

UNLOCKING THE POTENTIAL OF RARE EARTH RESOURCES IN EUROPE

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Abstract

During the last decade the non-energy raw materials have become part of the EU's new industrial strategy and growth agenda, with increased funding opportunities in the field of mineral resources. The four-year (2009–2013) ProMine project has provided a well documented knowledge base of Europe's non-energy raw material resource potential. The ongoing EURARE project is focused on enhancing the value chain perspectives for European Rare Earth Elements (REE) and the Minerals 4EU project aims to provide harmonized data on European mineral resources.

This paper summarises ongoing work by the EURARE project (www.eurare.eu). REE mineral potential belts, including genetic types related to igneous, hydrothermal and sedimentary processes, have been identified across Europe. Potential REE deposits are hosted by carbonatites, alkaline igneous complexes and volcanic successions, granitic pegmatites, iron oxide copper gold deposits, and skarns, as well as secondary deposits such as laterites, bauxites and heavy mineral sands.

This paper considers issues of the various deposit types with respect to REE-bearing minerals, grades, volumes, Heavy (HREE) to Light REE (LREE) ratios, radioactive element concentrations, genetic aspects, all in a perspective of raising the awareness for exploration and the potential for exploitation.

Introduction

The European Union (EU) is highly dependent on imports of mineral raw materials that are crucial for a strong European industrial base, sustainable and competitive growth, and a thriving society. A specific group of minerals and metals are characterized as critical raw materials, because they are considered to have significant economic importance for the EU but have clear risks to their supply (1). All the rare earth elements (REE) belong within this group because of their importance in electronics and green technologies, and the dominance of China in their production. For several metals used in electronics and green technology industries, including the REE and platinum group elements, the EU completely relies on imports. The resulting annual shortage is about €11 billion, of which 90% corresponds to metallic minerals, particularly those of major high-tech applications. Recycling of metal scrap represents around 40% to 60% of the input to the EU's metal production, according to industry estimates.

Rare Earth Elements (REE) is the collective name for 17 chemically similar metallic elements (the lanthanides, scandium and yttrium) that occur together in a wide range of minerals and are mined collectively. They are usually divided into the light REE (LREE) and the heavy REE (HREE); the latter are found in relatively lower concentrations in the Earth's crust. China today

controls about 95 % of the world's REE production, making the supply of these elements for European industry highly vulnerable (2).

At the same time, Europe's mineral potential is under-explored, both with regard to the subsurface (particularly deeper than 150 metres), and the sea-bed in the EU member states' exclusive economic zones. Major opportunities for access to raw materials exist within the EU today, especially for mining at greater depths or in small deposits. The sea-bed could also contain valuable raw materials, including REE deposits, leading to growing world-wide competition for marine mineral deposits. More intense and advanced exploration for REE mineral deposits on land and in the marine environment is therefore needed, and seafloor mineral resources are the subject of growing European interest.

This paper aims to provide an overview of different REE mineral deposit types in Europe, and to provide a basis for further research into the mineralizing processes causing REE enrichments, and controlling the formation of feasible grades and volumes. It intends also to deliver some preliminary guides for exploration and exploitation potential.

Available datasets

Mineral occurrence databases exist for most countries, but they typically lack full information on REE resources, and very rarely include quantitative estimates of the resource size or how likely it is to go into production. This paper summarises the information that is available from a number of projects carried out under various EU funding schemes and commissioned studies (Fig.1), as follows:

- ProMine (<http://promine.gtk.fi>) has produced a pan-European primary mineral occurrence database and anthropogenic concentration (mainly mining wastes) database, which also contains REE information (3,4). About 270 REE occurrences were recorded. However this database does not provide information on size of occurrence or on ratio of LREE to HREE.
- EuroGeoSource (<http://www.eurogeosource.eu>) has collected mineral resource information, but only REE occurrences in Greenland are present.
- EuRare (<http://www.eurare.eu>) aims to set the basis for the development of a European rare earth element (REE) industry by safeguarding the uninterrupted supply of REE raw materials and products crucial for sectors of the EU economy. It will define and assess all exploitable REE mineral resources and REE demand in Europe (Appendix I), and develop an **Integrated Knowledge Management System (IKMS)** for EU REE resources, which will provide information on REE and build up the knowledge to be developed within the frame of the project.
- Minerals4EU (<http://www.minerals4eu.eu/>) will include the development of an EU Minerals Knowledge Base Platform that goes along and in line with the Strategic Implementation Plan for European Innovation Partnership on Raw Materials, and a Minerals Yearbook that will include resource and reserve data for primary minerals. Publication is anticipated in 2015.

