrothermal deposits | Bastnäs, Sweden |
| Dollaseite* | $CaLREE(Mg_2Al)[Si_2O_7][SiO_4]F(OH)$ | Hydrothermal deposits | Norberg, Sweden |
| Eudialyte* | $Na_{15}Ca_6Fe_3Zr_3Si(Si_{25}O_{73})(O,OH,H_2O)_3(Cl,OH)_2$ | Agpaitic igneous rocks | Norra Kärr, Sweden; Kringlerne, Greenland |
| Euxenite* | $(REE,Ca,Th,U)(Nb,Ta,Ti)_2O_6$ | Miaskitic igneous rocks | Třebíč, Czech Republic |
| Fergusonite* | $REENbO_4$ | Miaskitic igneous rocks | Ditrău, Romania |
| Fluocerite* | $REEF_3$ | Hydrothermal deposits | Kizilcaören, Turkey |
| Gadolinite* | $REE_2Fe^{2+}Be_2O_2(SiO_4)_2$ | Hydrothermal deposits; Miaskitic igneous rocks | Norberg, Sweden; Mourne Mts, N Ireland |
| Monazite* | $REE(PO_4)$ | Carbonatite; Placers; Hydrothermal deposits; Miaskitic igneous rocks | Olserum, Sweden; Fen, Norway; Central Wales; Ditrău, Romania |
| Parisite | $CaLREE_2(CO_3)_3F_2$ | Carbonatite | Fen, Norway |
| Perrierite* | $REE_4(Mg, Fe,Ti)_4O_8(Si_2O_7)_2$ | Placers | Nettuno, Italy |
| Pyrochlore* | $(Na,Ca)_2Nb_2O_6(OH,F)$ | Carbonatite | Sokli, Finland; Motzfeldt, Greenland; Delitzsch, Germany |
| Steenstrupine | $Na_{14}REE_6Mn_2Fe^{3+}{}_2Zr\ (PO_4)_7Si_{12}O_{36}(OH)_2 \cdot 3H_2O$ | Agpaitic igneous rocks | Kvanefjeld, Greenland |
| Strontianite | $Sr(CO)_3$ | Carbonatite | Siilinjärvi, Finland; Sokli, Finland |
| Synchysite* | $CaREE(CO_3)_2F$ | Carbonatite; Hydrothermal deposits | Sarfartoq, Greenland |
| Törnebohmite* | $REE_2Al(SiO_4)_2(OH)$ | Hydrothermal deposits | Bastnäs, Sweden |
| Västmanlandite | $Ce_3CaMg_2Al_2Si_5O_{19}(OH)_2F$ | Hydrothermal deposits | Norberg, Sweden |
| Xenotime* | $(Y,HREE)PO_4$ | Hydrothermal deposits; Miaskitic igneous rocks; Placers | Olserum, Sweden; Galiñeiro, Spain; Ditrău, Romania |
| Zircon | $ZrSiO_4$ | Miaskitic igneous rocks | Katajakangas, Finland |

potentially derived either from metasomatised lithospheric mantle or from mantle plumes (Fig. 1), or from interaction between the two (Downes et al., 2005; Wilson and Downes, 2006; Ernst and Bell, 2010). Further evolution of these small-degree partial melts in a near-closed system is typically needed to produce highly evolved igneous rocks enriched in REE minerals. Notably, many important REE deposits are associated with extremely peralkaline igneous rocks containing complex Na–K–Ca–(Fe, Zr, Ti) silicates such as eudialyte-group minerals

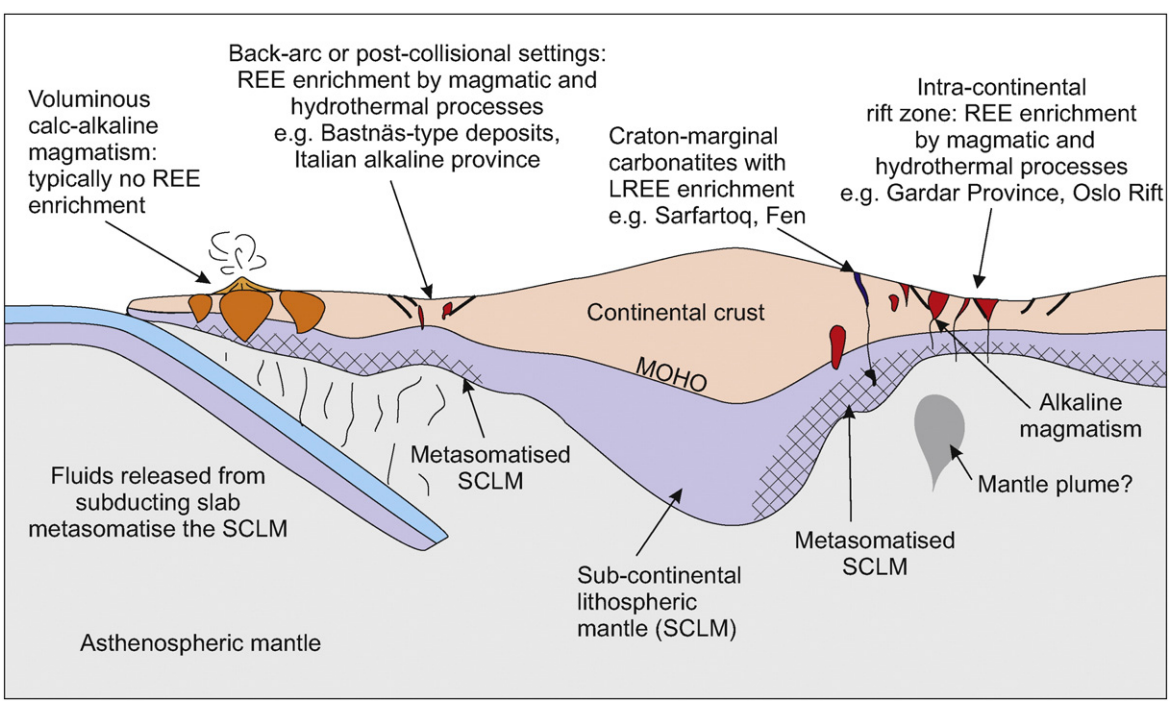


**Fig. 1.** Schematic diagram to illustrate the main environments of formation of alkaline igneous rocks and carbonatites, major hosts of many REE deposits.

and aenigmatite that are commonly also enriched in the REE; such rocks are termed 'agpaitic' (Sørensen, 1997; Marks et al., 2011). In contrast, in most other felsic igneous rocks the REE are hosted in accessory minerals such as zircon, allanite, apatite, and monazite, and these rocks are termed 'miaskitic'. Key REE minerals within carbonatites include bastnäsite, parisite, synchysite, monazite, pyrochlore and many others (Wall and Mariano, 1996). Major REE-bearing minerals found in European deposits are listed in Table 2.

The main REE metallogenetic provinces in Europe (Fig. 2) are those areas where extensional tectonics and introduction of enriched mantle melts have produced alkaline silicate and carbonatite magmatism. Major REE deposits are currently known where the plutonic complexes at depth in continental rift zones have been exposed by erosion (Goodenough et al., 2014). The most notable of these are the Mesoproterozoic Gardar Province of south-west Greenland (Upton et al., 2003), and the Protogine Zone, a major, multiply reactivated, in part extensional structure in southern Sweden (Åberg, 1988; Andréasson and Rodhe, 1990). Both of these zones currently host advanced REE exploration projects. Several intracontinental rift-related provinces of Palaeozoic age occur in Europe, including the Devonian Kola Alkaline Province, which extends from Russia into Finland, and the Permo-Carboniferous Oslo Rift in Norway. The Kola Alkaline Province contains some large peralkaline igneous complexes (Downes et al., 2005) that represent major Russian REE resources, but these lie outside the geographical scope of this paper.

Some episodes of European rifting have progressed to continental break-up and development of a new ocean, notably the formation of the Iapetus Ocean during the Neoproterozoic (Svenningsen, 2001), and the opening of the North Atlantic from the Jurassic into the Cenozoic (Saunders et al., 2013). Such rift phases are typically associated with large volumes of magmatism, but central complexes with alkaline compositions are rare, although isolated carbonatite bodies and dyke swarms are known.

Localised rifting and alkaline magmatism have developed periodically across much of central and southern Europe from the Triassic into the Cenozoic, both to the north of the Alpine collision zone and around the margins of the Mediterranean (Wilson and Downes, 2006). In these areas, alkaline volcanic rocks are typically exposed at the surface; the central complexes that might contain significant primary REE resources are still likely to be hundreds of metres to kilometres below the surface. In general, the major known potential for REE resources around the Mediterranean is dominated by secondary deposits such as bauxites.

Potential REE deposits can also be associated with magmatic and hydrothermal activity in other tectonic settings away from intracontinental rift zones. The most notable of these occur in the Palaeoproterozoic Bergslagen province in Sweden, including the Bastnäs deposits where the LREEs were first discovered. These deposits are considered to have formed through reaction of carbonates with fluids derived from subduction-related magmas (Holtstam et al., 2014; Jonsson et al., 2014). There are a number of other areas in Europe where alkaline magmatism has developed towards the end of an orogenic cycle, such as in the Caledonides, and these areas may also contain localised REE enrichments (Walters et al., 2013).

No significant secondary REE deposits with high tonnage and high grade are currently known in Europe, but at a number of localities

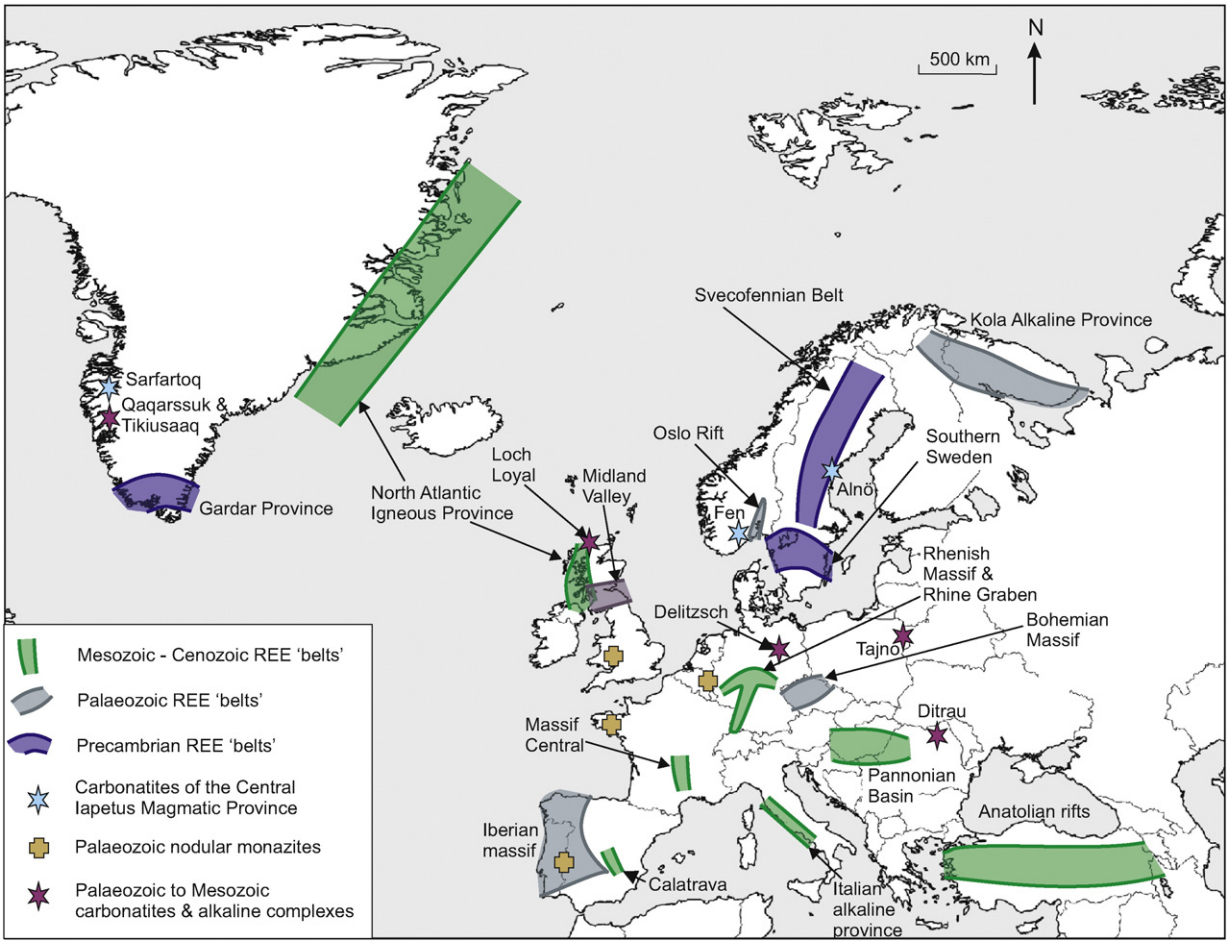


**Fig. 2.** Overview map of Europe showing the approximate extent of the key REE metallogenetic belts described in this paper. Notable REE deposits and occurrences that do not fall within a distinct belt and are not shown on other maps are indicated by symbols.

erosion and weathering processes have formed low-grade REE concentrations that have economic potential because of their relative ease of processing. These include heavy mineral placers, particularly along the Mediterranean coastlines, and bauxites in many parts of southern Europe. In China, and other parts of the world that have experienced tropical weathering, the REE are known to be enriched in weathered ion adsorption clay deposits (Kynicky et al., 2012). However, studies of weathered granitic rocks in Europe have shown no evidence of REE upgrading during the weathering process (Höhn et al., 2014).

## 3. REE metallogenetic belts in Europe

The EURARE project has identified almost 100 distinct localities of interest for the REE across Europe. These are summarised in Table 1 and described in more detail below. Some of these are recognised mineral deposits that have been actively explored; the most well known have estimates of the contained REE resources. Other localities, described here as occurrences, are noteworthy due to either high REE contents or the presence of abundant REE minerals. These occurrences may be potential REE deposits, but further research and exploration are needed. It is likely that there are many more REE occurrences across Europe than are described here, but there is very little information available. Here we group these deposits and occurrences into key metallogenetic provinces for the REE within Europe on the basis of age, tectonic setting, and genetic type (Fig. 2), and summarise their geodynamic context. Brief mention is also made of groups of deposits such as bauxites, where the REEs are only slightly enriched but there is potential for them to be produced as a by-product of another commodity.

### 3.1. Archaean to early Palaeoproterozoic alkaline rocks and carbonatites

No significant REE deposits of Archaean to early Palaeoproterozoic age are known in Europe, and indeed there are few alkaline igneous rocks of this age. Rare examples of alkaline magmatism include the c. 3000 Ma Tupertalik carbonatite in west Greenland (Fig. 3) (Bizzarro et al., 2002); the c. 2700 Ma Skjoldungen Alkaline Igneous Province of SE Greenland (Fig. 3), which includes nepheline syenites and carbonatites (Nutman and Rosing, 1994; Blichert-Toft et al., 1995); the c. 2600 Ma Siilinjärvi carbonatite in Finland (Fig. 4) (Tichomirowa et al., 2006; Rukhlov and Bell, 2010); and the c. 2050 Ma Katajakangas alkaline gneiss in Finland (Fig. 4) (Sarapää et al., 2013). Apatite is currently mined at Siilinjärvi as a phosphate resource. The main rock types at Siilinjärvi are enriched in REE (Hornig-Kjarsgaard, 1998), and

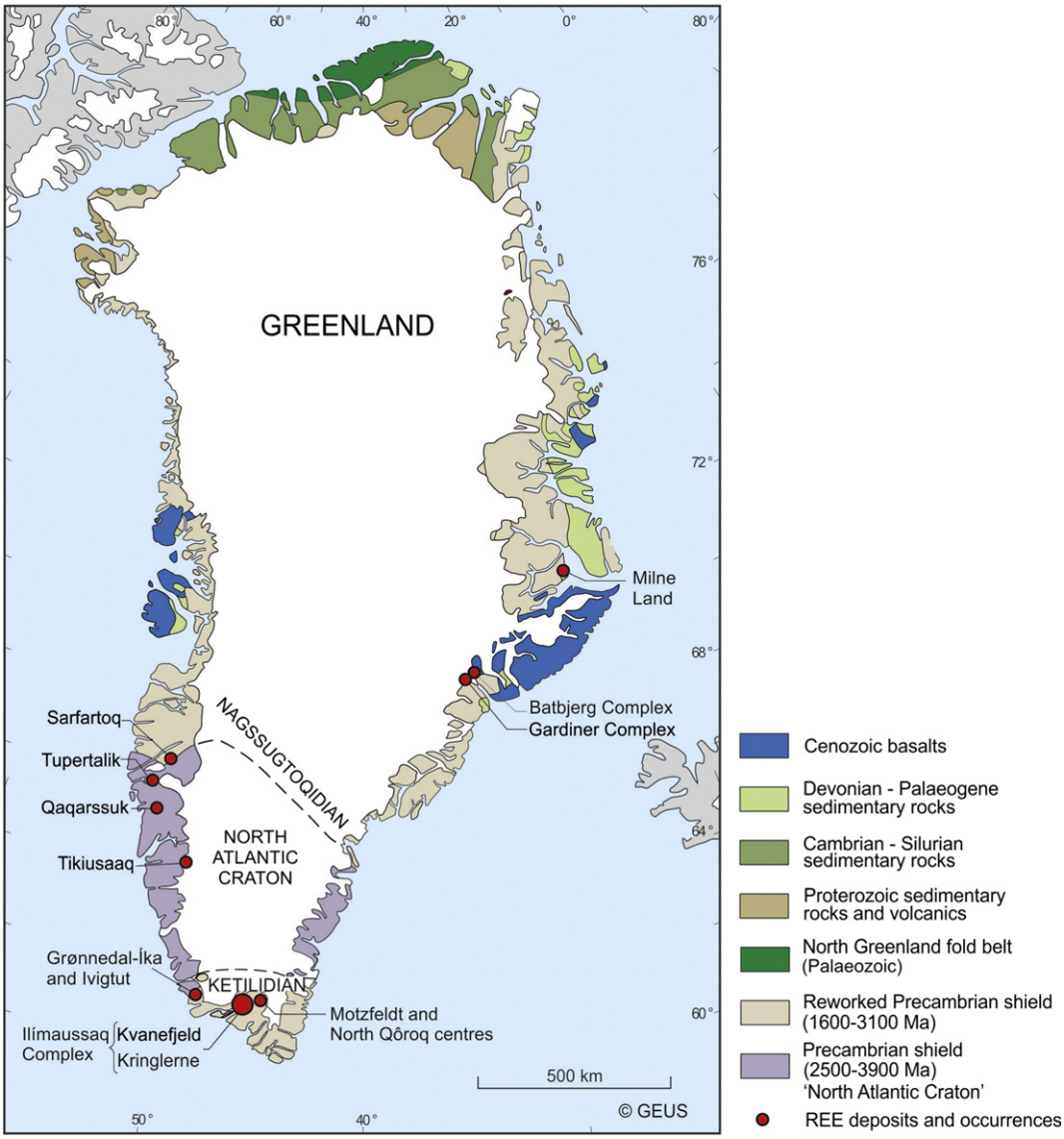


**Fig. 3.** Simplified geological map of Greenland showing the main REE deposits and occurrences. Base geological map from GEUS.

