

Rare Earth Elements

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Definitions, mineralogy and deposits

Definitions and characteristics

The rare earth elements (REE) (sometimes referred to as the rare earth metals) are a group of 17 chemically similar metallic elements, including the 15 lanthanides, scandium and yttrium. The lanthanides are elements spanning atomic numbers 57 (lanthanum, La) to 71 (lutetium, Lu) (Table 1). The lanthanides all occur in nature, although promethium¹, the rarest, only occurs in trace quantities in natural materials as it has no long-lived or stable isotopes (Castor and Hedrick, 2006). Scandium and yttrium are considered REE as they have similar chemical and physical properties. Separation of the individual REE was a difficult challenge for chemists in the 18th and 19th centuries, and consequently it was not until the 20th century that they were all identified. On account of their chemical similarity the REE can very easily substitute for one another making refinement to pure metal difficult.

The term rare earth is a misnomer arising from the rarity of the minerals from which they were originally isolated (Figures 1 and 2). In contrast REEs are relatively plentiful in the Earth's crust having an overall crustal abundance of 9.2 ppm (Rudnick et al. 2003). The crustal abundance of individual REE varies widely, from cerium the most abundant at 43 ppm (exceeding other important metals including copper — 27 ppm and lead — 11 ppm) to 0.28 ppm for thulium (Taylor and McLennan, 1985; Rudnick et al. 2003).

The lanthanides are commonly divided into: lower atomic weight elements, lanthanum through to europium, referred to as the light rare earth elements (LREE) and the heavy rare earth elements (HREE) — gadolinium through to lutetium and yttrium (Table 1). Yttrium is usually grouped with the HREE because of its chemical similarity. The division is somewhat arbitrary and the term middle REE (MREE) is sometimes used to refer to those elements between europium to dysprosium (Samson and Wood, 2004). The relative abundance of the REE varies

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| Element | Symbol | Atomic number | Atomic weight | Density (gcm ⁻³) | Melting Point (°C) | Vicker's hardness, (10 kg load, kg/mm ²) |
|-------------------------|--------|---------------|---------------|------------------------------|--------------------|--|
| Scandium | Sc | 21 | 44.95 | 2.989 | 1541 | 85 |
| Yttrium | Y | 39 | 88.90 | 4.469 | 1522 | 38 |
| Lanthanum | La | 57 | 138.90 | 6.146 | 918 | 37 |
| Cerium | Ce | 58 | 140.11 | 8.160 | 798 | 24 |
| Praseodymium | Pr | 59 | 140.90 | 6.773 | 931 | 37 |
| Neodymium | Nd | 60 | 144.24 | 7.008 | 1021 | 35 |
| Promethium ¹ | Pm | 61 | 145.00 | 7.264 | 1042 | - |
| Samarium | Sm | 62 | 150.36 | 7.520 | 1074 | 45 |
| Europium | Eu | 63 | 151.96 | 5.244 | 822 | 17 |
| Gadolinium | Gd | 64 | 157.25 | 7.901 | 1313 | 57 |
| Terbium | Tb | 65 | 158.92 | 8.230 | 1356 | 46 |
| Dysprosium | Dy | 66 | 162.50 | 8.551 | 1412 | 42 |
| Holmium | Ho | 67 | 164.93 | 8.795 | 1474 | 42 |
| Erbium | Er | 68 | 167.26 | 9.066 | 1529 | 44 |
| Thulium | Tm | 69 | 168.93 | 9.321 | 1545 | 48 |
| Ytterbium | Yb | 70 | 173.04 | 6.966 | 819 | 21 |
| Lutetium | Lu | 71 | 174.97 | 9.841 | 1663 | 77 |

Table 1 Selected properties of the REE. Compiled from Gupta and Krishnamurthy (2005).



Figure 1 Elongate prismatic fergusonite in an open cavity associated with albite and quartz, Arran, Scotland. Photograph: Fergus MacTaggart, BGS © NERC.

