THE IMPORTANCE OF TECTONIC SETTING IN ASSESSING EUROPEAN RARE EARTH POTENTIAL

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Abstract

Rare earth element (REE) resources are commonly found associated with alkaline igneous complexes or carbonatites, or as secondary deposits derived from igneous rocks. Globally, many REE deposits occur around the margins of Archaean cratons, most in continental rift zones. Europe contains many such rift zones, which are generally younger in the south. Many of these rifts are intracontinental, whereas others are associated with the opening of oceans such as the Atlantic.

All these rift systems have the potential to host REE resources, but whereas the older provinces of northern Europe are deeply exposed, exposures in southern Europe are largely at the supracrustal level. This paper considers how an understanding of the tectonic setting of Europe's REE resources is vital to guide future exploration.

Introduction

Although the rare earth elements (REE) can be concentrated by geological processes in a range of tectonic settings, the most significant concentrations are typically associated with alkaline-peralkaline silicate rocks and carbonatites formed in extensional intracontinental rifts[1]. Such rifts are found in all the continents, dating from the Archaean to the present day. However, the ultimate source of alkaline and carbonatitic magmatism within the rifts remains controversial: one hypothesis states that the emplacement of these magmas is largely controlled by structures in the underlying lithosphere[2], whilst the contrasting view invokes a role for mantle plumes[3].

This controversy is of the utmost importance for REE exploration. If mantle plumes are the most important control, REE enrichments could potentially be found anywhere – even in ocean islands. Alternatively, if the lithosphere is the most important control, it is perhaps more likely that REE enrichments would be focused in areas with long and complex lithospheric histories. This paper will assess alkaline magmatism across Europe in this context, and consider the implications for REE resources.

Intracontinental rifts in Europe

Europe has a long and complex geological history, from the Archaean cratons of Greenland and northern Scandinavia, to volcanic suites around the Mediterranean that are only a few years old. This history comprises several cycles of continental break-up and collision (Wilson Cycles) and thus includes many intracontinental rifts (Figure 1) that represent potential REE metallogenetic belts.

Archaean alkaline silicate and carbonatite magmatism is rare across the globe[4]. In Europe, the main examples date from c. 2700 Ma and include the Skjoldungen alkaline province, Greenland and the Siilinjärvi carbonatite in Finland[5]. Although these are enriched in the REE, as is typical for alkaline magmas, they are considered unlikely to host economic REE mineralisation; Siilinjärvi is currently mined for phosphate.