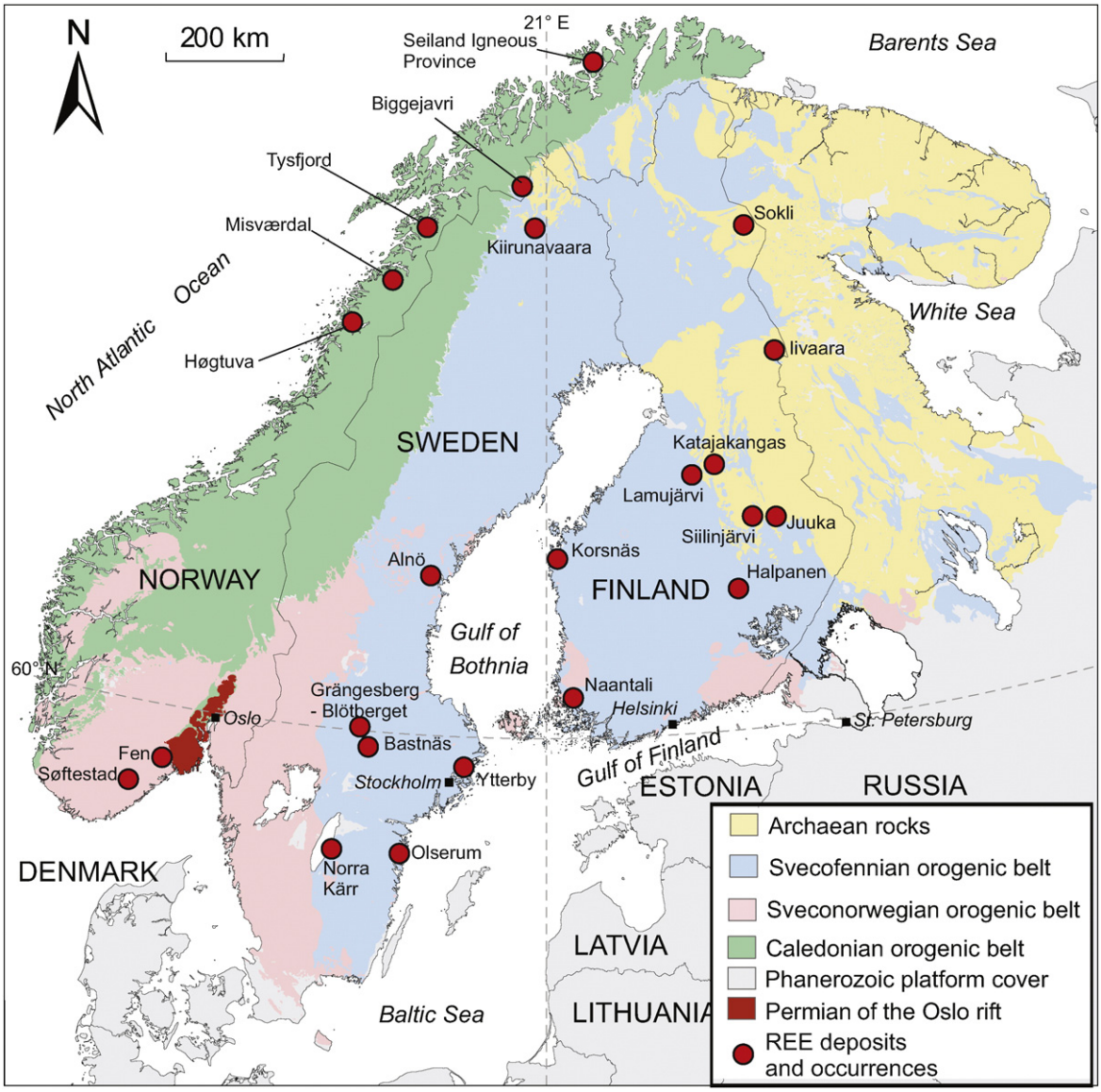


**Fig. 4.** Simplified geological map of the Scandinavian countries showing the main REE deposits and occurrences. Base geological map after Eilu (2012).

REE-hosting minerals in the carbonatite and associated "glimmerite" include monazite-(Ce), pyrochlore-group minerals, LREE-bearing strontianite and REE-bearing Ti–Nb-phases (Al-Ani, 2013). The Katajakangas gneisses contain mineralised layers rich in zircon, bastnäsite, columbite, and thorite, and an informal resource estimate suggests 0.46 million tonnes (Mt) grading 2.4% total rare earth oxides (TREO) (Sarapää et al., 2013).

### 3.2. Palaeoproterozoic: the Svecofennian belt

Magmatic and hydrothermal REE deposits are associated with many parts of the Svecofennian orogenic belt, which represents the earliest of Europe's distinct REE metallogenetic provinces. This belt formed during accretion and continental collision leading to amalgamation of the supercontinent Columbia (Nuna) in the Palaeoproterozoic (2000–1700 Ma) (Korja et al., 2006; Roberts, 2013). During this period, subduction around the margins of the growing supercontinent drove extensive igneous activity and also the generation of significant base and precious metal deposits. The tectonomagmatic belts generated in Europe at this time include the Svecofennian and Kola-Karelian of Fennoscandia, the Laxfordian in the Lewisian Gneiss Complex of the UK, and the Ketilidian and Nagssugtoqidian belts in Greenland (Zhao et al., 2002; Lahtinen et al., 2008), but important REE deposits and occurrences are only known from the Svecofennian (Fig. 2). In this belt, calc-alkaline magmatism was followed by widespread late-orogenic alkaline magmatism in the waning stages of the Svecofennian orogen (also termed the Svecokarelian orogen). The early stages of magmatism were associated with the development of significant hydrothermal activity.

Historically, the most important REE occurrences in Sweden were the Bastnäs-type deposits (Geijer, 1961) and the Ytterby pegmatite in the Bergslagen region (Fig. 4), which provided the samples from which many of the REE were originally isolated (Weeks, 1932; Williams-Jones et al., 2012). The Bastnäs-type deposits occur along a narrow zone that stretches for about 100 km NE–SW (the 'REE-line', Fig. 5; Jonsson et al. (2014)), and were likely the first hard-rock deposits in the world to be mined explicitly for REE extraction. They are situated within hydrothermally altered Palaeoproterozoic (1910–1880 Ma) felsic metavolcanics and metasedimentary rocks that formed in a continental back-arc setting (Allen et al., 1996; Holtstam et al., 2014). These REE deposits can be subdivided into two types: one enriched in LREE minerals, in the Riddarhyttan-Bastnäs area, and the other also showing enrichment in HREE + Y minerals, in the Norberg district (Holtstam and Andersson, 2007). Both types are iron-rich, skarn-type REE deposits

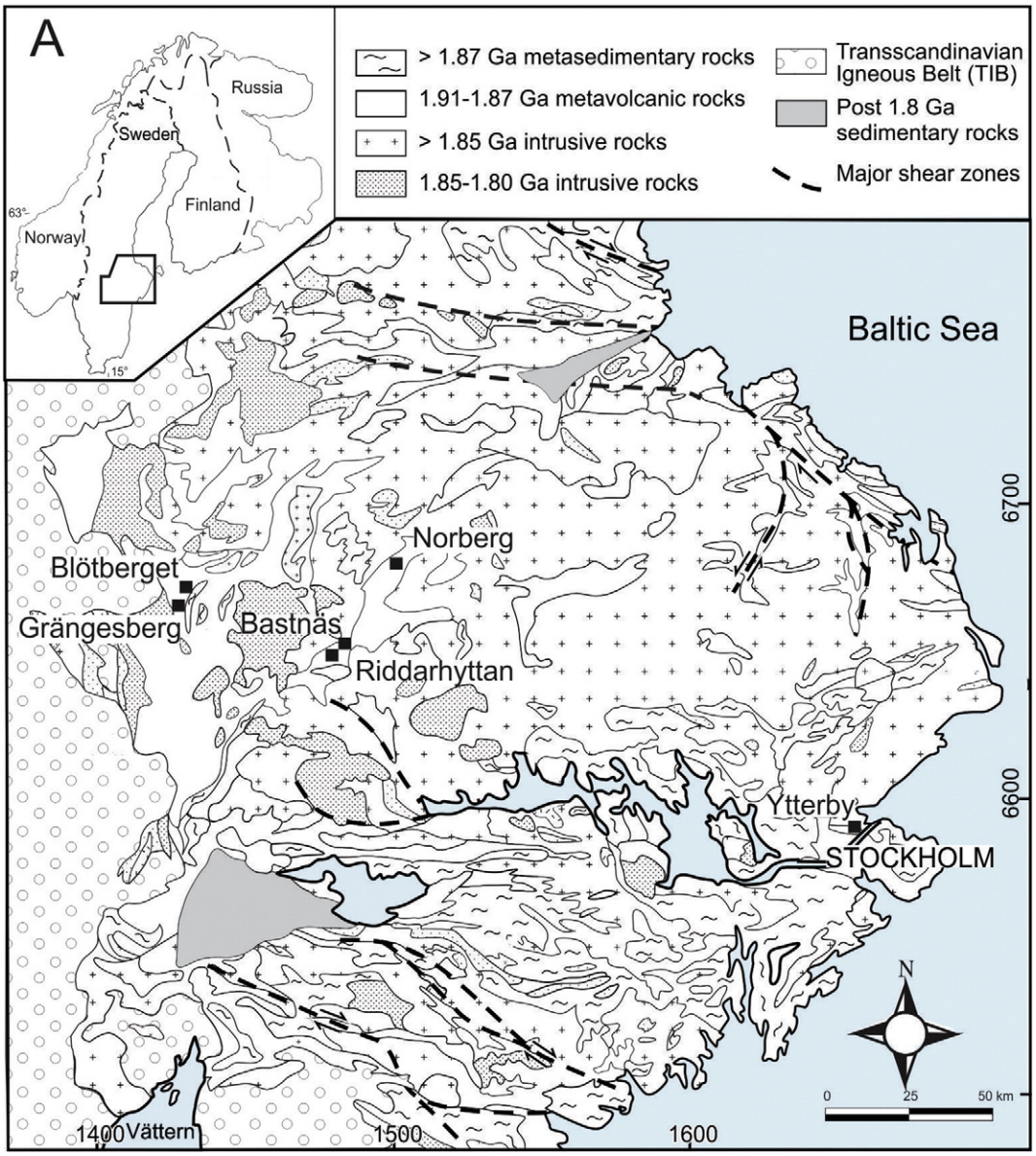


**Fig. 5.** Simplified geological map of Bergslagen, Sweden, showing the location of the main areas of REE deposits and occurrences. Modified after Jonsson et al. (2014).

associated with metasomatised marble horizons, and formed during hydrothermal activity associated with felsic magmatism (Holtstam et al., 2014). Historical mining in the area has typically focused on iron ore, with minor production of REE. The LREE subtype was mined at Bastnäs, where the key ore minerals included cerite-(Ce), ferriallanite-(Ce), törnebohmite-(Ce) and bastnäsite-(Ce), occurring in an amphibole-rich skarn associated with magnetite, haematite, and sulphides (Holtstam et al., 2014; Jonsson et al., 2014). The HREE-enriched subtype in the Norberg district is more highly enriched in Mg and F, and the REE minerals include fluorbritholite-(Ce), västmanlandite-(Ce), dollaseite-(Ce), gadolinite-(Ce) and gadolinite-(Y) (Holtstam et al., 2014; Jonsson et al., 2014).

Iron oxide-apatite deposits of Kiruna type in the Svecofennian belt are also enriched in the REE (Frietsch and Perdahl, 1995; Smith et al., 2009; Jonsson et al., 2013). These include Kiirunavaara (Kiruna) and Malmberget in the Norrbotten region of northern Sweden, and the Grängesberg–Blötberget deposits in Bergslagen, South Central Sweden (Fig. 4). The origin of these deposits, whether orthomagmatic or hydrothermal, continues to be debated. Recent work suggests that the Kiruna ores formed during the period 1920–1860 Ma, through hydrothermal alteration of volcanic rocks by high salinity fluids, with subsequent reworking of the mineralisation until around 1750 Ma (Smith et al., 2009). An orthomagmatic origin has also been suggested for these deposits (Jonsson et al., 2013), and in the case of the Grängesberg deposit, ore formation is considered to have taken place prior to 1895 Ma (Högdahl et al., 2013). The deposits are associated with either sodic alteration (albitisation) or potassic alteration. Although largely known as iron ore deposits, the magnetite-dominated ores host high concentrations of REE in fluorapatite, monazite-(Ce), allanite-(Ce), xenotime-(Y), and minor REE fluorcarbonates (Harlov et al., 2002; Jonsson et al., 2013; Majka et al., 2013). Albitised, REE-enriched felsic volcanic rocks of Palaeoproterozoic age at Biggejavri in northern Norway (Fig. 4) are likely to have been affected by hydrothermal alteration leading to albitisation at a similar time.

At the southern end of the Svecofennian orogen, Palaeoproterozoic metasedimentary rocks of the Västervik formation contain heavy-mineral layers, which may represent original placer deposits that have been variably affected by regional metamorphism, metasomatism, and REE remobilisation (Reed, 2013). Potentially related to these palaeoplacer deposits are the REE-enriched biotite–magnetite–apatite

veins of the Olserum area (Fig. 4), which occur within Västervik formation metasedimentary rocks cut by granitoids belonging to the Transscandinavian Igneous Belt (Högdahl et al., 2004). In these veins, REEs are mainly hosted in fluorapatite, monazite-(Ce), xenotime-(Y), and ferriallanite–allanite (Ce). The Olserum deposit has an NI-43–101 compliant indicated resource of 4.5 Mt. at 0.6% TREO, and an inferred resource of 3.3 Mt. at 0.63% TREO (using a TREO cut-off of 0.4%) (Reed, 2013).

The end-Svecofennian alkaline magmatism, around 1800 Ma, included both alkaline silicate intrusions and carbonatites. In Finland, the Korsnäs swarm of carbonatite dykes (Fig. 4) is dated at c. 1830 Ma, and cuts c. 1900 Ma gneisses (Sarapää et al., 2013). The largest of these dykes was mined for Pb and REE in the 1960s, with the REE chiefly hosted in apatite, monazite, allanite, ancylite, britholite, and bastnäsite, and grades averaging 0.91% total REE oxides (Al-Ani et al., 2010; Sarapää et al., 2013). Other carbonatite dykes of similar age are known in Finland (Fig. 4), including the Halpanen calcite carbonatite dyke emplaced at c. 1792 Ma (Rukhlov and Bell, 2010), the Naantali carbonatite at c. 1796 Ma (Woodard and Hetherington, 2014), and the Petäiskoski/Juuka carbonatite dykes (Tyni et al., 2003). All these carbonatites are LREE-enriched, have similar mineralogy, and are typically associated with marginal zones of sodic–potassic alteration (fenitisation) (Woodard and Hetherington, 2014).