- Production statistic data are compiled on a yearly basis by British Geological Survey (BGS) staff (<https://www.bgs.ac.uk/mineralsuk/statistics/europeanStatistics.html>). The numbers are based on data that are obtained from the national statistical agencies or geological surveys within the individual countries. These data are usually easily obtainable since companies are being taxed according to the actual production, and therefore obligations exist in most countries to report such information to the public authorities.

European geology and metallogeny

The geological evolution of Europe extends over some 3.8 billion years of Earth history. The oldest rocks in Europe are found in the Archaean cratons of Greenland, the UK, and the Scandinavian countries, whilst the youngest Cenozoic rocks are formed along the Mediterranean and Atlantic fringes. The rocks of Europe have been affected by a large number of orogenic events, such as the Svecofenian and Caledonian orogenies in the north and the Variscan and Alpine ones in central and southern Europe. These generated various types and grades of deformation and metamorphism, associated with a range of compositions and volumes of magmatic lithologies emplaced into widely varying tectonomagmatic settings. Metallogenic evolution throughout this period resulted in emplacement of several major mineral belts, such as the Fennoscandian VMS, IOCG and Iron Oxide deposits, the Iberian Pyrite belt, and the porphyry Cu and epithermal Au Carpathian-Balkan belt (3). Years of research have led to a good understanding of base and precious metal, copper, nickel and iron occurrences, but the genetic processes related to REE mineralisation are not as well understood. The importance of understanding tectonic setting in REE exploration is developed further by Goodenough et al. (this volume).

Primary resources: proposed genetic type classification

The majority of significant primary REE resources in Europe are in alkaline igneous rocks and carbonatites, and the most important deposits occur in extensional rift-related igneous provinces of a range of ages (Goodenough et al., this volume). In Northern Europe, these igneous provinces are deeply eroded and the major deposits lie within plutonic silicate and carbonatite igneous rocks, such as the spectacularly layered peralkaline syenites of the Ilimaussaq intrusion in southwest Greenland (Kringlerne and Kvanefjeld deposits; 5) or the Norra Kärr syenite in Sweden (6). Also of importance across Europe, but most particularly in Sweden, are zones of hydrothermal and pegmatite mineralization. In many cases the source of the REE in these mineralizing systems is not well understood. Each primary deposit has a different, commonly very complex, ore mineralogy and many REE-bearing minerals also have high contents of U and Th. For this reason, each deposit presents its own challenges in processing, and a range of factors will affect the economic and environmental case for the deposit.

In Southern Europe, the rift-related provinces are at much shallower levels of erosion, and the surface expression of alkaline magmatism is in alkaline volcanic rocks that do not contain significant REE concentrations. In these areas, secondary deposits formed by weathering (bauxites and laterites) and sedimentary processes are more important. It is likely that primary REE deposits remain to be discovered at depth within these rift zones.

Classification systems currently used by BGS, USGS and in Australia, as well as modified versions developed and applied in the ProMine, ASTER (7) and EuroGeoSource projects, have been evaluated, integrated and adjusted to fit the geological setting, metallogenetic evolution and mineral belts in Europe, as part of the EURARE project. Taking into account the INSPIRE Mineral Deposit Group and Mineral Deposit Type code lists, a simplified genetic classification approach (host rock type, mineral forming processes and composition, and LREE and HREE concentration and distribution) is applied, dividing REE mineralisations/deposits into two main categories:

- Primary deposits (Fig.1) linked to magmatic and hydrothermal REE-mineral forming processes :
 - Carbonatites (LREE-enriched deposits with bastnäsite, allanite, apatite and monazite as the main minerals e.g. Fen in Norway, Sökli in Finland (8), Sarfartoq and Qaqarssuk (9) in west Greenland)
 - Alkaline-peralkaline igneous rocks (LREE- or HREE-enriched deposits with apatite, eudialyte, gadolinite and loparite among the main minerals e.g. Norra Kärr in Sweden (6), Katajakangas in Finland, Kvanefjeld and Kringlerne in south Greenland). This deposit type includes the largest resources known in Europe at present.
 - Iron Oxide Apatite (IOA) and Iron Oxide Copper Gold (IOCG) deposits (usually LREE-enriched with apatite and/or allanite e.g. Kiruna magnetite-apatite deposits (10) in Sweden)
 - Granitic pegmatites (ranging from LREE-enriched, containing allanite and monazite, to HREE-enriched with gadolinite as main mineral e.g. Ytterby mineralisation in Sweden, Evje-lveland pegmatite district in Norway)
 - Hydrothermal/hydrogenetic (mainly LREE-enriched and varying grades, with bastnäsite, allanite, monazite, gadolinite and parisite as common minerals e.g. Bastnäs-Norberg-Nora (11) skarn mineralisation zone in Sweden)
 - Sedimentary concentrations on land and in the marine (12) environment (e.g. LREE-enriched in U-deposits, fluorite-barite mineralisations, with disseminations of synchysite and parisite, phosphates in NW Greece on land, and REE mineralisations associated with deep sea-floor polymetallic nodules and cobalt-rich crusts)
- Secondary deposits (Fig.1) related mainly to sedimentary remobilization and weathering processes of mainly REE-bearing igneous rocks:
 - Placers, of paleo-, marine and alluvial affiliation (commonly LREE and U-Th enriched, with monazite, xenotime, allanite as common minerals, e.g. Nea Peramos coastal heavy sands in northern Greece, Klocktorpet and Tåsjö paleoplacer apatite mineralisations in Sweden)
 - Residual-lateritic/bauxitic (usually LREE-enriched, high-graded and monazitic e.g. central Greece monazite-bastnäsite lateritic/bauxitic mineralisations),

