



RAW MATERIALS FOR DECARBONISATION

The potential for rare earth elements in the UK

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Introduction

The rare earth elements (REE) are a group of 17 chemically similar metallic elements that include the 15 lanthanides, spanning atomic numbers 57 (lanthanum) to 71 (lutetium), together with scandium and yttrium. The REE are commonly divided into two groups: (1) the light rare earth elements (LREE), which include scandium and the elements lanthanum through to europium; and (2) the heavy rare earth elements (HREE), which include yttrium and the elements gadolinium through to lutetium. As refined metals the REE are typically lustrous, dark grey to silvery in appearance.

They are soft, malleable and ductile, and have some unusual magnetic and optical properties. It is the magnetic and optical properties of the REE that make them useful in many chemical and metallurgical applications, for example in catalysts, glass and ceramics, super alloys and permanent magnets. In the UK REE are predominantly used in the manufacture of permanent magnets. The UK imports REE in several forms, which include metals, cerium compounds, yttrium and scandium compounds, and ferro-cerium. In 2017 the UK

imported six tonnes of REE metals, 1302 tonnes of cerium compounds, 628 tonnes of yttrium and scandium compounds, and 41 tonnes of ferro-cerium (Bide et al., 2019).

This profile provides an overview of the geological potential for rare earth elements in the UK. It forms part of a series on raw materials used in decarbonisation technologies that may occur in the UK, and is based on publically available data and information.

In 2017 seven countries were known to produce REE, amounting to almost 181 000 tonnes of contained rare earth oxides (REO). Production is dominated by China, which accounted for more than 77 per cent of the total in 2017. Other significant producers include Burma (Myanmar) (11%) and Australia (almost 9%). Between 1993 and 2017 global mine production of REE increased at a compound annual growth rate of almost six per cent.

REE-bearing mineral deposits occur in a diverse range of igneous, sedimentary and metamorphic rock types. However, the majority of economic REE resources are associated with just three minerals, bastnäsite ((Ce,La)(CO₃)₂F), monazite ((Ce,La,Nd,Th)PO₄) and xenotime (YPO₄). In mineral deposits the distribution of REE is controlled by rock-forming and/or hydrothermal processes, which include enrichment in magmatic or hydrothermal fluids, separation into mineral phases and precipitation. Subsequent redistribution and concentration through weathering and other surface processes may also be important. However, the environments in which the REE become economically concentrated can be broadly divided into two categories: (1) primary deposits associated with igneous and hydrothermal processes, for example those associated with carbonatites and alkaline igneous rocks; and (2) secondary deposits formed by sedimentary processes and weathering, for example ion-adsorption clays and placers (Walters and Lusty, 2011).

UK production and resources

In the UK there are many documented occurrences of REE-bearing minerals, which include: monazite, allanite ((Ce,Ca,Y)₂(Al,Fe³⁺)₃(SiO₄)₃OH), fergusonite (Ce,La,Nd)NbO₄, chevkinite ((Ce,La,Ca)₄(Fe²⁺,Mg)₂(Ti,Fe³⁺)₃Si₄O₂₂), gadolinite ((Ce,La,Nd,Y)₂Fe²⁺Be₂Si₂O₁₀) and synchysite (Ca(Ce,La)(CO₃)₂F). However, in most cases these occurrences comprise only minor low tenor REE enrichment over restricted areas. For example, many of these minerals are found as rare accessory phases in some Tertiary granites, or are minor accessories to lead-zinc-fluorite mineralisation in the Northern Pennine Orefield (Walters and Lusty, 2011). To date there has been no mine production of REE-bearing minerals in the UK, nor are there any deposits in which REE reserves or resources have been reported.

To date there has only been very limited evaluation of the REE potential in the UK. During the early 1990s BGS made a preliminary assessment of the REE contents of three late Caledonian alkaline intrusive complexes in north-west Scotland. Rock and drainage samples from Loch Borralan, Loch Ailsh and Loch Loyal were analysed for Ce, La and Y (Shaw and Gunn, 1993). During this period BGS undertook an assessment of the economic potential of mudstone-hosted nodular monazite in south-central Wales (Smith et al., 1994). More recently a BGS-hosted MSc student reappraised drillcore from the ultramafic section of the Loch Borralan Complex to further assess its potential as a REE resource (Griffith, 2011). In 2013 BGS studied the formation of late-stage allanite-bearing veins associated with the Loch Loyal Syenite Complex (Hughes et al., 2013; Walters et al., 2013).