Late-orogenic alkaline to calc-alkaline intrusions also formed within the Svecofennian belt, including numerous small shoshonitic (highly potassic) intrusions in southern Finland that show LREE-enrichment, with allanite as the main REE mineral (Andersson et al., 2006). In Central Finland, the c. 1850 Ma Lamujärvi syenites (Fig. 4) are also enriched in LREE, chiefly hosted in allanite and monazite (Sarapää et al., 2013). Granites and granitic pegmatites with ages around 1800 Ma are widely distributed in the Svecofennian Belt in Sweden and Norway, including the Ytterby pegmatite field in eastern Sweden (Fig. 4). Larger-volume magmatism is represented by the granitoid intrusions of the Transscandinavian Igneous Belt (TIB) which were emplaced in two major phases c. 1810–1770 and 1720–1660 Ma and which are now largely preserved within the nappes of the Caledonian orogenic belt and in southern Sweden (Romer et al., 1992; Åhäll and Larson, 2000). An exploration campaign in the Tysfjord granitic complex (Fig. 4) identified locally elevated REE concentrations in soil (up to c. 1500 ppm total rare earths, Sc and Y excluded; Finne and Eggen (2013)). The c. 1800 Ma Høgtuva igneous complex in Norway (Fig. 4) constitutes not only a major European Be deposit, but is also regarded as a REE-occurrence, with a mineralized zone rich in zircon and allanite that has a grade of 0.15% TREO (Wilberg, 1987). Primary enrichment of the high field strength elements (HFSE, including Zr and the REE) occurred during emplacement, but HFSE mobilisation and recrystallisation took place during the Caledonian orogeny. Although most other TIB intrusions are not thought to contain significant REE mineralization (Müller, 2010), more regional-scale data are required to determine the overall REE potential of the most evolved granitoids.

### 3.3. Mesoproterozoic rift systems

Collisional and accretionary tectonics continued to dominate within Fennoscandia and around the margins of the North Atlantic Craton until around 1500 Ma, when localised zones of extension and rifting began to develop in some areas (Bogdanova et al., 2008). Extensional tectonics became dominant after 1400 Ma, and eventually led to the break-up of the supercontinent of Columbia around 1200 Ma (Zhao et al., 2004). These extensional rifts represent significant belts of REE mineralisation in northern Europe.

In Sweden, a major roughly north–south zone of weakness known as the Protogine Zone developed in the Mesoproterozoic and was reactivated numerous times, with repeated magmatic episodes (Andréasson and Rodhe, 1990; Söderlund and Ask, 2006). To either side of this zone, voluminous rapakivi granite magmatism gave way to a phase of bimodal mafic–felsic, syn-tectonic, intracratonic magmatism at c. 1470–1440 Ma (Brander and Söderlund, 2009). Geochemically, the felsic part of this magmatic suite has features of A-type granites, such as moderate enrichment in the REE (Cecys and Benn, 2007). This A-type suite includes some small bodies of peralkaline syenite with elevated REE contents, most notably the Norra Kärr Alkaline Complex in southern Sweden (Fig. 4), emplaced at 1489 ± 8 Ma (Sjöqvist et al., 2013). Norra Kärr is a body of deformed, agpaitic, peralkaline nepheline syenite, about 1300 × 400 m in size, which is rich in eudialyte-group minerals and other REE-bearing minerals such as catapleiite (Sjöqvist et al., 2013). It has an NI-43–101 compliant indicated resource of 41.6 million tonnes (Mt) at 0.57% TREO, and an inferred resource of 16.5 Mt. at 0.64% TREO (using a TREO cut-off of 0.17%) (Gates et al., 2013). Probable mineral reserves are estimated at 23.5 Mt. at 0.59% TREO (Short et al., 2015). The Almunge nepheline syenite in Sweden has been considered to be of similar age (Doig, 1970), but recent dating suggests that it is Palaeoproterozoic in age and unrelated to the magmatism at Norra Kärr (Delin and Bastani, 2009); its REE potential has not been studied.

The Gardar Province of South Greenland (Fig. 2) is a Mesoproterozoic rift zone that developed along the southern margin of the Archaean North Atlantic Craton during two separate periods of activity, c. 1280–1250 Ma and 1180–1140 Ma (Upton and Emeleus, 1987; Upton et al., 2003; Upton, 2013). Both Gardar rifting events include volcanic rocks, large volumes of mafic dykes, major plutons of silica-saturated and silica-undersaturated syenite and peralkaline granite, and minor carbonatite bodies. Alkaline magmatism of similar age extends into Canada (e.g. Strange Lake, Miller et al. (1997)) and possibly into Sweden (e.g. the Kalix-Storö dykes, Kresten et al. (1981)), thus indicating a wide network of rift zones and alkaline magmatism associated with the break-up of Columbia. To date, the Gardar Province is considered to represent the most important area of REE resources in Europe.

The most well-known REE deposits in the Gardar Province lie within the Ilímaussaq Complex (Figs. 3, 6), a major layered granitic–syenitic intrusive complex (18 km × 8 km) with a significant component of peralkaline, agpaitic nepheline syenite (Larsen and Sørensen, 1987; Markl et al., 2001). The complex has been dated at 1160 ± 5 Ma (Krumrei et al., 2006), and is thus one of the younger intrusions within the Gardar Province. It has been affected by later faulting with downthrow to the north, such that both the roof and the lower parts of the magma chamber can be studied. The complex was formed by successive intrusions of increasingly differentiated alkaline melts; early augite syenites form the margins of the complex, and are locally intruded by sheets of quartz syenite and alkali granite. These were subsequently intruded by one or more pulses of agpaitic magma, forming the layered nepheline syenites in the main core of the complex (Markl et al., 2001; Sørensen, 2006; Pfaff et al., 2008). The extreme and unusual compositions of the agpaitic magma at Ilímaussaq produced a number of rare minerals, many of which are enriched in REE (Sørensen, 1992). Exploration interest has focused on the agpaitic nepheline syenites, notably the lower c. 300 m of spectacular layered kakortokites (eudialyte-arfvedsonite-nepheline syenites), and the overlying c. 500 m of lujavrite (melanocratic, eudialyte- or steenstrupine-bearing nepheline syenite).

Ilímaussaq hosts two separate REE exploration projects, Kringlerne and Kvanefjeld (Thrane et al., 2014). The Kringlerne deposit comprises the layered kakortokites in the southern part of the Ilímaussaq Complex (Fig. 6), with eudialyte-group minerals and their alteration products (notably catapleiite and nacareniobsite-(Ce)) (Borst et al., 2015) as the main economic minerals. Although formal resource information has not been published, estimates suggest the possibility of inferred resources of at least 4300 Mt. grading 0.65% TREO, 0.2% $Nb_2O_5$ and 1.8% $Zr_2O_5$ (Thrane et al., 2014).

The Kvanefjeld deposit lies in the northern part of the Ilímaussaq Complex (Fig. 6). The main ore rocks are fine-grained lujavrites that are considered to have formed from highly fractionated, volatile-rich agpaitic magmas emplaced in fracture systems beneath the solid roof

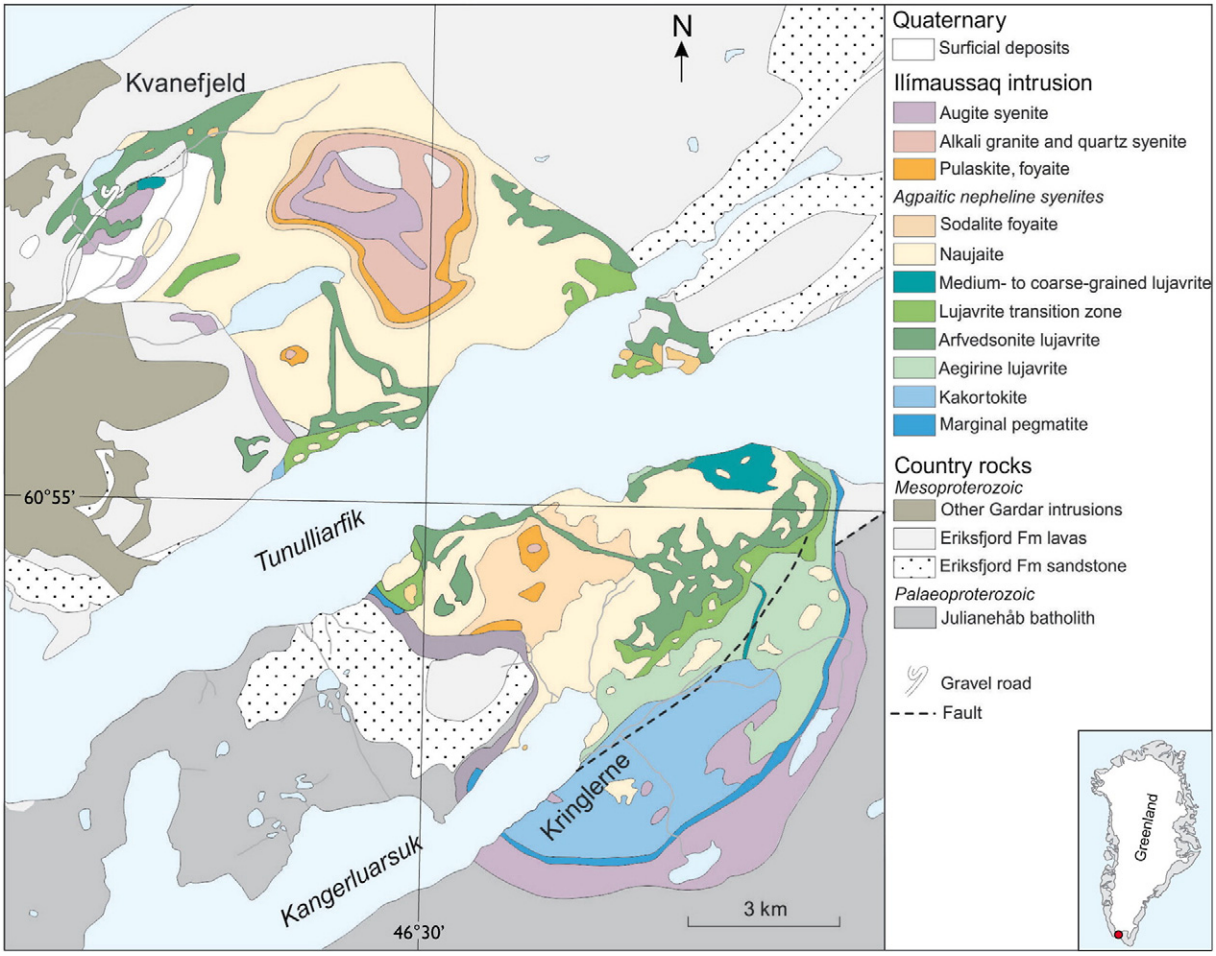


**Fig. 6.** Geological map of the Ilímaussaq syenite complex showing the location of the main REE deposits after Upton (2013).

of the magma chamber (Sørensen et al., 2011). Steenstrupine is the main REE ore mineral in this lithology. A JORC-compliant resource estimate for Kvanefjeld suggests indicated REE resources of 437 Mt. grading 1.1% TREO (Thrane et al., 2014). This was followed in 2015 by a maiden ore reserve estimate of 108 Mt. grading 1.4% TREO (GME, 2015). The deposit also contains economic concentrations of uranium, mainly in steenstrupine, and zinc in sphalerite.

The Gardar Province contains several other syenite complexes that have the potential for REE resources (Fig. 3); the most important of these is the Igaliko Complex, which contains four separate intrusive centres. One of these, the Motzfeldt centre, has been known for some time to host Th–U–Nb–Ta–Zr–REE mineralisation (Tukiainen, 1988). The Motzfeldt centre (1273 ± 6 Ma (McCreath et al., 2012)) is made up of multiple intrusions of nepheline syenite, the majority of which are miaskitic. However, the mineralisation is associated with the latest intrusive phase, comprising agpaitic peralkaline sheets that cut hydrothermally altered nepheline syenites, largely around the margins of the centre. Metasomatic alteration in older syenites was related to these latest, highly-fractionated agpaitic magmas (McCreath et al., 2012). The potential resources of REE and HFSE are thus hosted both in the altered syenites and in the peralkaline sheets themselves. Ore minerals include pyrochlore, columbite, bastnäsite, monazite, eudialyte-group minerals, and zircon. Current estimates suggest an exploration potential in one area of altered syenites (the Aries Prospect) of 200–500 Mt. grading 0.3–0.5% TREO, 0.18–0.22% $Nb_2O_5$, and 0.013–0.016% $Ta_2O_5$ (Tukiainen, 2014). Further resources are likely to exist in other outcrop areas of peralkaline sheets within the complex, particularly in North and South-east Motzfeldt (Tukiainen, 2014).

The North Qôroq Centre of the Igaliko Complex has many similarities to the Motzfeldt Centre, being made up of several nepheline syenite intrusions of which the latest are agpaitic and contain significant proportions of eudialyte-group minerals (Coulson and Chambers, 1996; Coulson, 2003). As at Motzfeldt, metasomatic alteration of older syenites is extensive, with evidence of REE mobilisation and formation of REE-fluorcarbonate minerals such as synchysite, parisite, and bastnäsite (Coulson and Chambers, 1996). There is thus potential for recognition of REE resources in North Qôroq. Agpaitic compositions have not been recognised in the other centres of the Igaliko Complex, or indeed elsewhere in the Gardar Province.

Peralkaline granites are minor constituents of the Gardar Province, the most famous being the Ivigtut granite, which was host to the world's most important cryolite deposit (now largely mined out). This granite stock was strongly affected by metasomatic alteration and REE remobilisation during formation of the cryolite deposit (Goodenough et al., 2000; Köhler et al., 2008) but there has been no detailed study of REE minerals and areas of REE enrichment. Carbonatites are also known within the Gardar Province, particularly at Grønnedal-Ika (Pearce et al., 1997) and Qassiarsuk (Andersen, 1997). These carbonatites typically show enrichment in the LREE (Coulson et al., 2003) but have not been explored in detail.

### *3.4. Neoproterozoic orogenic belts and rift systems in northern Europe*

From around 1100 Ma, accretionary and collisional tectonics again began to dominate in Europe as the supercontinent of Rodinia was assembled, forming the Grenville and Sveconorwegian orogenic belts (Li et al., 2008). The Sveconorwegian lacks the hydrothermal REE

deposits of the Svecofennian. However, local enrichment of REE occurs in numerous pegmatites of the Sveconorwegian orogenic belt (Fig. 4) (900 to 1100 Ma) extending from SW Sweden to SW Norway, and including the Evje-Iveland, Froland, and Glamsland pegmatite fields (Romer and Smeds, 1996; Müller et al., 2008). The most common REE minerals in these pegmatites are allanite, monazite, aeschynite, fergusonite, and gadolinite. Generally, these deposits are either too small or too low in grade to be commercially exploited solely for REE, but REE could potentially be by-products of feldspar and/or quartz mines, such as the Glamsland mine which closed in 2009. Vein-type apatite deposits were also formed in the Sveconorwegian of Norway, the largest at Søftestad (Fig. 4) (Ihlen et al., 2014), and may have some similarities to the REE-enriched Kiruna-type deposits.

After c. 850 Ma, Rodinia began to break up, with the development of continental rifts and eventual formation of the Iapetus Ocean. Some important European REE resources were formed towards the end of the Neoproterozoic, with emplacement of carbonatites and lamprophyres distributed around the North Atlantic Craton and Fennoscandian Shield, together with some more extensive areas of alkaline magmatism. These are part of the Central Iapetus Magmatic Province (Ernst and Bell, 2010) which developed on the Laurentian and Baltican margins of the newly-forming Iapetus Ocean. Siting of these individual intrusive bodies is likely to have been controlled by crustal-scale structures that provided magma pathways, but it is unclear whether the magma sources can be attributed to a plume or to extension in a number of separate rifts.

In West Greenland, the Sarfartoq carbonatite (Fig. 3), together with associated kimberlitic and lamprophyric minor intrusions, were emplaced into Archaean rocks at the margin of the North Atlantic Craton at c. 565 Ma (Hutchison and Heaman, 2008; Secher et al., 2009). The carbonatite is made up of a c. 10 $km^2$ core series of concentric dolomite carbonatite sheets, surrounded by a marginal zone with carbonatite dykes cutting highly altered (fenitised) Archaean gneisses. The REE are concentrated in shear zones and pyrochlore-rich veins within the marginal zone (Secher and Larsen, 1980). The main REE minerals are synchysite-(Ce), synchysite-(Nd), bastnäsite-(Ce), and monazite-(Ce) (Tuer, 2011). The Sarfartoq intrusion has a NI 43-101-compliant resource estimate including indicated resources of 5.9 Mt. grading 1.8% TREO, and inferred resources of 2.5 Mt. grading 1.6% TREO (using a TREO cut-off of 1%) (Tuer, 2012).