- Ion-adsorption clays/residual clays (HREE-enriched, commonly low-grade high-volume, associated with weathered REE-bearing granites, with REE being adsorbed by clay minerals such as kaolin and halloysite).

Secondary resources

Secondary resources are those not directly derived from natural REE occurrences, but rather from material that has already been used by humans. Mining wastes, including various waste streams such as weakly mineralized waste rocks, processing tailings and metallurgical residues, could turn out to be potential resources for recovery of exploitable grades of REE. The abandoned historical mine waste dumps in Bastnäs district and the stockpiled apatite leftovers in Kiruna, both in Sweden, as well as the red mud residues of Al smelting in Greece and elsewhere in Europe (Deady et al., this volume), are prominent examples of raw materials that might be secondary resources of REE. Recycling of material from the consumer electronics industries represents another source of the REE (2). However, in spite of the fact that recycling is a vital component of a resource efficient economy and a long-term target to secure REE supply, the EU will still be very much dependent on primary mineral resources extraction for the foreseeable future.

Exploration data availability

There have been several national-based geochemical surveys that have carried out soil, bedrock and stream sediment sampling across Europe. Many EU member states have produced geochemical maps for varying subsets of the REE on national and regional scales. However this information, although very valuable in regional-scale REE exploration campaigns, is rather variable and fragmented, and requires much harmonization before Europe-wide REE mineralised belts can be recognised. Projects reporting data and delivering pan-European geochemical maps include FOREGS (13,) and GEMAS (<http://www.eurogeosurveys.org/projects/gemas/>), carried out by the EuroGeoSurveys Geochemistry Expert Group, the latter based on sampling of agricultural and grazing land soils (14, 15, and 16).

Geophysical measurements applying airborne and ground magnetic, electromagnetic and gravimetric methods have been conducted across Europe on national and regional scales. They may provide valuable data and offer efficient REE exploration tools at a range of scales, but this is based more on the interpretation of the responses and signatures received from the wall and host rocks of the mineralisation rather than the REE mineralisation itself. As yet there is limited information to show how interpretation of geophysical data may be better used to pinpoint REE mineralization.

Preliminary recommendations

Economic aspects

There are some advanced REE projects listed on Table I, providing an overview of developments taking place in Europe. Economically feasible projects in Europe are progressing in Sweden (Norra Kärr) and Greenland (Kringlerne and Kvanefjeld) with a total potential (resources and reserves) of all three together in the order of 30 million tonnes REO.

The trend in Europe is the same as in the rest of the world since 1960s, showing that REE mining projects are mainly related to primary deposit types associated with carbonatites and alkaline igneous rocks, compared to prior to 1950 when most bulk REE production was derived from monazite-bearing placers.