UK occurrences

Wales

Monazite nodules are locally present in Lower Palaeozoic sedimentary rocks of the Welsh Basin. During the 1980s these were investigated by drainage surveys undertaken by BGS as part of the government-funded Mineral Reconnaissance Programme. The very high REE concentrations (>5000 ppm Ce) identified in some panned stream-sediment concentrates were found to be due to the presence of nodular monazite. The areas with the highest REE concentrations (>10 000 ppm Ce) in panned samples include: the Harlech Dome in the Snowdonia National Park; the Preseli Hills south-east of Newport; and the Berwyn Dome west of Llangollen. However, the most extensive area of high-cerium anomalies is in south-central Wales, north of the Brecon Beacons National Park, where monazite nodules are known to occur in catchments that drain Ordovician and Silurian sedimentary rocks (Cooper et al., 1983; Cooper and Read, 1984; Read, 1987; Smith et al., 1994).

This type of monazite has a distinctive appearance, which is very different to detrital monazite derived from the weathering of igneous (granitic) rocks. The nodules are grey, flattened, ellipsoidal and typically between 0.05 and 2 mm in diameter (Cooper et al., 1983; Cooper and Read, 1984). The nodules are compositionally zoned with the LREE typically decreasing towards the core while the HREE tend to increase. In terms of the REE

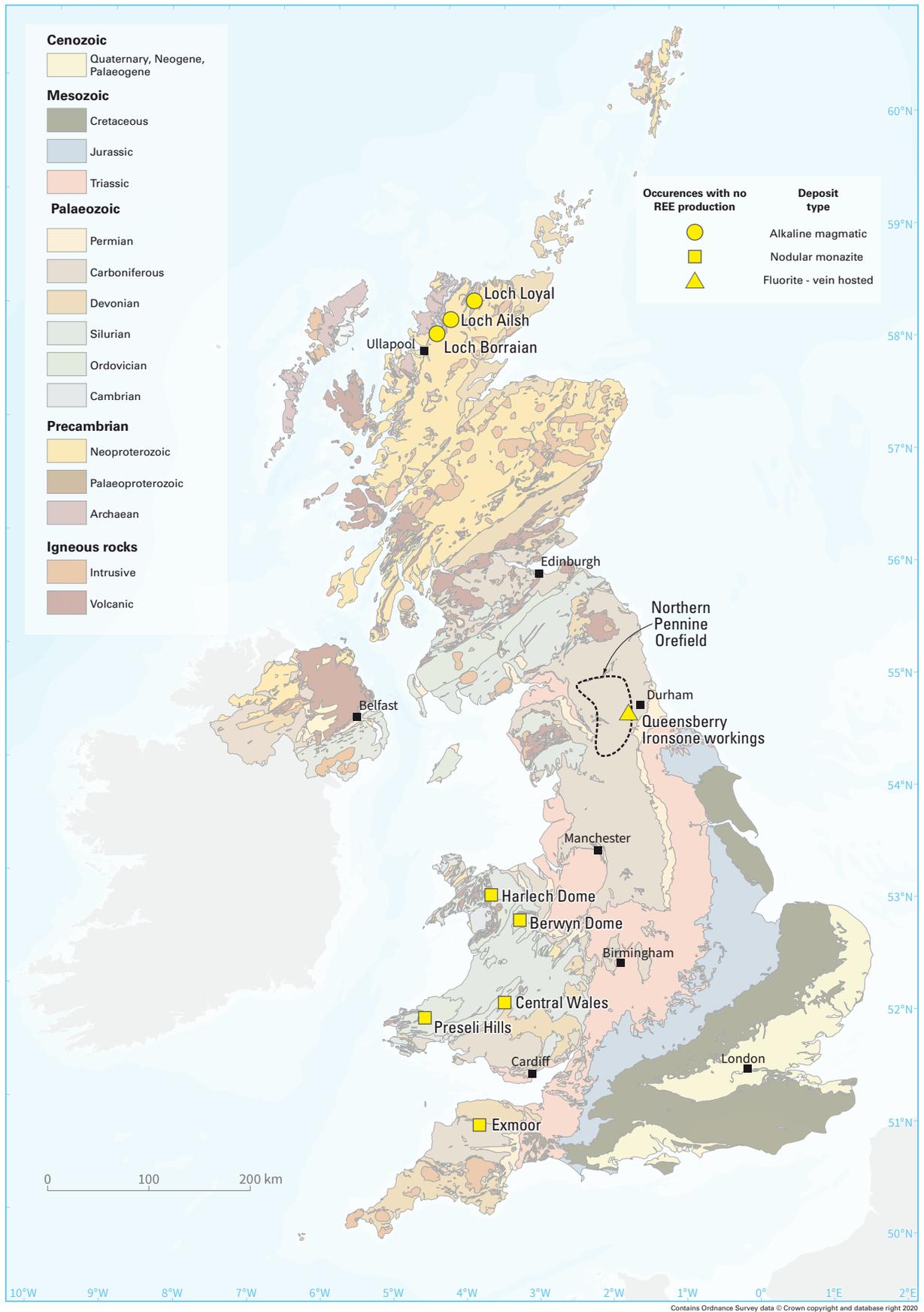


Figure 1 Location of principal REE occurrences in the United Kingdom.