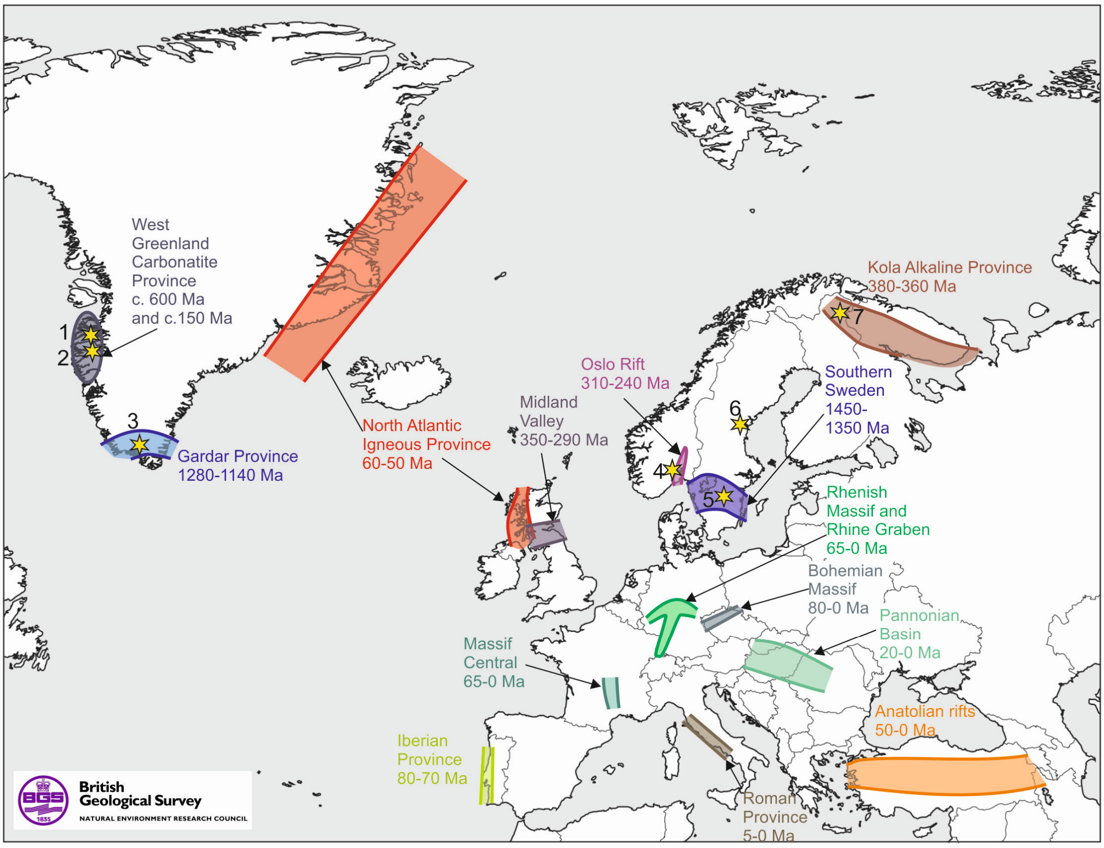

Figure 1: Map of Europe showing the approximate extent of some of the major alkaline provinces mentioned in the text. Yellow stars indicate important REE deposits. 1: Sarfartoq; 2: Qeqertaasaq; 3: Kvanefjeld, Kringlerne and Motzfeldt; 4: Fen; 5: Norra Kärr; 6: Alnö; 7: Sökli.

By contrast, some of Europe's most important REE mineralisation is associated with rifts of Proterozoic age. The Gardar Province of south-west Greenland was emplaced along the boundary between the North Atlantic Craton and a Palaeoproterozoic mobile belt to the south. The province comprises two periods of rift-related magmatism, one at c. 1280 Ma and a second at 1180-1140 Ma[6]. Both episodes are characterised by extensive dykes and emplacement of alkaline to peralkaline plutonic complexes. The Motzfeldt centre of the Igaliko complex, and the Ilimaussaq complex, both comprise peralkaline syenites with zones that have been enriched in REE by magmatic and/or hydrothermal processes. The Ilimaussaq complex contains two major REE deposits, Kvanefjeld and Kringlerne. Other syenitic and carbonatitic complexes within the Gardar Province are the focus of current REE exploration.

In Fennoscandia, the Mesoproterozoic was a time of complex accretionary tectonics, with collisional zones separated spatially and temporally by localised rifting and magmatism. Episodic rift-related magmatism occurred within Fennoscandia throughout much of the Mesoproterozoic[7, 8], although distinct rift-related igneous provinces have not been identified. Examples of alkaline intrusions formed at this time include the Norra Kärr and Almunge syenites in southern Sweden, of which the former is recognised as an important HREE-enriched deposit.

Although the Neoproterozoic and early Palaeozoic were marked by rifting in Europe as the supercontinent Rodinia broke up, there is relatively little evidence of alkaline magmatism at this time. The exceptions are zones of carbonatite and lamprophyre intrusion in Greenland and Scandinavia. In west Greenland, one such zone is dated at 555-605 Ma[9] and includes the Sarfartoq carbonatite which is currently being explored for REE. In Scandinavia, the Fen carbonatite complex in Norway and the Alnø alkaline-carbonatite complex in Sweden have both been dated at c. 580 Ma[10] and are known to contain zones of REE enrichment. Rift-related magmas were also emplaced elsewhere in Europe at this time, but appear to have been strongly affected by crustal assimilation, such that alkaline compositions are rarely seen.

In the aftermath of the Caledonian and Variscan orogenies, rifting and alkaline magmatism developed in many areas across northern Europe. The most dramatic of these rifts is the Kola Alkaline Province, which was emplaced into the Fennoscandian Shield during the Devonian. Notably, this area had been the site of repeated alkaline magmatism during the Precambrian[11]. The province comprises a number of alkaline ultramafic, syenite and carbonatite complexes which extend across the Kola Peninsula in Russia and into Finland. The most notable of these within Finland (and therefore in the area reviewed by this paper) is the Sökli phoscorite-carbonatite complex [12], which has been extensively explored for phosphate.

Rifting and alkaline magmatism also developed through the Carboniferous and Permian across the UK, southern Scandinavia (particularly the Oslo Rift), and into northern Germany[13]. In the Oslo Rift, exposures include both volcanic successions and alkaline plutons, some having notable enrichments in the REE. The UK Permo-Carboniferous magmatism in the Midland Valley of Scotland and Northern England is at a higher erosional level, with volcanics, dykes and sills but no plutonic rocks exposed.

The late Mesozoic and Cenozoic represent a major period of rifting in Europe, with alkaline magmas being emplaced in many areas. In western Europe, Mesozoic to Cenozoic rifting associated with the formation of the Atlantic Ocean generated large areas of flood basalt with associated mafic to ultramafic layered complexes that do not have elevated REE concentrations. However, some alkaline and carbonatitic magmatism was generated. The Jurassic Qeqertaasaq and Tikiussaq carbonatites at the margin of the North Atlantic Craton in West Greenland are currently being explored for REE. In east Greenland, the Gardiner Complex is a Cenozoic alkaline ultramafic, syenite and carbonatite intrusion which contains some REE-enriched zones. Plutons of similar age also occur in the UK, but are typically granitic in composition and show only minor REE enrichment. Further south, late Cretaceous (94-72 Ma[14]) alkaline magmatism in the Iberian peninsula produced numerous syenitic intrusions, forming the Iberian Alkaline Province.