¹ Promethium: is a radioactive element.

| Mineral | Formula | Approximate REO % |
|------------------|---|-------------------|
| Aeschnite-(Ce) | (Ce,Ca,Fe,Th)(Ti,Nb) ₂ (O,OH) ₆ | 32 |
| Allanite-(Ce) | (Ce,Ca,Y) ₂ (Al,Fe ³⁺) ₃ (SiO ₄) ₃ OH | 38 |
| Apatite | Ca ₅ (PO ₄) ₃ (F,Cl,OH) | 19 |
| Bastnäsite-(Ce) | (Ce,La)(CO ₃)F | 75 |
| Brannerite | (U,Ca,Y,Ce)(Ti,Fe) ₂ O ₆ | 9 |
| Britholite-(Ce) | (Ce,Ca) ₅ (SiO ₄ ,PO ₄) ₃ (OH,F) | 32 |
| Eudialyte | Na ₄ (Ca,Ce) ₂ (Fe ²⁺ ,Mn,Y)ZrSi ₈ O ₂₂ (OH,Cl) ₂ (?) | 9 |
| Euxenite-(Y) | (Y,Ca,Ce,U,Th)(Nb,Ta,Ti) ₂ O ₆ | 24 |
| Fergusonite-(Ce) | (Ce,La,Nd)NbO ₄ | 53 |
| Gadolinite-(Ce) | (Ce,La,Nd,Y) ₂ Fe ²⁺ Be ₂ Si ₂ O ₁₀ | 60 |
| Kainosite-(Y) | Ca ₂ (Y,Ce) ₂ Si ₄ O ₁₂ CO ₃ ·H ₂ O | 38 |
| Loparite | (Ce,La,Na,Ca,Sr)(Ti,Nb)O ₃ | 30 |
| Monazite-(Ce) | (Ce,La,Nd,Th)PO ₄ | 65 |
| Parisite-(Ce) | Ca(Ce,La) ₂ (CO ₃) ₃ F ₂ | 61 |
| Xenotime | YPO ₄ | 61 |
| Yttrocerite | (Ca,Ce,Y,La)F ₃ ·nH ₂ O | 53 |
| Huanghoite-(Ce) | BaCe(CO ₃) ₂ F | 39 |
| Cebaite-(Ce) | Ba ₃ Ce ₂ (CO ₃) ₅ F ₂ | 32 |
| Florencite-(Ce) | CeAl ₃ (PO ₄) ₂ (OH) ₆ | 32 |
| Synchysite-(Ce) | Ca(Ce,La)(CO ₃) ₂ F | 51 |
| Samarskite-(Y) | (Y,Ce,U,Fe ³⁺) ₃ (Nb,Ta,Ti) ₅ O ₁₆ | 24 |
| Knopite | (CaTi,Ce) ₂ O ₃ | na |

Table 2 A selection of REE-bearing minerals. Mineral formulae sourced from Clark (1993) and estimates of REO content based on Webmineral composition, with the exception of apatite (Caster and Hedrick 2006). Where the mineral name is followed by brackets the formula is for the specific chemical variant of the mineral identified. Note one or more other chemical variants, in which the dominant element varies from the one shown, may exist. na: not available.

considerably and relates to two main factors: REE with even atomic numbers have greater abundance than their odd numbered neighbours (Oddo-Harkins effect); and Secondly the lighter REE are more incompatible (because they have larger ionic radii) and consequently more strongly concentrated in the continental crust than the REE with larger atomic numbers. The REE are trivalent (Ln³⁺), with the exception of cerium (Ce⁴⁺) and europium (Eu²⁺) in some environments. The chemically similar nature (ionic radii and oxidation states) of the REE means they can substitute for one another in crystal structures. This results in the occurrence of multiple REE within a single mineral and a broad distribution in the Earth's crust (Castor and Hedrick, 2006).



Figure 2 Allanite crystal associated with albite and quartz in an open cavity, Arran, Scotland. Photograph: Fergus MacTaggart, BGS © NERC.

As refined metals the REE are lustrous, iron grey to silvery in appearance. They are characteristically soft, malleable, ductile and typically reactive. The electron structure of REE gives them some unusual magnetic and optical properties. With a few exceptions melting points of REE increase across the series, from 798°C for cerium to 1663°C for lutetium. Melting point has direct implications for the reduction process used in metal production. The REE, with the exception of Sc, Y, La, Yb and Lu, are strongly paramagnetic² and have strong magnetic anisotropy³ (Gupta and Krishnamurthy, 2005).

Mineralogy

REE do not occur naturally as metallic elements. REE occur in a wide range of mineral types including halides, carbonates, oxides, phosphates and silicates (Table 2). The REE are largely hosted by rock-forming minerals where they substitute for major ions. Higher concentrations of REE are required to form their own minerals (Möller, 1986). Around 200 minerals are known to contain REE, although a relatively small number are, or may become, commercially significant (Table 2). REE-bearing minerals generally contain most of the REE in varying concentrations, but tend to be biased towards either the LREE or HREE. The most abundant REE in a mineral is usually indicated by

² Paramagnetic: a type of magnetism which only occurs in the presence of an external magnetic field.