In Norway, the Fen carbonatite (Fig. 4) was emplaced into Mesoproterozoic orthogneisses at c. 580 Ma (Meert et al., 1998). It forms a subcircular body of c. 9 $km^2$ at the surface, and includes a variety of carbonatite types: pyroxene- and amphibole-bearing sövite (calcite carbonatite), dolomite carbonatite, ankerite ferrocarbonatite, and haematite carbonatite, as well as minor intrusions of nepheline syenite (Andersen, 1988). The gneisses around the complex have been intensely altered by alkaline metasomatic fluids, giving rise to the term 'fenitisation'. Highest REE contents are found in the ferrocarbonatite and haematite carbonatite, which are LREE-enriched; the main REE-bearing minerals are monazite, bastnäsite, parisite, and apatite (Andersen, 1986). The carbonatites have previously been mined for iron ore and subsequently for Nb at the Søve mine, and have more recently been considered for their resources of REE, Th and apatite (Ihlen et al., 2014). In the south and east of the complex, an inferred resource of 84 Mt. grading 1.08% TREO (0.8% TREO cut-off) has been outlined (Lie and Østergaard, 2014), but the resources in the complex as a whole are likely to be greater.

In Sweden, the Alnö carbonatite complex (Fig. 4) was emplaced contemporaneously with the Fen carbonatite, at c. 585 Ma (Meert et al., 2007; Rukhlov and Bell, 2010). It comprises a number of intrusive centres, including the main carbonatite–syenite–ijolite–pyroxenite centre on Alnö Island, a smaller centre on the mainland at Söråker, and a swarm of carbonatite dykes (Morogan and Woolley, 1988). Fenitisation is extensive around most of the intrusions, and the REEs were mobilised by these metasomatic fluids; the fenites have total REE up to 350 ppm and are typically enriched in LREE over HREE (Morogan, 1989). REE contents are highest in the carbonatitic rocks, and specifically in the sövites (up to 1463 ppm) (Hornig-Kjarsgaard, 1998). The carbonatites include a wide range of REE-bearing minerals such as apatite, monazite, titanite, pyrochlore, bastnäsite, and synchysite, but except for some recent activity in the Söråker area, there has been no formal exploration within the complex.

A major area of latest Neoproterozoic alkaline and carbonatitic igneous rocks is the Seiland Igneous Province, which occurs in the allocthonous Caledonian nappes of northern Norway (Fig. 4). The most voluminous parts of the province comprise sub-alkaline to mildly alkaline gabbroic rocks, but the latest intrusions include syenites, nepheline syenites, and carbonatites dated at 580–560 Ma (Roberts et al., 2010). REE enrichments have not been identified in the main igneous complexes but are present in carbonatite dykes and fenites (Ihlen et al., 2014), and there may be potential for exploration.

### 3.5. Cambrian to Silurian rift systems and sedimentary basins

Neoproterozoic continental rifting in northern Europe was largely terminated by the transition to drift and the opening of the Iapetus Ocean. Within Europe, the main locus of continental rifting shifted southward, with rifts developing in the northern part of Gondwana during the Cambrian. These rifts would eventually lead to opening of the Rheic Ocean during the Ordovician (Nance et al., 2010). Magmatism associated with this period of rifting is now well-preserved in the Bohemian Massif (Pin et al., 2007) and in the Iberian massif of Spain and Portugal (Sánchez-García et al., 2010). The main rift-related sequence in the Iberian massif (Fig. 2) is dominated by volcanic rocks with some plutons, typically sub-alkaline to alkaline in nature (Sánchez-García et al., 2003). These include a large area of peralkaline granitoids, the 482 ± 2 Ma Galiñeiro Complex (Montero et al., 2009). This complex has notable enrichments in the REE, hosted in a range of minerals including allanite, monazite, xenotime, zircon, bastnäsite, thorite, and REE niobotantalates (aeschynite, fergusonite, samarskite, and pyrochlore group minerals) (Montero et al., 1998).

An unusual suite of REE-enriched rocks exists in the form of authigenic nodular monazite layers in Palaeozoic sedimentary basins across western and Central Europe. Such monazite nodules are found in Lower Palaeozoic turbidite sequences in Central Wales and in Belgium (Fig. 2), and are considered to have formed by remobilisation of REE from volcanogenic or heavy mineral layers during diagenesis (Burnotte et al., 1989; Milodowski and Zalasiewicz, 1991). They are typically characterised by cores that show enrichment in the middle REE with LREE-enriched rims, and are lower in Th than igneous monazites (Milodowski and Zalasiewicz, 1991). In Brittany, similar monazite nodules have locally been eroded from their host sedimentary rocks and concentrated into alluvial placers (Donnot et al., 1973). These monazites similarly show MREE-enriched cores and LREE-enriched rims (Tuduri et al., 2013). Within the Iberian massif, REE enrichments are found in Ordovician quartzites in Vale de Cavalos in Portugal (de Oliveira, 1998). The REE are hosted in detrital minerals such as zircon and rutile, and also in nodular monazite.

### 3.6. Silurian post-collisional magmatism: the Caledonian belt

During the Silurian, closure of the Iapetus Ocean and collision between Laurentia, Baltica, and Avalonia formed the Caledonide orogenic belt which extends through northern Germany, Norway, the northern British Isles, and east Greenland, and into the Appalachians of North America (McKerrow et al., 2000). Parts of the Caledonian belt are marked by voluminous syn- to post-collisional calc-alkaline to alkaline magmatism (Atherton and Ghani, 2002) with localised areas of more highly alkaline magmatism.

In northern Scotland, a suite of high-K syenitic to pyroxenitic plutons, with one small carbonatite body, was emplaced at 431–425 Ma (Goodenough et al., 2011). Of these, the most significant REE

enrichments are found in the Loch Loyal Complex (Fig. 2) (Hughes et al., 2013), where allanite-rich mafic syenites have been affected by late-stage hydrothermal alteration that has concentrated the REE into biotite–magnetite-rich veins with up to 2% TREO (Walters et al., 2013). The main REE-bearing minerals are allanite, apatite, titanite, and REE-carbonate (Walters et al., 2013). In Norway, the Misværdal Complex (c. 440 Ma) also comprises high-K intrusions of pyroxenite and granitoid, intruded into the Caledonian belt (Fig. 4). The pyroxenites show local enrichments in allanite and apatite, with significant REE contents (c. 0.5 wt.% TREO) (Ihlen et al., 2014). Similar high-K magmatism also occurs in east Greenland (Fig. 3), with examples in the Batbjerg Complex (Brooks et al., 1981) and in Milne Land (Kalsbeek et al., 2008). In Milne Land, heavy minerals have been eroded from the plutons and subsequently concentrated in Jurassic placer deposits (Larsen et al., 2003) that are of interest for their REE enrichment. In Jämtland, Sweden, nepheline syenites and carbonatitic rocks occur within the Caledonide nappes (Fig. 4). These rocks contain REE hosted by pyrochlore-group minerals and bastnäsite (Jonsson and Stephens, 2004). Recent exploration in the area has so far failed to find any evidence for larger carbonatitic bodies.

### 3.7. Devonian to Permian rifting and Variscan belts

During the Devonian and Carboniferous, much of central and southern Europe was affected by Variscan orogenesis associated with the closure of the Rheic Ocean, whilst rifting, and alkaline magmatism developed in the foreland to the Variscan (Timmerman, 2004). Pronounced continental rifting in the Baltic Shield at 390–360 Ma led to the formation of the Kola Alkaline Province (Fig. 2), one of the most well-studied areas of alkaline magmatism in the world (Arzamastsev et al., 2001; Downes et al., 2005; Kogarko et al., 2010). During the early Carboniferous, around 350 Ma, a phase of rifting affected the British Isles, Norway, and into north Germany and Poland. Minor alkaline magmatism also developed during the Carboniferous in a post-collisional setting within the Variscan orogenic belt, notably in the Bohemian massif. Subsequently, an extensive rift system developed to the north of the Variscan orogenic belt through the late Carboniferous and early Permian (Wilson et al., 2004). These continental rifts represent notable areas of alkaline magmatism with significant potential for REE deposits.

The majority of the Kola Alkaline Province lies in Russia, where it contains significant REE deposits in the Khibiny and Lovozero intrusive complexes (Kogarko et al., 2010), but is outside the geographical scope of this paper. The westernmost part of the province falls within the Finnish border, with two main intrusions: the Sokli phoscorite–carbonatite complex, and the Iivaara alkaline complex (Fig. 4). Sokli was emplaced at c. 380 Ma (Rukhlov and Bell, 2010) into Archaean gneisses, and covers an area of c. 20 km$^2$. It has a magmatic carbonatite–phoscorite core in which several intrusive phases can be identified, surrounded by an aureole of fenitised gneiss and pyroxenite (Vartiainen and Paarma, 1979; Lee et al., 2006). The earlier intrusions within the carbonatite comprise calcite carbonatite and phoscorite, with abundant pyrochlore in the phoscorites. Late-stage dykes of dolomite carbonatite cut the earlier intrusions and the fenites, and contain apatite and monazite together with Sr–Ba-LREE-bearing carbonates such as strontianite, alstonite, bastnäsite-(Ce), and ancylite-(Ce) (Lee et al., 2006; Sarapää et al., 2013). Analysis of these veins has indicated TREE contents up to 1.83% (Al-Ani and Sarapää, 2013). The Iivaara alkaline complex is a c. 9 km$^2$ plug of ijolitic rocks surrounded by a zone of fenitised gneisses (Sindern and Kramm, 2000). Although some apatite and allanite are present in samples from the plug, REE contents are relatively low (Sarapää et al., 2013).

Early Carboniferous magmatism in the Variscan foreland is well known from the British Isles, particularly the Midland Valley and Northern England, where it largely comprises mafic volcanic rocks (Timmerman, 2004). Alkaline intrusions may be present at depth in this area. In Poland, geophysical investigations and drilling have revealed a buried alkaline plutonic province of Early Carboniferous age (354–345 Ma) which includes the Pisz and Elk gabbroic to syenitic plutons, and the Tajno pyroxenite–carbonatite–syenite body (Fig. 2) (Demaiffe et al., 2013). The late carbonatite veins in the Tajno body show LREE enrichment with reported total rare earth oxide content up to 9 wt.% (Demaiffe et al., 2005).

Late-stage alkaline post-collisional magmatism occurred in many parts of the Variscan belt, and can be considered as analogous to the similar magmatism in the Caledonian belt described above. Although alkaline intrusions represent only a small percentage by volume of the voluminous Variscan batholiths that extend across Central Europe, there has been limited study of their REE potential. The Bohemian Massif in the Czech Republic (Fig. 2) hosts ultrapotassic syenitic plutons such as the c. 335–340 Ma Třebíč Pluton (Kotková et al., 2010; Kusiak et al., 2010) which are cut by fields of late, REE-enriched pegmatites with a range of REE minerals including allanite, bastnäsite, and euxenite (Škoda and Novák, 2007). Late-Variscan A-type microgranite dykes have also been recognised from the Krušné hory mountains; they show HREE enrichment and contain minerals such as monazite, thorite, xenotime, and pyrochlore (Breiter, 2012).

Widespread rift-related magmatism developed in the British Isles, in the Oslo Rift in Norway, in southern Sweden, and in the North German Basin during the late Carboniferous and into the early Permian (Neumann et al., 2004). Much of this magmatism is still preserved as lava flows, dykes, and sills at the surface, such that the plutons that might contain REE resources remain buried. One of the most important areas of alkaline magmatism of this age is the Oslo Rift (Fig. 4), which has been subdivided into six stages of rifting and magmatism from c. 300 Ma to c. 240 Ma (Neumann et al., 1992; Larsen et al., 2008; Corfu and Dahlgren, 2008). Lavas are extensive within the rift, and are intruded by a number of alkaline plutons of varying composition. The plutons are dominated by monzonitic compositions and many have marginal pyroxenite bodies, such as the Kodal apatite deposit, which consists of a 1900 m-long zone of closely-spaced pyroxenite lenses within the monzonitic Larvik Plutonic Complex (Ihlen et al., 2014). This deposit is currently being explored for phosphate and Fe–Ti, but has also been recorded as having high REE contents in apatite (Ihlen et al., 2014). Syenitic pegmatites, of both miaskitic and agpaitic types, are also recorded throughout the Larvik Plutonic Complex and may contain REE-bearing minerals (Andersen et al., 2010). Other magmatic bodies within the rift that may be of interest for the REE include Sæteråsen in Norway, a Nb-REE mineralisation hosted in a trachytic lava flow (Ihlen, 1983), and Särna in Sweden.

### 3.8. Mesozoic rifts: Alpine Tethys and Atlantic

Rifting continued throughout Europe during the Mesozoic and into the Cenozoic, with varying amounts of associated magmatism. In western Europe, Atlantic rifting generated the voluminous Central Atlantic Magmatic Province and subsequently the North Atlantic Igneous Province, whereas rifting of the Alpine Tethys in southern and eastern Europe appears to have been associated with rather limited magmatic activity (Stampfli, 2000).

Alpine Tethyan rifting during the Triassic generated alkaline magmatism in the Carpathians, which is still relatively little-known. The most notable REE mineralisation is associated with the c. 230 Ma Ditrău Alkaline Complex in the Eastern Carpathians of Romania (Fig. 2) (Dallmeyer et al., 1997; Morogan et al., 2000; Fall et al., 2007). REE-rich mineral veins are found within the alkaline complex at Jolotca, and outside the complex at Belcina. The REE mineralised veins include monazite-(Ce), xenotime-(Y), allanite-(Ce), apatite, bastnäsite, parisite, synchysite, fergusonite, polycrase, and aeschynite in association with sulphides, carbonates and a wide range of other minerals (Hirtopanu et al., 2010). Disseminated enrichments in REE, Nb, and Zr are also found within the roof zone of the alkaline complex in the Lazarea area.

A small Triassic alkaline intrusive body associated with REE mineralisation has also been identified in the Slovakian Carpathians (Ondrejka et al., 2007). This area may well have significant potential for discovery of further REE mineralisation.

In contrast, rifting of the Atlantic led to the development of voluminous magmatism. The Central Atlantic Magmatic Province, associated with rifting of the Pangaea supercontinent and formation of the central Atlantic Ocean, comprises extensive flood basalts erupted around the Triassic–Jurassic boundary at c. 200 Ma (Marzoli et al., 1999; Blackburn et al., 2013). As the ocean opened, subsequent late Cretaceous rifting cycles (100–70 Ma) emplaced alkaline magmas along the Iberian margin in Spain and Portugal and also in the Pyrenees (Solé et al., 2003; Miranda et al., 2009; Grange et al., 2010). REE mineralisation is not currently known in association with this alkaline magmatic phase, but there may be potential for further investigation.

During the Jurassic, continental extension began to develop northwards, marked in Europe by the emplacement of carbonatites and lamprophyres in west Greenland (Fig. 3) at 165–145 Ma (Secher et al., 2009; Tappe et al., 2009). Both the Qaqarssuk (Qeqertaasaq) and Tikiusaaq carbonatite intrusions are enriched in LREE. The Qaqarssuk carbonatite comprises a series of calcite- and dolomite-carbonatite and silicocarbonatite ring-dykes (Knudsen, 1991) with late-stage sheets of calcite- and ferro-carbonatite that show significant REE enrichment. The major REE minerals are ancylite, burbankite, huanghoite, and qaqarssukite (Thrane et al., 2014). The Tikiusaaq carbonatite similarly comprises calcite- and dolomite-carbonatites with later ferrocarbonatite dykes (Tappe et al., 2009). Both carbonatites are surrounded by zones in which the country rock has been fenitised.

Rifting and ocean opening, together with impingement of the Iceland plume, led to development of tholeiitic flood basalt magmatism of the North Atlantic Igneous Province during the Cenozoic, beginning at 62 Ma (Saunders et al., 2013). In East Greenland, the alkaline Gardiner Complex formed at c. 55 Ma (Tegner et al., 2008). It comprises ultramafic cumulates with syenites and carbonatite sheets (Nielsen, 1980) and may have potential for REE mineralisation, although it is extremely difficult to access. On the other margin of the Atlantic, in Scotland and Northern Ireland, REE minerals including chevkinite-group minerals, fergusonite, gadolinite, allanite, and monazite have been reported from Cenozoic granites in Arran, Skye, and the Mourne Mountains (Hyslop et al., 1999; Moles and Tindle, 2011; Macdonald et al., 2013). However, the bulk compositions of the granites do not exhibit significant REE enrichment.

### 3.9. Cretaceous to Cenozoic circum-Mediterranean rifts

Intraplate, extensional magmatism has been common through much of Europe during the Cenozoic, particularly in areas of Variscan basement around the Alpine collisional zone (Wilson and Downes, 2006). To the north and west of the Alps, alkaline volcanism developed around the Rhenish Massif and Rhine Graben in Germany, the Massif Central in France, Calatrava in Spain, and the Bohemian Massif in the Czech Republic (Fig. 2). To the south and east, subduction-related magmatism was followed by more alkaline volcanism in Italy, Greece, Turkey and parts of Eastern Europe such as the Pannonian Basin (Agostini et al., 2007). In all of these areas, the current surface expression of the magmatism constitutes volcanic fields and their eruptive products, most commonly basanitic and basaltic (Wilson and Downes, 2006). Carbonatitic magmas are rare, but locally present. It seems highly likely that plutons with potential for REE enrichment may exist beneath these areas.