the nodules are compositionally very similar to detrital (granitic) monazites; however, the nodules tend to contain less thorium and uranium, but more europium (Read, 1987). Detailed work by Milodowski and Zalaciewicz (1991) showed that the monazite nodules might have formed during diagenesis, involving: (1) the deposition of unstable volcanogenic REE-bearing minerals during sedimentation; (2) the breakdown of these minerals during burial and compaction; (3) the transport and redistribution of REE by porewaters during the late stages of diagenesis; and finally (4) the precipitation of new REE minerals under reducing conditions in organic-rich sediments.

In 1994 BGS undertook a preliminary economic assessment of in situ nodular monazite in the Newcastle Emlyn area of south-central Wales. Despite the favourable chemistry of the nodules (i.e. high-levels of europium, and very low-levels of thorium and uranium) the density of one nodule per 15 cm² in rocks in the Newcastle Emlyn area is far too low to be of economic interest. Upgrading during fluvial transport and sorting has resulted in the concentration of nodular monazite in sediments over a large area of south-central Wales. In some areas concentrations were found to exceed 1 per cent monazite in the <2 mm sediment fraction, which equates to 20 kilograms of monazite per cubic metre in tributary drainage. However, five kilograms of monazite per cubic metre is more typical. These grades are comparable with minimum exploitable grades in other parts of the world where monazite is extracted (Smith et al., 1994).

North-west Scotland

During the late 1980s and early 1990s the ultramafic sections of the Caledonian intrusive complexes at Loch Ailsh and Loch Borrallan were investigated by BGS for their platinum-group metal (PGM) potential (Gunn and Styles, 2002). The Loch Ailsh Complex, located about 25 km north-east of Ullapool, covers an area of about 10 km² and comprises a suite of early ultramafic pyroxenites and late leucosyenites (Styles et al., 2004). Assay data from Loch Ailsh show the complex is enriched in REE. Lanthanum and cerium values are highest in the late leucosyenites, with concentrations up to 3239 ppm La and 3956 ppm Ce recorded (Shaw et al., 1994). REE concentrations are typically

lower in the pyroxenites with maximum values of 840 ppm La and 1456 ppm Ce. These rocks are also enriched in Th (up to 244 ppm) and U (up to 65 ppm). In the pyroxenite there is a significant correlation between Y and Zr; however, in samples of syenite Y is instead associated with La, Ce, Zn, Ti, Mn, V and Ca, indicating the possible presence of complex REE-minerals such as allanite (Shaw and Gunn, 1993). More detailed work is needed to fully understand the distribution of REE in the Loch Ailsh Complex, especially as the syenites were not systematically investigated in the PGM-focussed studies undertaken by BGS.

The Loch Borrallan Complex is located about 2 km south-west of Loch Ailsh and comprises a similar suite of pyroxenites and syenitic rocks of various types. The complex has an area of approximately 26 km², with the marginal ultramafic body estimated to be about 400 metres thick (Styles et al., 2004). A drilling programme was undertaken at the Loch Borrallan Complex during the 1980s to assess the phosphate potential (Notholt et al., 1985). A second phase of drilling was undertaken during the 1990s to assess the PGM potential of the complex (Shaw and Gunn, 1993). Analysis of drillcore from the first phase of drilling revealed significant amounts of apatite in the pyroxenite units (between 1 and 10 wt. %). The presence of REE in the apatite was also established at this time by XRF analysis (Notholt et al., 1985). Both drilling programmes identified minor REE enrichment in some drillcore intersections, with maximum values of 739 ppm La and 1764 ppm Ce. The REE enrichment is associated with the highest concentrations of apatite (locally up to two per cent), making it the most abundant REE-bearing phase within the Loch Borrallan Complex (Shaw and Gunn, 1994). More recently BGS reappraised borehole logs and assay data from Loch Borrallan using modern methods. A selection of drillcore samples (n = 33) were also reanalysed by ICP-MS to determine the REE content. This study found that background REE (La+Ce) concentrations are highest in the pyroxenite units (median 345 ppm) and lower in the syenite units (median 277 ppm). It also established that apatite is the most important host of REE in the pyroxenite units, whereas in the syenite units allanite is the most abundant REE-mineral. In addition a complicated suite of REE-minerals was also identified in the Complex, including: monazite, REE-carbonates, zirkelite

(Zr-REE-oxide), ancylite (Sr-REE-carbonate), and kainosite (Ca-REE-silicate). However, these minerals were found to be present in only very minor amounts (Griffith, 2011).