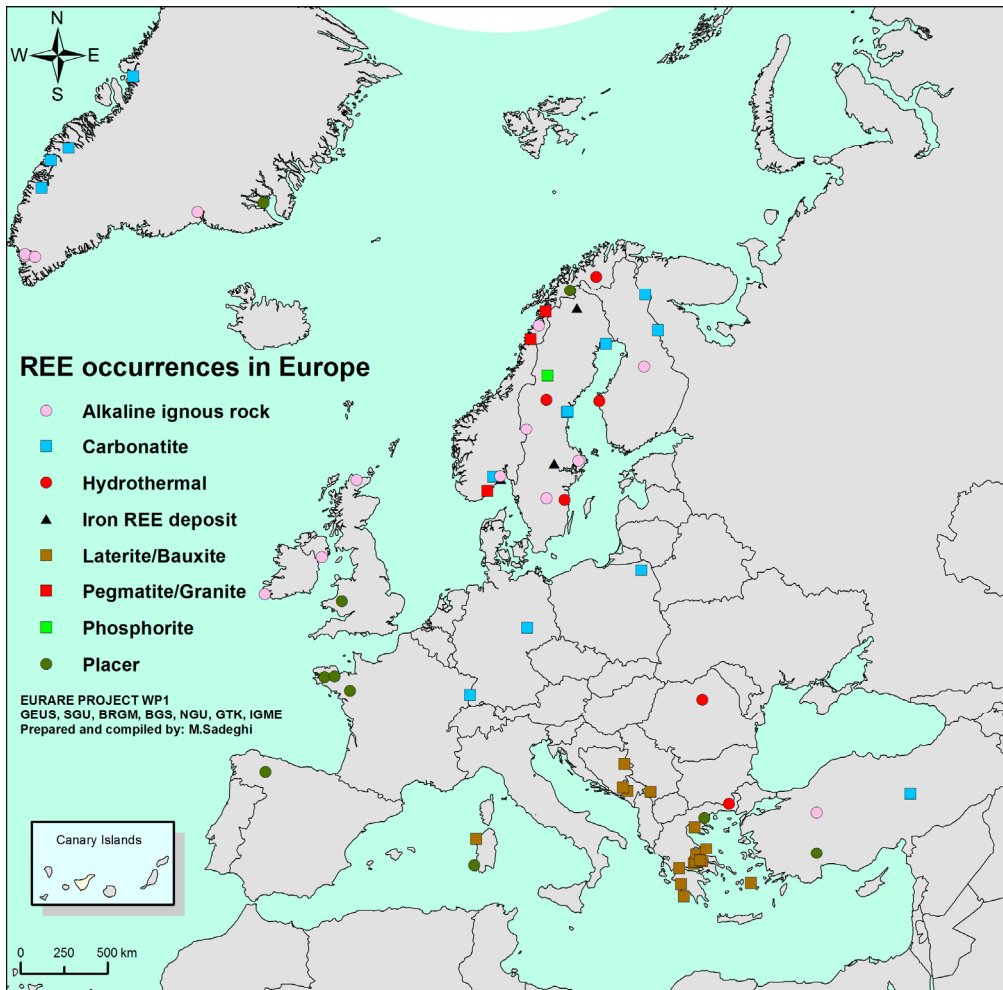


Fig.1: Overview of major REE mineralisation types in Europe and Greenland based on EURARE data and information (17). There is obvious exploration potential and high prospective interest for primary deposits in Greenland, the Nordic countries and the British islands, and secondary deposits in mainly NW France, Greece and west Balkans

Table I: Major REE advanced projects in Europe and Greenland

Deposit name	Country	Type	Size
Norra Kärr	Sweden	Alkaline igneous	41.6 Mt @ 0.57% TREO
Olserum	Sweden	Iron oxide - apatite	4.5 Mt @ 0.6% TREO
Kvanefjeld	Greenland	Alkaline igneous	122 Mt @ 1.4% TREO
Sarfartoq	Greenland	Carbonatite	5.9 Mt @ 1.8% TREO
Aksu Dıamas	Turkey	Placer	494 Mt @ 0.07% TREO

Exploitation potential

Based on the geological and compositional characteristics of the major REE mineralisation types in Europe and Greenland, it is obvious that the strongest exploration potential and highest prospective interest are for primary deposits in Greenland and the Nordic countries, and secondary deposits in NW France, Greece and the west Balkans. A range of factors may affect exploitation potential of REE deposits: these include ratio of more valuable HREE to LREE; overall grade and tonnage; content of the radioactive elements; environmental considerations; proximity to transport and infrastructure; and availability of processing routes for the deposit type and mineralogy. Currently, the larger, high-grade carbonatites and alkaline rocks are of highest exploration potential and priority, but processing of these hard-rock deposits is energy intensive and costly. For this reason, development of new exploitation technologies could mean that the lower-grade but more easily processed secondary deposits may grow in importance.

More efficient exploration

Mineral exploration is the only way to ensure secure and sustainable supply of raw materials. Even if 100% recycling efficiency is attained this will never be able to meet the increasing supply demand for REE. Exploration has for many years been focused on base metal sulphide and iron oxide mineralised environments. New advanced technologies related to geochemistry and geophysics were mainly developed to fit to the geological and metallogenetic characteristics of these systems. There is now a need to better understand the REE ore forming processes of all the primary and secondary deposit types, in order to develop the right exploration guides and apply them to European geological settings, making the discovery of new ore deposits possible. Carbonatites and alkaline rocks may be of high priority but other types such as the granitic pegmatite IOA & IOCG ones need to be explored more efficiently. Examples of required end products might be,

- Distribution of REE (total, HREE, LREE and individual elements) occurrences in Europe (Map)

- Reserves and resources in Europe and in individual countries (Reports, Excel spreadsheets, maps)
- Mineral potential maps for the REE in Europe

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