Following collision during the Alpine orogeny and subduction around the Mediterranean, Cenozoic rifts and associated alkaline magmatism developed across much of central and southern Europe[15]. North of the Alpine collision zone, the Massif Central in France, the Rhenish Massif and Rhine Graben in Germany, and the Bohemian massif all include alkaline volcanic rocks, including some differentiated compositions. Carbonatites are rare but those that have been identified are of interest for their REE contents (e.g. the Storkwitz project in Germany). Alkaline volcanism also occurs in many areas around the margins of the Mediterranean, particularly in the Roman province of Italy and on Sicily and Sardinia, and in the Pannonian Basin and Anatolian rifts further east. The current level of erosion means that in these areas, the central complexes that might contain significant primary REE resources are still hundreds of metres to kilometres below the surface.

Magmatism in intracontinental rifts and REE enrichments

Intracontinental rifting is a key part of the Wilson Cycle, and as such has occurred at many times in the geological history of Europe. The majority of Europe's largest REE resources are associated with mantle-derived alkaline magmatism in these intracontinental rifts.

The original source of magmas in these rifts is in many cases the subject of debate; some authors suggest derivation from mantle plumes, some from the sub-continental lithospheric mantle, and some from the convecting asthenosphere. Whilst the contribution from mantle plumes typically remains uncertain, it is likely that most continental rifts include magmas sourced both in the lithospheric mantle and in the deeper asthenospheric mantle. However, it is notable that alkaline magmatism develops repeatedly in certain areas, often where major lithospheric structures provide pathways for magma to rise up into the crust. In these areas, the lithospheric mantle keels are also likely to have been enriched in a range of elements through repeated metasomatism associated with fluids rising from subducting slabs.

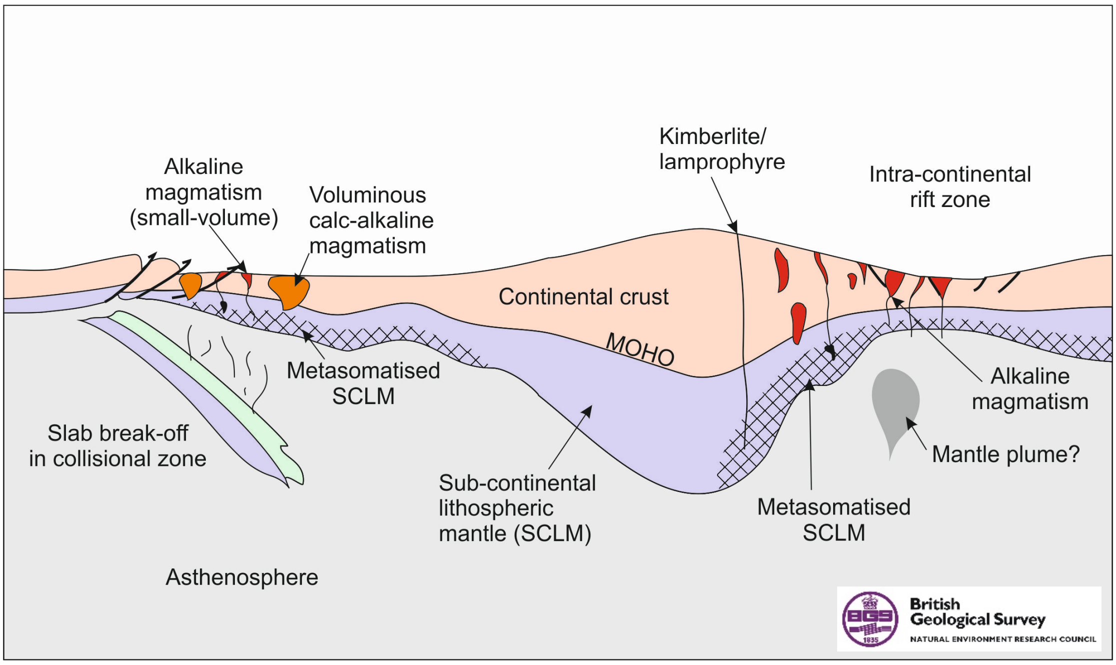

Figure 2: Schematic diagram illustrating development of lithospheric complexity. The left-hand side shows how subduction at the margins of a craton with thick lithospheric keel will introduce magmas and fluids, carrying a range of elements, into the overlying crust and lithospheric mantle. The right-hand side shows how subsequent extension of this complex lithosphere may produce alkaline magmatism derived from asthenospheric and metasomatised lithospheric sources.

In Europe, the most important such areas include the margins of the North Atlantic Craton in Greenland and the margins of the Fennoscandian Shield in Scandinavia. It is these areas that contain the most significant currently identified European REE deposits. However, repeated orogenic cycles since the Precambrian have developed the same level of lithospheric complexity in southern and central Europe, providing a basis for the Cenozoic alkaline magmatism in these areas. In these younger provinces, the plutonic counterparts to the surface volcanics are rarely exposed.

To summarise, the principal REE metallogenetic belts in Europe are those in which alkaline magmas have been emplaced, during extension, into zones of complex continental lithosphere that offer both a range of magma sources and structural pathways for magma to rise into the crust. REE are typically concentrated in plutonic rocks and thus near-surface resources are found in the more deeply eroded alkaline provinces of northern Europe. However, it is very likely that comparable primary REE resources remain to be discovered at depth within southern Europe’s younger rift provinces.

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