In 1990 a short reconnaissance survey was undertaken by BGS over the Loch Loyal Complex and the associated Cnoc nan Cuilean Intrusion located 130 km north-east of Ullapool, close to the village of Tongue. This was to investigate occurrences of REE-minerals previously identified by earlier BGS investigations in the region (Atkin et al., 1969). A small set of stream sediment and rock samples was collected and analysed for La, Ce and Y. Two rock samples from the Cnoc nan Cuilean Intrusion returned very high REE concentrations, with up to 5667 ppm La and 19 785 ppm Ce in a heterogeneous basic syenite. Samples collected from catchments draining the Allt Liath area were also observed to have elevated REE concentrations, with maximum values of 1922 ppm Ce in a stream sediment sample and 1409 ppm Ce in a sample of panned concentrate (Shaw and Gunn, 1993). Detailed mapping and geochemical sampling to investigate REE in the Cnoc nan Cuilean Intrusion were undertaken by BGS in 2011 (Hughes, 2011). This study found the intrusion broadly comprises two lithological zones, a massive leucosyenite and a complex 'mixed' syenite zone which includes both melasyenite and leucosyenite. The study also established that allanite is the most abundant REE-mineral in the Cnoc nan Cuilean Intrusion, where it mostly occurs in the mafic melasyenites and in cross-cutting biotite-magnetite veins (Hughes et al., 2013). Additional work by Walters et al. (2013) confirmed that the REE are most enriched in the late-stage, hydrothermal veins in the Cnoc nan Cuilean Intrusion where they occur not only in allanite, but also in REE-bearing apatite, and minor ancylite and bastnäsite. These veins contain up to 2 wt. % total rare earth oxides (TREO), but they are typically very thin and discontinuous, and, therefore, unlikely to be economic.

Other REE occurrences

Nodular monazite is known to occur in an east-west-trending belt of Devonian sedimentary rocks in the Exmoor area of south-west England (Read et al., 1987). Compositionally the monazite nodules

from south-west England are very similar to those found in south-central Wales (Cooper and Read, 1983); however, they typically have lower cerium contents and have, therefore, not been studied as closely as those in Wales (Smith et al., 1994).

Historical work in the Northern Pennine Orefield (NPO) identified: (1) the presence of REE-bearing minerals in some mineralised veins (Ixer and Stanley, 1987; Ixer et al., 1996); (2) elevated REE concentrations in fluorite associated with Pb-Zn mineralisation (Shepherd et al., 1982). In 2011 samples of fluorite from the NPO were analysed by BGS to assess the REE potential (Walters, 2011). Compared to samples of fluorite from other parts of the UK (e.g. Southern Pennine Orefield) fluorite from the NPO was found to contain relatively high concentrations of REE (up to 900 ppm). Of particular interest was the observed enrichment in yttrium (up to 310 ppm) and europium (up to 46 ppm) in samples from the Queensberry Ironstone Workings at Cowshill, Weardale. However, all values were found to be sub-economic (Walters, 2011).

Resource potential

Even though REE minerals are known to occur in the UK, many of them are quite rare and are typically found in minor amounts in a few localities. It is worth noting that REE have never been commercially extracted in the UK, nor has there been any systematic exploration for REE.

A priority target for further investigation is the Cnoc nan Cuilean Intrusion in north-west Scotland. The hydrothermal, allanite-bearing veins that crosscut the intrusion contain the highest REE grades recorded in the UK (up to 2 wt. % TREO) (Walters et al., 2013). The known occurrence of significant hydrothermal, REE-mineralised veins associated with alkaline igneous rocks elsewhere in the world provides a strong basis for evaluating this area further. However, there is currently no commercial process for extracting REE from allanite; this coupled with the thin and discontinuous nature of the veins, makes them unlikely to be economic.

It is also important to note that previous work by BGS on the Caledonian alkaline intrusions of north-west Scotland has focussed on the PGM potential

of selected parts of these bodies. Systematic investigations over the entirety of these complex intrusions are recommended in order to fully evaluate their REE potential.

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