In eastern Germany, the Delitzsch carbonatite–lamprophyre complex (Fig. 2) lies buried beneath c. 100 m of Cenozoic sediments. It was discovered during exploration for uranium deposits in the 1960s and 1970s. Extensive drilling has proved lamprophyres and carbonatite dykes and plugs down to c. 1100 m, across an area of c. 450 km$^2$ (Krűger et al., 2013). The presence of xenoliths of coarse carbonatite in diatreme breccias is considered to indicate a carbonatitic pluton at greater depths (Seifert et al., 2000). REE minerals in the carbonatites include apatite, pyrochlore and bastnäsite. One of the carbonatitic diatremes, the Storkwitz diatreme, has estimated total (indicated and inferred) resources of 4.4 Mt. @ 0.45% TREO (Deutsche-Rohstoff, 2013). Recent dating (Krűger et al., 2013) suggests an emplacement age for the complex of 75–71 Ma, indicating early reactivation of Variscan structures in the Alpine foreland.

Extrusive carbonatites and alkaline volcanic rocks are known from a number of localities around the Rhine Graben, including Kaiserstuhl, Hegau and centres in the Eifel volcanic province (Woolley and Church, 2005). One of the more well-known carbonatites of this age is the Miocene Kaiserstuhl Volcanic Complex (Keller, 1981; Kraml et al., 2006; Wang et al., 2014) in the Rhine Graben. It comprises volcanic rocks and dykes of alkaline silicate composition, as well as carbonatitic dykes, intrusions, and diatreme breccias. The carbonatites show significant REE enrichment (Hornig-Kjarsgaard, 1998) and hydrothermal alteration of phonolites has generated an economic zeolite deposit which contains the rare earth-bearing phase götzenite (Weisenberger et al., 2014). It seems likely that plutonic rocks of interest for their REE concentrations may be present beneath Kaiserstuhl. The same may be true of the alkaline–carbonatite complexes in the Eifel volcanic province, such as Rockeskyll (Riley et al., 1999) and Laacher See (Schmitt et al., 2010), and also of extrusive carbonatite complexes at Calatrava in Spain (Bailey et al., 2005).

In southern Europe, extrusive carbonatites occur in association with alkaline to peralkaline volcanic rocks at a number of localities in Italy, including San Venanzo, Polino and Cupaello in the Intra-Montane Ultra-alkaline province, and the Monte Vulture volcanic complex (Stoppa and Woolley, 1997; Downes et al., 2002). In these areas, compressional tectonics associated with Apennine folding and thrusting have passed into an extensional regime over the last 5 Ma (Lavecchia and Boncio, 2000). The presence of coarse-grained carbonatite tephra at Monte Vulture indicates that intrusive carbonatites are present at depth, and these rocks are enriched in the LREE as is typical of carbonatites (Rosatelli et al., 2000; Mongelli et al., 2013). Beach sands along the Italian coastline, particularly at Nettuno near Rome, contain REE minerals such as perrierite-(Ce) that may be derived from the alkaline volcanics (Macdonald et al., 2009).

In Greece, alkaline volcanic rocks are known from many localities in the Aegean (Agostini et al., 2007). However, the most important REE concentrations are not associated with alkaline rocks, but are found in heavy mineral sands on the coast in the Nea Peramos and Strymonikos Gulf areas. REE-bearing minerals in these placers include monazite, allanite, titanite, uraninite, zircon, and apatite (Eliopoulos et al., 2014). Geochemical and mineralogical studies indicate that these minerals are derived from the Symvolon and Kavala plutons, which are deformed granodioritic complexes of Miocene age (Dinter et al., 1995).

Alkaline igneous rocks and carbonatites of Cretaceous to Cenozoic age are common in the Anatolian rift systems in Turkey (Fig. 2), and would deserve further work to understand their potential for REE mineralisation. Of particular significance is the c. 25 Ma Kizilcaören Complex, which comprises phonolite and trachyte stocks, carbonatite dykes, and a fluorite-barite-LREE deposit forming veins and breccias fillings in the Palaeozoic country rock (Gültekin et al., 2003; Nikiforov et al., 2014). The ore assemblage contains barite, fluorite, quartz, calcite, feldspar, and phlogopite, with bastnäsite as the main REE mineral accompanied by brockite, fluocerite, monazite, and parisite (Gültekin et al., 2003; Nikiforov et al., 2014). The mineralisation can be related to hydrothermal activity associated with the alkaline magmatism. Late Cretaceous syenites with associated carbonatites and fluorite mineralisation have been described from east-central Anatolia, including the Karaçayir pluton (Cooper et al., 2011) and the area around Malatya, which contains the Sofular carbonatite (Ozgenc, 1999; Ozgenc and Ilbeyli, 2009). The Quaternary alkaline volcanism of Gölcűk, close to Isparta in south-western Turkey, shows enrichment in the REE

(Platevoet et al., 2014) and has been proposed as a possible source for heavy minerals in the nearby Çanakli placer (Aksu Diamas REE prospect). This prospect has an inferred resource estimate of 494 Mt. at 0.07–0.08 wt.% TREO (Cox et al., 2013).

### 3.10. Bauxites

Bauxite deposits occur along the northern shore of the Mediterranean Sea (Fig. 7), from Spain to Turkey, encompassing parts of southern France, Hungary, Italy, Greece and the Balkans (Bárdossy, 1982; Özlü, 1983). Many of these bauxites, which formed by intense lateritic weathering of residual clays, are currently mined for aluminium, and the red mud waste from bauxite processing represents a potential REE resource (Deady et al., 2014). A pioneer study described the existence of authigenic REE-bearing minerals within karst bauxites of the San Giovanni Rotondo deposit, in Italy (Bárdossy and Panto, 1973). The presence of REE-bearing minerals within bauxites was confirmed by Bárdossy et al. (1976) for the Nagyharsány deposit, in Hungary and subsequently for a range of other deposits (Maksimovic and Panto, 1996). The most abundant REE-bearing minerals are members of the bastnäsite group, and the most frequent is hydroxylbastnäsite ($REE(CO_3)(OH)$), followed by synchysite-(Nd), bastnäsite-(Ce), and bastnäsite-(Nd). Other minerals described include monazite-(Nd), monazite-(La), Nd-rich goyazite, florencite and crandallite (Maksimovic and Panto, 1996). The REE contained within bauxites pass into red mud wastes after processing, and represent a low-grade but potentially large-tonnage resource of REE in Europe (Deady et al., 2014).

## 4. Discussion

From the assessment above, it is clear that Europe already has substantial known REE resources, and that there is significant potential for further resources to be recognised. Although detailed estimation of total European REE demand is complex, recent work by the ASTER project indicates that the current demand for certain critical REE could be met by the known REE resources within Europe (Guyonnet et al., 2015). However, if demand is to be met into the future, continued research into, and exploration of Europe's resources will be needed. This overview should provide a basis for such potential future work. An important aspect is the identification of areas that are prospective for deposits of different types and mineralogies, which may become important as REE mineral processing methods continue to evolve.

The majority of the known resources, and many potential future exploration areas, are associated with alkaline magmatism and carbonatites developed in intracontinental rift settings. However, REE can be concentrated in other settings, most notably associated with post-collisional alkaline magmas. The REE deposits of the Svecofennian belt are unique in Europe, in that they were formed by hydrothermal processes associated with active subduction. Secondary deposits are also of interest, although typically low-grade; they include diagenetic nodular monazites, sedimentary placers, and deposits formed by weathering such as bauxites. REE-enriched placers in particular are typically found in areas where alkaline magmatism exists nearby, although few REE placers have been studied in any detail.

Many of Europe's current exploration projects for REE are associated with carbonatites, including Sarfartoq and Qaqarssuk in Greenland, Fen in Norway, and Storkwitz in Germany. Many of these have the advantage that they contain the mineral bastnäsite, currently the most commonly processed REE ore mineral (Jordens et al., 2013). However, the majority of carbonatites are strongly enriched in the LREE (Chakhmouradian and Zaitsev, 2012) and have lower contents of the most critical HREE. In a worldwide context, current REE production comes largely from high-grade carbonatites such as Bayan Obo and Mountain Pass; the European carbonatites are typically somewhat lower grade (Fig. 8).

Higher concentrations of the most critical REE are found in deposits where the main REE minerals include xenotime, eudialyte-group minerals, or to a lesser extent monazite (Chakhmouradian and Wall, 2012). Both monazite and xenotime have been mined outside Europe from heavy mineral placers, and processing methods have been established for both minerals (Jordens et al., 2013). These minerals are typically formed in miaskitic igneous rocks and several potential REE

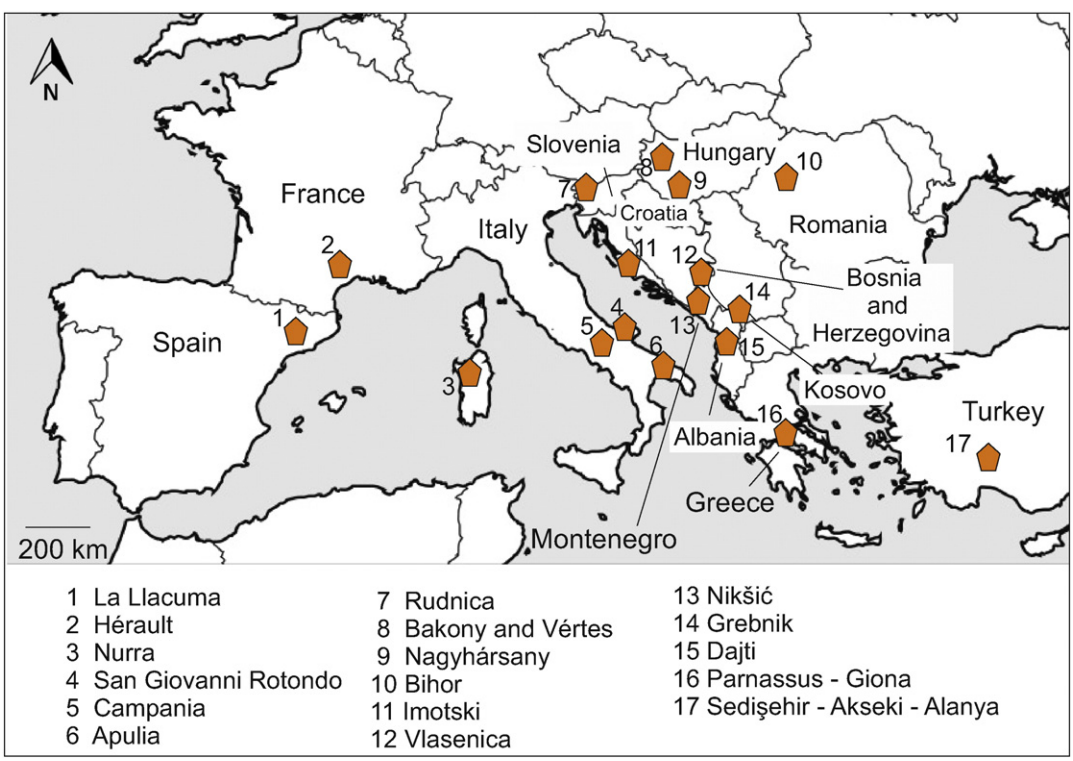


**Fig. 7.** Map of the bauxite deposits in the Mediterranean area, after Deady et al. (2014).

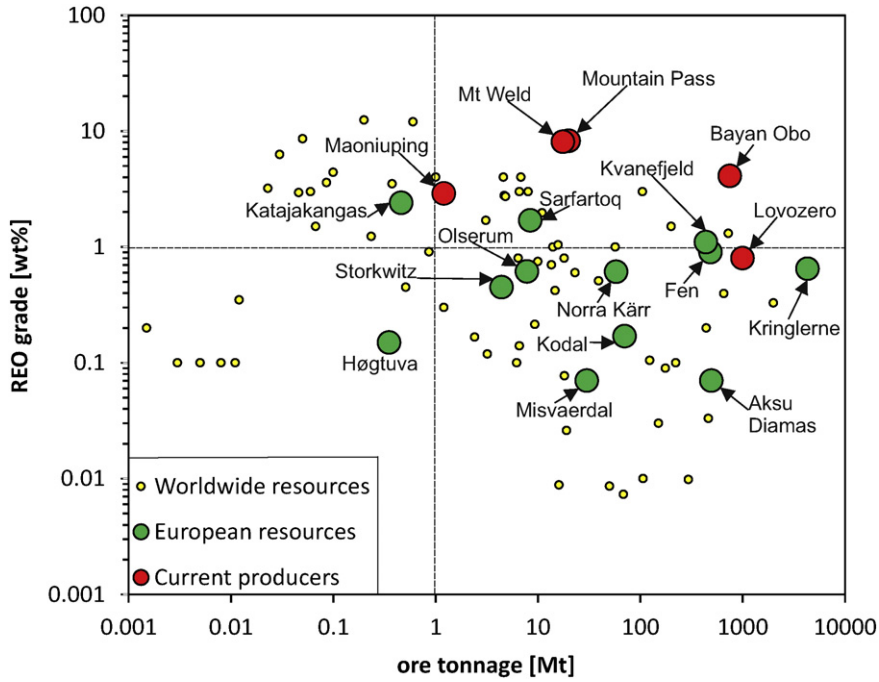


**Fig. 8.** Grade and tonnage plot comparing European REE deposits with those worldwide. Background data for worldwide resources from Orris and Grauch (2002); for current producers from Wall (2014); and for European resources from references quoted in this paper.

deposits of this type are known in Europe, including the xenotime-bearing mineralisation associated with the Galiñeiro and Ditrãu complexes. A number of heavy mineral placers formed by erosion of miaskitic plutons also occur within Europe. However, both xenotime and monazite typically contain high levels of Th and U, creating possible issues with radioactive waste (Chakhmouradian and Wall, 2012). Nonetheless, most REE deposits of this type in Europe have been the subject of only limited research and exploration, and would deserve much more investigation.

Currently, there is a significant European focus on eudialyte-group minerals and their alteration products as a source of the critical REE, particularly needed in the magnet industry. These minerals are most commonly found in large, agpaitic igneous complexes. Ores containing eudialyte-group minerals may have lower REE grades than those bearing monazite and xenotime, but they are also typically characterised by lower Th and U contents. Research into eudialyte-group mineral beneficiation and processing is ongoing as part of the EURARE project, but has not been successfully carried out on a commercial scale. Europe has resources of eudialyte-group minerals in Norra Kärr and in the intrusions of the Gardar Province, particularly Ilímaussaq; other significant agpaitic intrusions are not known at the present time, but may remain to be discovered. These intrusions are typically fairly low grade (commonly <1 wt.% TREO) but large tonnage (Fig. 8).

Europe has a wide variety of REE deposits and it is very likely that many more remain to be discovered. A key point that emerges from this review is the existence of 'fertile zones' for REE mineralisation. The stable cratonic areas in Greenland and Scandinavia have only limited evidence of alkaline magmatism despite their long histories, and there are no recognised Archaean REE deposits in Europe. However, many of Europe's carbonatites are focused along craton margins. These craton margins represent more fertile zones, which have initially been affected by subduction in accretionary orogens, potentially fertilising the lithospheric mantle. Subsequently, in many cases hundreds of millions of years later, reactivation of these areas by extensional tectonics has led to alkaline igneous activity and enrichment in REE. This pattern of repeated enrichment of mantle sources appears to be fundamental to the formation of REE-enriched magmas. A clear example of this comes from Southern Greenland, where Gardar Province magmas were derived from lithospheric mantle that was metasomatised and fertilised some 600 million years earlier during subduction and formation of the Ketilidian belt (Goodenough et al., 2002). In Norway, the Fen carbonatite and associated dyke swarms, and the subsequent Oslo Rift, represent two episodes of alkaline magmatism (Dahlgren, 1994) localised along the margin of a Neoproterozoic subduction-related igneous province associated with the Sveconorwegian event (Slagstad et al., 2013). Further south in Europe, many areas that were affected by the Variscan orogeny have been reactivated during the Cenozoic, with the emplacement of alkaline magmas. A notable example is the Bohemian Massif, in which Palaeozoic subduction-related magmatism (Schulmann et al., 2009) was followed by post-collisional alkaline magmatism, with subsequent reactivation and formation of a rift-related alkaline igneous province during the Cenozoic (Ulrych et al., 2011). In the Iberian massif, initial alkaline magmatism associated with Rheic Ocean rifting was followed by Variscan collision and then by a further period of alkaline magmatism. In general, areas where Variscan belts have been reactivated by later rifting with alkaline magmatism would appear to be of great interest for REE exploration. To the south of the Alpine mountain chain, there is significant potential for REE enrichments at depth beneath the alkaline volcanic rocks of Italy and Turkey.

## 5. Conclusions

This overview demonstrates that Europe has a wide range of REE deposits and occurrences. The most significant primary deposits are associated with alkaline igneous rocks and carbonatites formed in extensional settings, although a range of deposits of hydrothermal and igneous origin can be formed in other geodynamic settings. Secondary deposits include placers, which can commonly be linked back to an igneous source, and bauxites in southern Europe.

The most well-known primary deposits are those associated with Mesoproterozoic rift-related magmatism in Greenland and Sweden, and with Neoproterozoic to Palaeozoic carbonatites across Greenland and the Fennoscandian Shield. However, there are a number of less-well known deposits in areas where Europe's Variscan belts have been reactivated by later rifting with the emplacement of alkaline magmas,

and these represent important targets for further research. It is clear that Europe has the potential REE deposits needed to secure its own supply of these elements for the foreseeable future, but that there is a need to develop beneficiation and processing methods in order to ensure sustainable exploitation.

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## References

Åberg, G., 1988. Middle Proterozoic anorogenic magmatism in Sweden and worldwide. Lithos 21, 279–289.

Agostini, S., Doglioni, C., Innocenti, F., Manetti, P., Tonarini, S., Savaşçin, M.Y., 2007. The transition from subduction-related to intraplate Neogene magmatism in the western Anatolia and Aegean area. Geol. Soc. Am. Spec. Pap. 418, 1–15.

Åhäll, K.I., Larson, S.A., 2000. Growth-related 1.85–1.55 Ga magmatism in the galtic shield; a review addressing the tectonic characteristics of svecofennian, TIB 1-related, and gothian events. GFF 122, 193–206.

Al-Ani, T., 2013. Mineralogy and petrography of Siilinjärvi carbonatite and glimmerite rocks, eastern Finland. Geological Survey of Finland Report 164/2013.

Al-Ani, T., Sarapää, O., 2013. Geochemistry and mineral phases of REE in jammi carbonatite veins and fenites, southern end of the sokli complex, NE Finland. Geochem. Explor. Environ. Anal. 13, 217–224.

Al-Ani, T., Sarapää, O., Torppa, A., 2010. Mineralogy and petrography of REE-bearing minerals of Iivaara, Otanmäki and Korsnäs alkaline rocks. Geological Survey of Finland report M42/2010/15.

Allen, R.L., Lundström, I., Ripa, M., Christofferson, H., 1996. Facies analysis of a 1.9 Ga, continental margin, back-arc, felsic caldera province with diverse Zn–Pb–Ag–(Cu–Au) sulfide and Fe oxide deposits, bergslagen region, Sweden. Econ. Geol. 91, 979–1008.

Andersen, T., 1986. Compositional variation of some rare earth minerals from the fen complex (Telemark, SE Norway): implications for the mobility of rare earths in a carbonatite system. Mineral. Mag. 50, 503–509.

Andersen, T., 1988. Evolution of peralkaline calcite carbonatite magma in the fen complex, southeast Norway. Lithos 22, 99–112.

Andersen, T., 1997. Age and petrogenesis of the qassiarsuk carbonatite–alkaline silicate volcanic complex in the gardar rift, south Greenland. Mineral. Mag. 61, 499–513.

Andersen, T., Erambert, M., Larsen, A.O., Selbekk, R.S., 2010. Petrology of nepheline syenite pegmatites in the Oslo rift, Norway: zirconium silicate mineral assemblages as indicators of alkalinity and volatile fugacity in mildly agpaitic magma. J. Petrol. 51, 2303–2325.

Andersson, U.B., Eklund, O., Fröjdö, S., Konopelko, D., 2006. 1.8 Ga magmatism in the fennoscandian shield; lateral variations in subcontinental mantle enrichment. Lithos 86, 110–136.

Andréasson, P.-G., Rodhe, A., 1990. Geology of the protogine zone south of Lake Vättern, southern Sweden: a reinterpretation. Geol. Fören. Stockh. Förh. 112, 107–125.

Arzamastsev, A.A., Bea, F., Glaznev, V.N., Arzamastseva, L.V., Montero, P., 2001. Kola alkaline province in the Paleozoic: evaluation of primary mantle magma composition and magma generation conditions. Russ. J. Earth Sci. 3, 1–32.

Atherton, M.P., Ghani, A.A., 2002. Slab breakoff: a model for Caledonian, late granite syncollisional magmatism in the orthotectonic (metamorphic) zone of Scotland and Donegal, Ireland. Lithos 62, 65–85.

Bailey, K., Garson, M., Kearns, S., Velasco, A.P., 2005. Carbonate volcanism in calatrava, central Spain: a report on the initial findings. Mineral. Mag. 69, 907–915.

Bárdossy, G., 1982. Karst Bauxites. Elsevier, Amsterdam.

Bárdossy, G., Panto, G., 1973. Trace mineral and element investigation on bauxites by electron probe. 3rd International Congress. ICSOBA (International Committee for Study of Bauxite, Alumina and Aluminium), Nice, France, pp. 47–53.

Bárdossy, G., Panto, G., Varhegyi, G., 1976. Rare metals of Hungarian bauxites and conditions of their utilization. Travaux ICSOBA (International Committee for Study of Bauxite, Alumina and Aluminium) 13, pp. 221–231.

Binnemans, K., Jones, P.T., Blanpain, B., Van Gerven, T., Yang, Y., Walton, A., Buchert, M., 2013. Recycling of rare earths: a critical review. J. Clean. Prod. 51, 1–22.

Bizzarro, M., Simonetti, A., Stevenson, R.K., David, J., 2002. Hf isotope evidence for a hidden mantle reservoir. Geology 30, 771–774.

Blackburn, T.J., Olsen, P.E., Bowring, S.A., McLean, N.M., Kent, D.V., Puffer, J., McHone, G., Rasbury, E.T., Et-Touhami, M., 2013. Zircon U–Pb geochronology links the end-Triassic extinction with the central Atlantic magmatic province. Science 340, 941–945.

Blichert-Toft, J., Rosing, M.T., Lesher, C.E., Chauvel, C., 1995. Geochemical constraints on the origin of the late Archean skjoldungen alkaline igneous province, SE Greenland. J. Petrol. 36, 515–561.

Bogdanova, S.V., Bingen, B., Gorbatschev, R., Kheraskova, T.N., Kozlov, V.I., Puchkov, V.N., Volozh, Y.A., 2008. The east European craton (baltica) before and during the assembly of rodinia. Precambrian Res. 160, 23–45.

Borst, A.M., Friis, H., Andersen, T., Nielsen, T.F.D., Waight, T.E., Smit, M.A., (in press) 2015. Zirconosilicates in the Kakortokites of the Ilimaussaq Complex, South Greenland: Implications for Fluid Evolution and HFSE-REE Mineralisation in Agpaitic Systems. Mineral. Mag.

Brander, L., Söderlund, U., 2009. Mesoproterozoic (1.47–1.44 Ga) orogenic magmatism in Fennoscandia; baddeleyite U–Pb dating of a suite of massif-type anorthosite in S. Sweden. Int. J. Earth Sci. 98, 499–516.

Breiter, K., 2012. Nearly contemporaneous evolution of the a- and s-type fractionated granites in the krušné hory/Erzgebirge Mts., Central Europe. Lithos 151, 105–121.

Brooks, C.K., Fawcett, J.J., Gittins, J., Rucklidge, J.C., 1981. The batbjerg complex, east Greenland: a unique ultrapotassic Caledonian intrusion. Can. J. Earth Sci. 18, 274–285.

Burnotte, E., Pirard, E., Michel, G., 1989. Genesis of gray monazites; evidence from the Paleozoic of Belgium. Econ. Geol. 84, 1417–1429.

Cecys, A., Benn, K., 2007. Emplacement and deformation of the ca. 1.45 Ga karlshamn granitoid pluton, southeastern Sweden, during ENE–WSW danopolonian shortening. Int. J. Earth Sci. 96, 397–414.

Chakhmouradian, A.R., Wall, F., 2012. Rare earth elements: minerals, mines, magnets (and more). Elements 8, 333–340.

Chakhmouradian, A.R., Zaitsev, A.N., 2012. Rare earth mineralization in igneous rocks: sources and processes. Elements 8, 347–353.

Cooper, A., Boztuğ, D., Palin, J.M., Martin, C., Numata, M., 2011. Petrology and petrogenesis of carbonatitic rocks in syenites from central Anatolia, Turkey. Contrib. Mineral. Petrol. 161, 811–828.

Corfu, F., Dahlgren, S., 2008. Perovskite U–Pb ages and the Pb isotopic composition of alkaline volcanism initiating the permo-carboniferous Oslo rift. Earth Planet. Sci. Lett. 265, 256–269.

Coulson, I.M., 2003. Evolution of the north qoroq Centre nepheline syenites, south Greenland: alkali-mafic silicates and the role of metasomatism. Mineral. Mag. 67, 873–892.

Coulson, I.M., Chambers, A.D., 1996. Patterns of zonation in rare-earth-bearing minerals in nepheline syenites of the north qoroq center, south Greenland. Can. Mineral. 34, 1163–1178.

Coulson, I.M., Goodenough, K.M., Pearce, N.J.G., Leng, M.J., 2003. Carbonatites and lamprophyres of the gardar province — a 'window' to the sub-gardar mantle? Mineral. Mag. 67, 855–872.

Cox, J.J., Masun, K.M., Fayram, T., 2013. Technical Report on the Aksu Diamas Rare Earth Element and Minor Metals, Isparta District, Southwest Turkey NI-43–101 Report. RPA Inc., Toronto.

Dahlgren, S., 1994. Late Proterozoic and carboniferous ultramafic magmatism of carbonatitic affinity in southern Norway. Lithos 31, 141–154.

Dallmeyer, D., Krautner, H.-G., Neubauer, F., 1997. Middle-late Triassic $^{40}Ar/^{39}Ar$ hornblende ages for early intrusions within the ditrau alkaline massif, Rumania: implications for alpine rifting in the Carpathian orogen. Geol. Carpath. 48, 347–352.

de Oliveira, D., 1998. The rare earth-bearing Llandeilian quartzites in the Vale de Cavalos–Portalegre area, Central Iberian Zone, Portugal—their better understanding through geological mapping and rock geochemistry. Comunicações. Actas do V Congresso de Geologia, pp. B142–B145.

Deady, E., Mouchos, E., Goodenough, K.M., Williamson, B., Wall, F., 2014. Rare earth elements in karst-bauxites: a novel untapped European resource? ERES2014: 1st Conference on European Rare Earth Resources, Milos, Greece

Delin, H., Bastani, M., 2009. Berggrundskartan 11I Uppsala NO (bedrock map with short description in Swedish).

Demaiffe, D., Wisniewska, J., Brassinnes, S., 2005. A petrological–geochemical overview of the tajno carbonatite complex (NE Poland): a comparison with the kola carbonatite province (Russia). Mineral. Soc. Poland Spec. Pap. 26, 29–35.

Demaiffe, D., Wisniewska, J., Krzeminska, E., Williams, I.S., Stein, H., Brassinnes, S., Ohnenstetter, D., Deloule, E., 2013. A hidden alkaline and carbonatite province of early carboniferous age in northeast Poland: zircon U–Pb and pyrrhotite Re-os geochronology. J. Geol. 121, 91–104.

Deutsche-Rohstoff, 2013. Seltenerden Storkwitz AG announces results of JORC report [Online]. Available: http://rohstoff.de/en/blog/2013/01/31/deutsche-rohstoff-ag-seltenerden-storkwitz-ag-veroffentlicht-ergebnisse-des-jorc-gutachtens/.

Dinter, D.A., Macfarlane, A., Hames, W., Isachsen, C., Bowring, S., Royden, L., 1995. U–Pb and 40Ar/39Ar geochronology of the symvolon granodiorite: implications for the thermal and structural evolution of the Rhodope metamorphic core complex, northeastern Greece. Tectonics 14, 886–908.

Doig, R., 1970. An alkaline rock province linking Europe and North America. Can. J. Earth Sci. 7, 22–28.

Donnot, M., Guigues, J., Lulzac, Y., Magnien, A., Parfenoff, A., Picot, P., 1973. Un nouveau type de gisement d'europium: la monazite grise à europium en nodules dans les schistes paléozoïques de Bretagne. Mineral. Deposita 8, 7–18.

Downes, H., Kostoula, T., Jones, A., Beard, A., Thirlwall, M., Bodinier, J.L., 2002. Geochemistry and Sr–Nd isotopic compositions of mantle xenoliths from the Monte vulture carbonatite–melilitite volcano, central southern Italy. Contrib. Mineral. Petrol. 144, 78–92.

Downes, H., Balaganskaya, E., Beard, A., Liferovich, R., Demaiffe, D., 2005. Petrogenetic processes in the ultramafic, alkaline and carbonatitic magmatism in the kola alkaline province: a review. Lithos 85, 48–75.

Du, X., Graedel, T.E., 2011. Uncovering the global life cycles of the rare earth elements. Sci. Rep. 1.

Du, X., Graedel, T.E., 2013. Uncovering the end uses of the rare earth elements. Sci. Total Environ. 461–462, 781–784.

EC, 2014. Report on Critical Raw Materials for the EU.
Eilu, P., 2012. Mineral deposits and mineralogy of Fennoscandia. Geological Survey of Finland Special Paper 53.
Eliopoulos, D., Economou, G., Tzifas, I., Papatrechas, C., 2014. The potential of rare earth elements in Greece. ERES2014: First European Rare Earth Resources Conference, Milos, Greece.
Ernst, R.E., Bell, K., 2010. Large igneous provinces (LIPs) and carbonatites. Mineral. Petrol. 98, 55–76.
Fall, A., Bodnar, R.J., Szabo, C., Pal-Molnar, E., 2007. Fluid evolution in the nepheline syenites of the ditrău alkaline massif, Transylvania, Romania. Lithos 95, 331–345.
Finne, T.E., Eggen, O.A., 2013. Soil geochemical data from Nord-salten, Nordland. NGU Report No. 2013.015.
Frietsch, R., Perdahl, J.-A., 1995. Rare earth elements in apatite and magnetite in Kiruna-type iron ores and some other iron ore types. Ore Geol. Rev. 9, 489–510.
Gadolin, J., 1794. Undersökning af en svart Tung stenart ifrån ytterby stenbrott i roslagen. Kongl Vetenskaps Academiens Nya Handlingar 15, pp. 137–155.
Gates, P., Horlacher, C.F., Reed, G.C., 2013. Amended and Restated Preliminary Economic Assessment NI 43-101 Technical Report for the Norra Kärr (REE–Y–Zr) Deposit, Gränna, Sweden. Tasman Metals, Vancouver.
Geijer, P., 1961. The geological significance of the cerium mineral occurrences of the bastnäs type in central Sweden. Arkiv. Mineral. Geol. 3, 99–105.
GME, 2015. Kvanefjeld Project Ore Reserve Statement. Greenland Minerals and Energy Ltd., Subiaco, Western Australia.
Goodenough, K.M., Upton, B.G.J., Ellam, R.M., 2000. Geochemical evolution of the ivigtut granite, south Greenland: a fluorine-rich "a-type" intrusion. Lithos 51, 205–221.
Goodenough, K.M., Upton, B.G.J., Ellam, R.M., 2002. Long-term memory of subduction processes in the lithospheric mantle: evidence from the geochemistry of basic dykes in the gardar province of south Greenland. J. Geol. Soc. 159, 705–714.
Goodenough, K.M., Millar, I., Strachan, R.A., Krabbendam, M., Evans, J.A., 2011. Timing of regional deformation and development of the moine thrust zone in the Scottish caledonides: constraints from the U–Pb geochronology of alkaline intrusions. J. Geol. Soc. 168, 99–114.
Goodenough, K.M., Deady, E., Wall, F., Shaw, R.A., Lusty, P., 2014. The importance of tectonic setting in assessing European rare earth potential. European Rare Earth Resources 2014, Milos, Greece.
Grange, M., Scharer, U., Merle, R., Girardeau, J., Cornen, G., 2010. Plume–lithosphere interaction during migration of cretaceous alkaline magmatism in SW Portugal: Evidence from U–Pb ages and Pb–Sr–Hf isotopes. J. Petrol.
Gültekin, A.H., Örgün, Y., Suner, F., 2003. Geology, mineralogy and fluid inclusion data of the kizilcaören fluorite–barite–REE deposit, Eskisehir, Turkey. J. Asian Earth Sci. 21, 365–376.
Guyonnet, D., Planchon, M., Rollat, A., Escalon, V., Tuduri, J., Charles, N., Vaxelaire, S., Dubois, D., Fargier, H., 2015. Material Flow Analysis Applied to Rare Earth Elements in Europe. J. Clean. Prod.
Harlov, D.E., Andersson, U.B., Förster, H.-J., Nyström, J.O., Dulski, P., Broman, C., 2002. Apatite–monazite relations in the kiirunavaara magnetite–apatite ore, northern Sweden. Chem. Geol. 191, 47–72.
Hatch, G.P., 2012. Dynamics in the global market for rare earths. Elements 8, 341–346.
Hirtopanu, P., Andersen, J.C., Fairhurst, R.J., 2010. Nb, Ta, REE (Y), Ti, Zr, Th, U and Te rare element minerals within the ditrau alkaline intrusive complex, eastern Carpathians, Romania. In: Szakall, S., Kristaly, F. (Eds.), Mineralogy of Székelyland, Eastern Transylvania, Romania. Csik County Nature and Conservation Society, Miercurea-Ciuc.
Hisinger, W., Berzelius, J.J., 1804. Cerium: ein neuer metall aus einer schwedischen steinart, bastnäs tungstein gennant. Neues Allgemeines J. Chem. 2, 397–418.
Högdahl, K., Andersson, U.B., Eklund, O., 2004. The Transscandinavian Igneous Belt (TIB) in Sweden: a review of its character and evolution. Geological Survey of Finland Special Paper 37.
Högdahl, K., Troll, V.R., Nilsson, K.P., Jonsson, E., 2013. Structural evolution of the apatite-iron oxide deposit at Grängesberg, Bergslagen, Sweden. 1650–1653. In: Jonsson, E. (Ed.), Mineral Deposit Research for a High-Tech World. Society for Geology Applied to Mineral Deposits.
Höhn, S., Frimmel, H.E., Pašava, J., 2014. The rare earth element potential of kaolin deposits in the bohemian massif (Czech Republic, Austria). Mineral. Deposita 49, 967–986.
Holtstam, D., Andersson, U.B., 2007. The ree minerals of the bastnäs-type deposits, South-Central Sweden. Can. Mineral. 45, 1073–1114.
Holtstam, D., Andersson, U.B., Broman, C., Mansfeld, J., 2014. Origin of REE mineralization in the bastnäs-type Fe–REE-(Cu–Mo–bi–Au) deposits, bergslagen, Sweden. Mineral. Deposita 933–966.
Hornig-Kjarsgaard, I., 1998. Rare earth elements in sövitic carbonatites and their mineral phases. J. Petrol. 39, 2105–2121.
Hughes, H.S.R., Goodenough, K.M., Walters, A.S., McCormac, M., Gunn, A.G., Lacinska, A., 2013. The structure and petrology of the cnoc nan cuilean intrusion, loch loyal syenite complex, north-west Scotland. Geol. Mag. 150, 783–800.
Hutchison, M.T., Heaman, L.M., 2008. Chemical and physical characteristics of diamond crystals from garnet lake, Sarfartoq, West Greenland: an association with carbonatitic magmatism. Can. Mineral. 46, 1063–1078.
Hyslop, E.K., Gillanders, R.J., Hill, P.G., Fakes, R.D., 1999. Rare-earth-bearing minerals fergusonite and gadolinite from the Arran granite. Scott. J. Geol. 35, 65–69.
Ihlen, P.M., 1983. Undersøkelse av statens bergrettigheter. Geologiske og petrokjemiske resultater fra diamantboring på Sæteråsen niob-forekomst. NGU report 1800/76B. NGU, Oslo.
Ihlen, P.M., Schiellerup, H., Gautneb, H., Skar, O., 2014. Characterization of apatite resources in Norway and their REE potential — a review. Ore Geol. Rev. 58, 126–147.
Jonsson, E., Stephens, M.B., 2004. Investigation of alkaline rocks in the Prästrun and Åkersjön areas, Jämtland. SGU Report 08/1129/2004.
Jonsson, E., Troll, V.R., Högdahl, K., Harris, C., Weis, F., Nilsson, K.P., Skelton, A., 2013. Magmatic origin of giant 'Kiruna-type' apatite-iron-oxide ores in central Sweden. Sci. Rep. 3.
Jonsson, E., Högdahl, K., Sahlström, F., Nysten, P., Sadeghi, M., 2014. The palaeoproterozoic skarn-hosted ree mineralisations of bastnas-type: overview and mineralogical-geological character. European Rare Earth Resources 2014, Milos, Greece.
Jordens, A., Cheng, Y.P., Waters, K.E., 2013. A review of the beneficiation of rare earth element bearing minerals. Miner. Eng. 41, 97–114.
Kalsbeek, F., Higgins, A.K., Jepsen, H.F., Frei, R., Nutman, A.P., 2008. Granites and granites in the east Greenland caledonides. Geol. Soc. Am. Mem. 202, 227–249.
Keller, J., 1981. Carbonatitic volcanism in the kaiserstuhl alkaline complex: evidence for highly fluid carbonatitic melts at the earth's surface. J. Volcanol. Geotherm. Res. 9, 423–431.
Knudsen, C., 1991. Petrology, Geochemistry, and Economic Geology of the Qaqarssuk Carbonatite Complex, southern West Greenland. Monograph Series of Mineral Deposits 29.
Kogarko, L.N., Williams, C.T., Woolley, A.R., 2002. Chemical evolution and petrogenetic implications of loparite in the layered, agpaitic lovozero complex, Kola Peninsula, Russia. Mineral. Petrol. 74, 1–24.
Kogarko, L.N., Lahaye, Y., Brey, G.P., 2010. Plume-related mantle source of super-large rare metal deposits from the lovozero and khibina massifs on the Kola Peninsula, eastern part of Baltic shield: Sr, Nd and Hf isotope systematics. Mineral. Petrol. 98, 197–208.
Köhler, J., Konnerup-Madsen, J., Markl, G., 2008. Fluid geochemistry in the ivigtut cryolite deposit, south Greenland. Lithos 103, 369–392.
Korja, A., Lahtinen, R., Nironen, M., 2006. The svecofennian orogen: a collage of microcontinents and island arcs. Geol. Soc. Lond. Mem. 32, 561–578.
Kotková, J., Schaltegger, U., Leichmann, J., 2010. Two types of ultrapotassic plutonic rocks in the bohemian massif — coeval intrusions at different crustal levels. Lithos 115, 163–176.
Kraml, M., Pik, R., Rahn, M., Selbekk, R., Carignan, J., Keller, J., 2006. A new multi-mineral age reference material for 40Ar/39Ar, (U–Th)/he and fission track dating methods: the limberg t3 tuff. Geostand. Geoanal. Res. 30, 73–86.
Kresten, P., Åhman, E., Brunfelt, A., 1981. Alkaline ultramafic lamprophyres and associated carbonatite dykes from the kalix area, northern Sweden. Geol. Rundsch. 70, 1215–1231.
Krűger, J.C., Romer, R.L., Kämpf, H., 2013. Late cretaceous ultramafic lamprophyres and carbonatites from the Delitzsch Complex, Germany. Chem. Geol. 353, 140–150.
Krumrei, T.V., Villa, I.M., Marks, M.A.W., Markl, G., 2006. A $^{40}Ar/^{39}Ar$ and U/Pb isotopic study of the Ilímaussaq Complex, south Greenland: implications for the $^{40}K$ decay constant and for the duration of magmatic activity in a peralkaline complex. Chem. Geol. 227, 258–273.
Kusiak, M.A., Dunkley, D.J., Suzuki, K., Kachlík, V., Kędzior, A., Lekki, J., Opluštil, S., 2010. Chemical (non-isotopic) and isotopic dating of Phanerozoic zircon—a case study of durbachite from the třebíč pluton, bohemian massif. Gondwana Res. 17, 153–161.
Kynicky, J., Smith, M.P., Xu, C., 2012. Diversity of rare earth deposits: the key example of China. Elements 8, 361–367.
Lahtinen, R., Garde, A.A., Melezhik, V.A., 2008. Palaeoproterozoic evolution of Fennoscandia and Greenland. Episodes 31, 20–28.
Larsen, L.M., Sørensen, H., 1987. The Ilimaussaq intrusion — progressive crystallization and formation of layering in an agpaitic magma. In: Fitton, J.G., Upton, B.G.J. (Eds.), Alkaline Igneous RocksGeological Society of London Special Publication 30. Geological Society, London, pp. 473–488.
Larsen, M., Piasecki, S., Surlyk, F., 2003. Stratigraphy and sedimentology of a basement-onlapping shallow marine sandstone succession, the Charcot bugt formation, middle–upper Jurassic, east Greenland. Geological Survey of Denmark and Greenland Bulletin 1, pp. 893–930.
Larsen, B.T., Olaussen, S., Sundvoll, B., Heeremans, M., 2008. The permo-carboniferous Oslo rift through six stages and 65 million years. Episodes 31, 52–58.
Lavecchia, G., Boncio, P., 2000. Tectonic setting of the carbonatite–melilitite association of Italy. Mineral. Mag. 64, 583–592.
Lee, M.J., Lee, J.I., Garcia, D., Moutte, J., Williams, C.T., Wall, F., Kim, Y., 2006. Pyrochlore chemistry from the sokli phoscorite–carbonatite complex, Finland: implications for the genesis of phoscorite and carbonatite association. Geochem. J. 40, 1–13.
Li, Z.X., Bogdanova, S.V., Collins, A.S., Davidson, A., De Waele, B., Ernst, R.E., Fitzsimons, I.C.W., Fuck, R.A., Gladkochub, D.P., Jacobs, J., Karlstrom, K.E., Lu, S., Natapov, L.M., Pease, V., Pisarevsky, S.A., Thrane, K., Vernikovsky, V., 2008. Assembly, configuration, and break-up history of rodinia: a synthesis. Precambrian Res. 160, 179–210.
Lie, A., Østergaard, C., 2014. The Fen Rare Earth Element Deposit, Ulefoss, South Norway. 21st North, Svendborg, Denmark.
Macdonald, R., Belkin, H.E., Wall, F., Bagiński, B., 2009. Compositional variation in the chevkinite group: new data from igneous and metamorphic rocks. Mineral. Mag. 73, 777–796.
Macdonald, R., Bagiñski, B., Dzierżanowski, P., Fettes, D.J., Upton, B.G.J., 2013. Chevkinite-group minerals in UK palaeogene granites: underestimated ree-bearing accessory phases. Can. Mineral. 51, 333–347.
Majka, J., Jonsson, E., Högdahl, K., Troll, V.R., Harlov, D.E., Nilsson, K.P., 2013. Textural relations and mineral chemistry of REE in the Grängesberg apatite-iron oxide deposit, Sweden: the role of fluids. In: Jonsson, E. (Ed.), Mineral Deposit Research for a High-Tech World. Society for Geology Applied to Mineral Deposits, pp. 1728–1731.
Maksimovic, Z., Panto, G., 1996. Authigenic rare earth minerals in karst-bauxites and karstic nickel deposits. In: Jones, A.P., Wall, F., Williams, C.T. (Eds.), Rare Earth Minerals: Chemistry, Origin and Ore Deposits. Mineralogical Society, pp. 257–279.
Markl, G., Marks, M.A.W., Schwinn, G., Sommer, H., 2001. Phase equilibrium constraints on intensive crystallization parameters of the Ilímaussaq Complex, south Greenland. J. Petrol. 42, 2231–2257.

Marks, M.A.W., Hettmann, K., Schilling, J., Frost, B.R., Markl, G., 2011. The mineralogical diversity of alkaline igneous rocks: critical factors for the transition from miaskitic to agpaitic phase assemblages. J. Petrol. 52, 439–455.

Marzoli, A., Renne, P.R., Piccirillo, E.M., Ernesto, M., Bellieni, G., Min, A.D., 1999. Extensive 200-million-year-old continental flood basalts of the central Atlantic magmatic province. Science 284, 616–618.

Massari, S., Ruberti, M., 2013. Rare earth elements as critical raw materials: focus on international markets and future strategies. Resour. Policy 38, 36–43.

McCreath, J.A., Finch, A.A., Simonsen, S.L., Donaldson, C.H., Armour-Brown, A., 2012. Independent ages of magmatic and hydrothermal activity in alkaline igneous rocks: the motzfeldt Centre, gardar province, south Greenland. Contrib. Mineral. Petrol. 163, 967–982.

McKerrow, W.S., Mac Niocaill, C., Dewey, J.F., 2000. The Caledonian orogeny redefined. J. Geol. Soc. 157, 1149–1154.

Meert, J.G., Torsvik, T.H., Eide, E.A., Dahlgren, S., 1998. Tectonic significance of the fen province, S. Norway: constraints from geochronology and paleomagnetism. J. Geol. 106, 553–564.

Meert, J.G., Walderhaug, H.J., Torsvik, T.H., Hendriks, B.W.H., 2007. Age and paleomagnetic signature of the alnø carbonatite complex (NE Sweden): additional controversy for the Neoproterozoic paleoposition of baltica. Precambrian Res. 154, 159–174.

Miller, R.R., Heaman, L.M., Birkett, T.C., 1997. U–Pb zircon age of the strange lake peralkaline complex: implications for Mesoproterozoic peralkaline magmatism in north-central Labrador. Precambrian Res. 81, 67–82.

Milodowski, A.E., Zalasiewicz, J.A., 1991. Redistribution of rare earth elements during diagenesis of turbidite/hemipelagite mudrock sequences of Llandovery age from central wales. Geol. Soc. Lond., Spec. Publ. 57, 101–124.

Miranda, R., Valdares, V., Terrinha, P., Mata, J., Azevedo, M., Gaspar, M., Kullberg, J.C., Ribeiro, C., 2009. Age constraints on the late cretaceous alkaline magmatism on the west Iberian margin. Cretac. Res. 30, 575–586.

Moles, N.R., Tindle, A.G., 2011. Alluvial occurrences of fergusonite and gadolinite in the mourne mountains, Northern Ireland. J. Russell Soc. 14, 1–3.

Mongelli, G., Paternoster, M., Rizzo, G., Sansone, M.T.C., Sinisi, R., 2013. Trace element geochemistry of the Mt vulture carbonatites, southern Italy. Int. Geol. Rev. 55, 1541–1552.

Montero, P., Floor, P., Corretge, G., 1998. The accumulation of rare-earth and high-field-strength elements in peralkaline granitic rocks; the Galineiro Orthogneissic Complex, Northwestern Spain. Can. Mineral. 36, 683–700.

Montero, P., Bea, F., Corretgé, L.G., Floor, P., Whitehouse, M.J., 2009. U–Pb ion microprobe dating and Sr and Nd isotope geology of the galiñeiro igneous complex: a model for the peraluminous/peralkaline duality of the cambro-ordovician magmatism of Iberia. Lithos 107, 227–238.

Morogan, V., 1989. Mass transfer and REE mobility during fenitization at alnö, Sweden. Contrib. Mineral. Petrol. 103, 25–34.

Morogan, V., Woolley, A., 1988. Fenitization at the alnö carbonatite complex, Sweden; distribution, mineralogy and genesis. Contrib. Mineral. Petrol. 100, 169–182.

Morogan, V., Upton, B.G.J., Fitton, J.G., 2000. The petrology of the ditrau alkaline complex, eastern Carpathians. Mineral. Petrol. 69, 227–265.

Müller, A., 2010. Potential for rare earth element and Zr-, Be-, U-, Th-, (W-) mineralisations in central and northern Nordland. NGU Report 2009.037.

Müller, A., Ihlen, P.M., Kronz, A., 2008. Quartz chemistry in polygeneration sveconorwegian pegmatites, froland, Norway. Eur. J. Mineral. 20, 447–463.

Nance, R.D., Gutiérrez-Alonso, G., Keppie, J.D., Linnemann, U., Murphy, J.B., Quesada, C., Strachan, R.A., Woodcock, N.H., 2010. Evolution of the Rheic Ocean. Gondwana Res. 17, 194–222.

Neumann, E.-R., Olsen, K.H., Baldridge, W.S., Sundvoll, B., 1992. The Oslo rift: a review. Tectonophysics 208, 1–18.

Neumann, E.-R., Wilson, M., Heeremans, M., Spencer, E.A., Obst, K., Timmerman, M.J., Kirstein, L., 2004. Carboniferous–Permian rifting and magmatism in southern Scandinavia, the North Sea and northern Germany: a review. In: Wilson, M., Neumann, E.-R., Davies, G.R., Timmerman, M.J., Heeremans, M., Larsen, B.T. (Eds.), Permo-Carboniferous Magmatism and Rifting in EuropeGeological Society of London Special Publication 223. Geological Society, London, pp. 11–40.

Nielsen, T.F.D., 1980. The petrology of a melilitolite, melteigite, carbonatite and syenite ring dike system, in the Gardiner complex, east Greenland. Lithos 13, 181–197.

Nikiforov, A.V., Öztürk, H., Altuncu, S., Lebedev, V.A., 2014. Kizilcaören ore-bearing complex with carbonatites (northwestern Anatolia, Turkey): formation time and mineralogy of rocks. Geol. Ore Deposits 56, 35–60.

Nutman, A.P., Rosing, M.T., 1994. SHRIMP U–Pb zircon geochronology of the late Archaean ruinnæsset syenite, skjoldungen alkaline province, southeast Greenland. Geochim. Cosmochim. Acta 58, 3515–3518.

Ondrejka, M., Uher, P., Pršek, J., Ozdín, D., 2007. Arsenian monazite-(Ce) and xenotime-(Y), REE arsenates and carbonates from the Tisovec-Rejkovo rhyolite, Western Carpathians, Slovakia: composition and substitutions in the (REE,Y)XO4 system (X = P, As, Si, Nb, S). Lithos 95, 116–129.

Orris, G.J., Grauch, R.I., 2002. Rare earth element mines, deposits and occurrences. US Geological Survey Open File Report 02-189.

Ozgenc, I., 1999. Carbonatite-hosted fluorite and britholite mineralisation at Sofular area, Malatya, Turkey. In: Stanley, C.J. (Ed.), Mineral Deposits: Processes to Processing. Balkema, Rotterdam, pp. 663–666.

Ozgenc, I., Ilbeyli, N., 2009. Geochemical constraints on petrogenesis of late cretaceous alkaline magmatism in east-central Anatolia (hasancelebi–basören, Malatya), Turkey. Mineral. Petrol. 95, 71–85.

Özlü, N., 1983. Trace-element content of "karst bauxites" and their parent rocks in the Mediterranean belt. Mineral. Deposita 18, 469–476.

Pearce, N.J.G., Leng, M.J., Emeleus, C.H., Bedford, C.M., 1997. The origins of carbonatites and related rocks from the gronnedal-Ika nepheline syenite complex, south Greenland; C–O–Sr isotope evidence. Mineral. Mag. 61, 515–529.

Pfaff, K., Krumrei, T., Marks, M., Wenzel, T., Rudolf, T., Markl, G., 2008. Chemical and physical evolution of the 'lower layered sequence' from the nepheline syenitic ilímaussaq intrusion, south Greenland: implications for the origin of magmatic layering in peralkaline felsic liquids. Lithos 106, 280–296.

Pin, C., Kryza, R., Oberc-Dziedzic, T., Mazur, S., Turniak, K., Waldhausrová, J., 2007. The diversity and geodynamic significance of late Cambrian (ca. 500 Ma) felsic anorogenic magmatism in the northern part of the bohemian massif: a review based on Sm–Nd isotope and geochemical data. Geol. Soc. Am. Spec. Pap. 423, 209–229.

Platevoet, B., Elitok, Ö., Guillou, H., Bardintzeff, J.-M., Yagmurlu, F., Nomade, S., Poisson, A., Deniel, C., Özgür, N., 2014. Petrology of quaternary volcanic rocks and related plutonic xenoliths from gölcük volcano, Isparta angle, Turkey: origin and evolution of the high-K alkaline series. J. Asian Earth Sci. 92, 53–76.

Reed, G.C., 2013. Amended and Restated Technical Report for Olserum REE deposit, southern Sweden. Tasman Metals, Vancouver.

Riley, T. R., Bailey, D. K., Harmer, R. E., Liebsch, H., Lloyd, F. E., Palmer, M. R., 1999. Isotopic and geochemical investigation of a carbonatite–syenite–phonolite diatreme, west Eifel (Germany). Mineral. Mag. 63, 615–615.

Roberts, N.M.W., 2013. The boring billion? — lid tectonics, continental growth and environmental change associated with the Columbia supercontinent. Geosci. Front. 4, 681–691.

Roberts, R.J., Corfu, F., Torsvik, T.H., Hetherington, C.J., Ashwal, L.D., 2010. Age of alkaline rocks in the seiland igneous province, northern Norway. J. Geol. Soc. 167, 71–81.

Romer, R.L., Smeds, S.-A., 1996. U–Pb columbite ages of pegmatites from sveconorwegian terranes in southwestern Sweden. Precambrian Res. 76, 15–30.

Romer, R.L., Kjosnes, B., Korneliussen, A., Lindahl, I., Skyseth, M., Sundvoll, B., 1992. The Archaean–Proterozoic boundary beneath the Caledonides of northern Norway and Sweden: U–Pb, Rb–Sr and epsNd isotope data from the Rombak–Tysfjord area. NGU rapport 91.

Rosatelli, G., Stoppa, F., Jones, A.P., 2000. Intrusive calcite-carbonatite occurrence from Mt. Vulture volcano, southern Italy. Mineral. Mag. 64, 615–624.

Rudnick, R.L., Gao, S., 2004. Composition of the continental crust. In: Rudnick, R.L. (Ed.), The CrustTreatise on Geochemistry Volume 3. Elsevier-Pergamon, Oxford, pp. 1–64.

Rukhlov, A.S., Bell, K., 2010. Geochronology of carbonatites from the Canadian and Baltic shields, and the Canadian cordillera: clues to mantle evolution. Mineral. Petrol. 98, 11–54.

Salvi, S., Williams-Jones, A.E., 2006. Alteration, HFSE mineralisation and hydrocarbon formation in peralkaline igneous systems: insights from the strange lake pluton, Canada. Lithos 91, 19–34.

Sánchez-García, T., Bellido, F., Quesada, C., 2003. Geodynamic setting and geochemical signatures of Cambrian–Ordovician rift-related igneous rocks (ossa-morena zone, SW Iberia). Tectonophysics 365, 233–255.

Sánchez-García, T., Bellido, F., Pereira, M.F., Chichorro, M., Quesada, C., Pin, C., Silva, J.B., 2010. Rift-related volcanism predating the birth of the Rheic Ocean (Ossa-Morena zone, SW Iberia). Gondwana Res. 17, 392–407.

Sarapää, O., Al Ani, T., Lahti, S.I., Lauri, L.S., Sarala, P., Torppa, A., Kontinen, A., 2013. Rare earth exploration potential in Finland. J. Geochem. Explor. 133, 25–41.

Saunders, A.D., Fitton, J.G., Kerr, A.C., Norry, M.J., Kent, R.W., 2013. The North Atlantic Igneous Province. Large Igneous Provinces: Continental, Oceanic, and Planetary Flood Volcanism. American Geophysical Union, pp. 45–93.

Schilling, J., Marks, M.A.W., Wenzel, T., Vennemann, T., Horváth, L., Tarassoff, P., Jacob, D.E., Markl, G., 2011. The magmatic to hydrothermal evolution of the intrusive Mont saint-hilaire complex: insights into the late-stage evolution of peralkaline rocks. J. Petrol. 52, 2147–2185.

Schmitt, A.K., Wetzel, F., Cooper, K.M., Zou, H., Wörner, G., 2010. Magmatic longevity of Laacher See Volcano (Eifel, Germany) indicated by U–Th dating of intrusive carbonatites. J. Petrol.

Schulmann, K., Konopásek, J., Janoušek, V., Lexa, O., Lardeaux, J.-M., Edel, J.-B., Štípská, P., Ulrich, S., 2009. An Andean type palaeozoic convergence in the bohemian massif. Compt. Rendus Geosci. 341, 266–286.

Secher, K., Larsen, L.M., 1980. Geology and mineralogy of the sarfartôq carbonatite complex, southern west Greenland. Lithos 13, 199–212.

Secher, K., Heaman, L.M., Nielsen, T.F.D., Jensen, S.M., Schjoth, F., Creaser, R.A., 2009. Timing of kimberlite, carbonatite, and ultramafic lamprophyre emplacement in the alkaline province located 64°–67° N in southern west Greenland. Lithos 112, 400–406.

Seifert, W., Kämpf, H., Wasternack, J., 2000. Compositional variation in apatite, phlogopite and other accessory minerals of the ultramafic delitzsch complex, Germany: implication for cooling history of carbonatites. Lithos 53, 81–100.

Sheard, E.R., Williams-Jones, A.E., Heiligmann, M., Pederson, C., Trueman, D.L., 2012. Controls on the concentration of zirconium, niobium, and the rare earth elements in the Thor lake rare metal deposit, Northwest Territories, Canada. Econ. Geol. 107, 81–104.

Short, M., Apelt, T., Moseley, G., Mounde, M., La Touche, G.D., 2015. Amended & Restated Prefeasibility Study — NI 43-101 — Technical report for the Norra Kärr Rare Earth Element Deposit. GBM Minerals Engineering Consultants Ltd.

Sindern, S., Kramm, U., 2000. Volume characteristics and element transfer of fenite aureoles: a case study from the iivaara alkaline complex, Finland. Lithos 51, 75–93.

Sjöqvist, A.S.L., Cornell, D.H., Andersen, T., Erambert, M., Ek, M., Leijd, M., 2013. Three compositional varieties of rare-earth element ore: eudialyte-group minerals from the norra kärr alkaline complex, southern Sweden. Minerals 3, 94–120.

Škoda, R., Novák, M., 2007. Y,REE,Nb,Ta,Ti-oxide (AB2O6) minerals from REL–REE euxenite-subtype pegmatites of the Třebíč Pluton, Czech Republic; substitutions and fractionation trends. Lithos 95, 43–57.

Slagstad, T., Roberts, N.M.W., Marker, M., Røhr, T.S., Schiellerup, H., 2013. A non-collisional, accretionary sveconorwegian orogen. Terra Nova 25, 30–37.
Smith, M.P., Storey, C.D., Jeffries, T.E., Ryan, C., 2009. In situ U–Pb andTrace element analysis of accessory minerals in the Kiruna district, Norrbotten, Sweden: new constraints on the timing and origin of mineralization. J. Petrol. 50, 2063–2094.
Söderlund, U., Ask, R., 2006. Mesoproterozoic bimodal magmatism along the protogine zone, S Sweden: three magmatic pulses at 1.56, 1.22 and 1.205 Ga, and regional implications. GFF 128, 303–310.
Solé, J., Pi, T., Enrique, P., 2003. New geochronological data on the late cretaceous alkaline magmatism of the northeast Iberian Peninsula. Cretac. Res. 24, 135–140.
Sørensen, H., 1992. Agpaitic nepheline syenites: a potential source of rare elements. Appl. Geochem. 7, 417–427.
Sørensen, H., 1997. The agpaitic rocks; an overview. Mineral. Mag. 61, 485–498.
Sørensen, H., 2006. The Ilimaussaq Alkaline Complex, South Greenland — an Overview of 200 years of Research and an Outlook, Copenhagen. The Commission for Scientific Research in Greenland.
Sørensen, H., Bailey, J.C., Rose-Hansen, J., 2011. The emplacement and crystallization of the U–Th–REE rich agpaitic and hyperagpaitic lujavrites at kvanefjeld, ilímaussaq alkaline complex, south Greenland. Bull. Geol. Soc. Den. 59, 69–92.
Stampfli, G.M., 2000. Tethyan oceans. Geol. Soc. Lond., Spec. Publ. 173, 1–23.
Stoppa, F., Woolley, A.R., 1997. The Italian carbonatites: field occurrence, petrology and regional significance. Mineral. Petrol. 59, 43–67.
Svenningsen, O.M., 2001. Onset of seafloor spreading in the Iapetus Ocean at 608 Ma: precise age of the sarek dyke swarm, northern Swedish caledonides. Precambrian Res. 110, 241–254.
Tappe, S., Steenfelt, A., Heaman, L.M., Simonetti, A., 2009. The newly discovered Jurassic tikiusaaq carbonatite–aillikite occurrence, west Greenland, and some remarks on carbonatite–kimberlite relationships. Lithos 112, 385–399.
Tegner, C., Brooks, C.K., Duncan, R.A., Heister, L.E., Bernstein, S., 2008. $^{40}$Ar–$^{39}$Ar ages of intrusions in east Greenland: rift-to-drift transition over the Iceland hotspot. Lithos 101, 480–500.
Thrane, K., Kalvig, P., Keulen, N., 2014. REE deposits and occurrences in Greenland. ERES2014: 1st European Rare Earth Resources Conference, Milos, Greece.
Tichomirowa, M., Grosche, G., Gotze, J., Belyatsky, B.V., Savva, E.V., Keller, J., Todt, W., 2006. The mineral isotope composition of two Precambrian carbonatite complexes from the kola alkaline province — alteration versus primary magmatic signatures. Lithos 91, 229–249.
Timmerman, M.J., 2004. Timing, geodynamic setting and character of permo-carboniferous magmatism in the foreland of the variscan orogen, NW Europe. Geol. Soc. Lond., Spec. Publ. 223, 41–74.
Tuduri, J., Chevillard, M., Colin, S., Gloaguen, E., Gouin, J., Potel, S., Pourret, O., 2013. Formation of monazite-(MREE) from Paleozoic shales: role of host rock chemical composition and organic material. Mineral. Mag. 77, 2362.
Tuer, J., 2011. Hudson Resources Reports Significant Rare Earth Mineral Resource Estimate at Sarfartoq [online], Hudson Resources (Available: http://www.hudsonresources.ca/home.asp [Accessed Jan 2015).
Tuer, J., 2012. Hudson Resources Reports Updated Mineral Resource: Significant Grade Increases and Indicated Resources Confirmed [online], Hudson Resources (Available: http://www.hudsonresources.ca/home.asp [Accessed Jan 2015).
Tukiainen, T., 1988. Niobium–tantalum mineralisation in the Motzfeldt Centre of the Igaliko Nepheline Syenite Complex, South Greenland. In: Boissonnas, J., Omenetto, P. (Eds.), Mineral Deposits Within the European Community. Springer-Verlag, Berlin Heidelberg, pp. 230–246.
Tukiainen, T., 2014. The Motzfeldt Centre of the Igaliko Nepheline Syenite Complex, South Greenland — a major resource of REE. ERES2014: 1st European Rare Earth Resources Conference, Milos, Greece.
Tyni, M., Puustinen, K., Karhu, J., Vaasjoki, M., 2003. The Petaiskoski carbonate veins at Juuka, eastern Finland. Special Paper—Geological Survey Of Finland, pp. 13–16.
Ulrych, J., Dostal, J., Adamovič, J., Jelínek, E., Špaček, P., Hegner, E., Balogh, K., 2011. Recurrent Cenozoic volcanic activity in the bohemian massif (Czech Republic). Lithos 123, 133–144.
Upton, B.G.J., 2013. Tectono-Magmatic Evolution of the Younger Gardar Southern Rift, South Greenland, Copenhagen. Geological Survey of Denmark and Greenland.
Upton, B.G.J., Emeleus, C.H., 1987. Mid-Proterozoic alkaline magmatism in southern Greenland: the gardar province. Geol. Soc. Lond., Spec. Publ. 30, 449–471.
Upton, B.G.J., Emeleus, C.H., Heaman, L.M., Goodenough, K.M., Finch, A.A., 2003. Magmatism of the mid-Proterozoic gardar province, south Greenland: chronology, petrogenesis and geological setting. Lithos 68, 43–65.
Vartiainen, H., Paarma, H., 1979. Geological characteristics of the sokli carbonatite complex, Finland. Econ. Geol. 74, 1296–1306.
Wall, F., 2014. Rare earth elements. In: Gunn, A.G. (Ed.), Critical Metals Handbook. John Wiley & Sons, pp. 312–339.
Wall, F., Mariano, A.N., 1996. Rare earth minerals in carbonatites: a discussion centred on the Kangankunde Carbonatite, Malawi. In: Jones, A.P., Wall, F., Williams, C.T. (Eds.), Rare Earth Minerals: Chemistry, Origin and Ore Deposits. Chapman and Hall, pp. 193–226.
Walters, A.S., Goodenough, K.M., Hughes, H.S.R., Roberts, N.M.W., Gunn, A.G., Rushton, J., Lacinska, A., 2013. Enrichment of rare earth elements during magmatic and post-magmatic processes: a case study from the loch loyal syenite complex, northern Scotland. Contrib. Mineral. Petrol. 166, 1177–1202.
Wang, L.-X., Marks, M.A.W., Wenzel, T., Von Der Handt, A., Keller, J., Teiber, H., Markl, G., 2014. Apatites from the Kaiserstuhl Volcanic Complex, Germany: new constraints on the relationship between carbonatite and associated silicate rocks. Eur. J. Mineral.
Weeks, M.E., 1932. The discovery of the elements. XVI. The rare earth elements. J. Chem. Educ. 9, 1751.
Weisenberger, T., Spürgin, S., Lahaye, Y., 2014. Hydrothermal alteration and zeolitization of the fohberg phonolite, Kaiserstuhl Volcanic Complex, Germany. Int. J. Earth Sci. 103, 2273–2300.
Wilberg, R., 1987. Granitophile elements in granitoid rocks in the Precambrian basement windows in Nordland, Northern Norway, with special reference to the rare-element enriched gneiss at Bordvedåga, Høgtuva window. Norges geologiske undersøkelse report 87.043.
Williams-Jones, A.E., Migdisov, A.A., Samson, I.M., 2012. Hydrothermal mobilisation of the rare earth elements — a tale of "ceria" and "yttria". Elements 8, 355–360.
Wilson, M., Downes, H., 2006. Tertiary–Quaternary intra-plate magmatism in Europe and its relationship to mantle dynamics. In: Gee, D.G., Stephenson, R.A. (Eds.), European Lithosphere DynamicsGeological Society of London Memoir 32. Geological Society of London, London.
Wilson, M., Neumann, E.-R., Davies, G.R., Timmerman, M.J., Heeremans, M., Larsen, B.T., 2004. Permo-Carboniferous magmatism and rifting in Europe: introduction. In: Wilson, M., Neumann, E.-R., Davies, G.R., Timmerman, M.J., Heeremans, M., Larsen, B.T. (Eds.), Permo-Carboniferous Magmatism and Rifting in EuropeGeological Society of London Special Publication 223. Geological Society of London, London.
Woodard, J., Hetherington, C.J., 2014. Carbonatite in a post-collisional tectonic setting: geochronology and emplacement conditions at naantali, SW Finland. Precambrian Res. 240, 94–107.
Woolley, A.R., Church, A.A., 2005. Extrusive carbonatites: a brief review. Lithos 85, 1–14.
Wübbeke, J., 2013. Rare earth elements in China: policies and narratives of reinventing an industry. Resour. Policy 38, 384–394.
Zhao, G., Cawood, P.A., Wilde, S.A., Sun, M., 2002. Review of global 2.1–1.8 Ga orogens: implications for a pre-rodinia supercontinent. Earth Sci. Rev. 59, 125–162.
Zhao, G., Sun, M., Wilde, S.A., Li, S., 2004. A Paleo–Mesoproterozoic supercontinent: assembly, growth and breakup. Earth Sci. Rev. 67, 91–123.