³ Magnetic anisotropy: the dependence of materials magnetic properties on direction.

chemical symbol, for example in bastnäsite -(Ce), cerium is the dominant REE, but it can also contain lanthanum, neodymium and praseodymium.

The vast majority of resources are associated with just three minerals, bastnäsite, monazite and xenotime. In some REE minerals the LREE are particularly enriched relative to the HREE, whilst in others the opposite is the case. Bastnäsite and monazite are the primary source of the LREE, mainly Ce, La and Nd. Monazite has a different balance as it contains less La and more Nd and HREE. It is also significant to note that monazite contains the radioactive element thorium. Xenotime is dominated by the heavier REE including Y, Dy, Er, Yb and Ho (Harben, 2002).

Major deposit classes

REE mineral deposits occur in a broad range of igneous⁴, sedimentary⁵ and metamorphic⁶ rocks. The concentration and distribution of REE in mineral deposits is influenced by rock forming and hydrothermal⁷ processes including enrichment in magmatic⁸ or hydrothermal fluids, separation into mineral phases and precipitation, and subsequent redistribution and concentration through weathering and other surface processes. Environments in which REE are enriched can be broadly divided into two categories: primary deposits associated with igneous and hydrothermal processes; and secondary deposits concentrated by sedimentary processes and weathering. Within these two groups REE deposits can be further subdivided depending on their genetic associations⁹, mineralogy and form of occurrence. Classification of some deposits is complicated by unclear genetic associations and/ or the involvement of multiple geological processes. For example deposits associated with carbonatites can be divided into those directly associated with magmatic processes and crystallisation, others of vein/replacement types and residual/surface weathering deposits, or a combination of these.

The global distribution of selected REE occurrences, deposits and mines is shown in Figure 3. The most comprehensive listing of REE deposits and occurrences is provided by Orris and Grauch (2002) (Table 3). The most commercially important REE deposits are associated

4 Igneous: rocks which have a crystalline texture and appear to have consolidated from molten rock.

5 Sedimentary: a rock formed from sediment which may of organic or inorganic in origin.

6 Metamorphic: rocks changed by temperature and pressure within the Earth's crust.

7 Hydrothermal: hot fluids.

8 Magmatic: related to magma, molten rock and fluid originating deep within or below the Earth's crust.

9 Genetic associations — the geological processes associated with the formation of a mineral deposit.

with magmatic processes and are found in, or related to, alkaline igneous rocks and carbonatites.

Primary deposits

The REE are preferentially enriched in partial melts or fluids from the upper mantle and in melts of crustal origin because of their large ionic radius¹⁰ (Möller, 1986). Within the magmatic and hydrothermal environment REE minerals may be associated with quartz- and fluorite-bearing veins and breccia¹¹ zones, skarns¹² and pegmatites¹³. The economic potential of a REE deposit is strongly influenced by its mineralogy and the geological processes from which it has formed. Deposits which have a spatial and genetic association with alkaline igneous rocks can be divided into two categories, one associated with carbonatites¹⁴ and related igneous rocks and the other with peralkaline¹⁵ igneous rocks (Samson and Wood, 2004).

Carbonatite-associated deposits

Carbonatites are igneous rocks that contain more than 50 per cent carbonate minerals. They are thought to originate from carbon dioxide-rich and silica-poor magmas from the upper mantle. Carbonatites are frequently associated with alkaline igneous provinces and generally occur in stable cratonic regions, commonly in association with areas of major faulting particularly large-scale rift structures. More than 500 carbonatite occurrences are documented worldwide, with the main concentrations in the East African Rift zones, eastern Canada, northern Scandinavia, the Kola Peninsula in Russia and southern Brazil (Woolley and Kjarsgaard, 2008).

Carbonatites take a variety of forms including intrusions within alkali complexes, isolated dykes and sills, small plugs or irregular masses that may not be associated with other alkaline rocks. Pipe-like bodies, which are a common form, may be up to 3–4 km in diameter (Birkett and Simandl, 1999). Intrusive carbonatites are commonly surrounded by a zone of metasomatically¹⁶ altered¹⁷ rock, enriched in sodium and/or potassium. These

10 Ionic radius: half the distance between the centres of two ions in an element.

11 Breccia: a rock that has been mechanically, hydraulically or pneumatically broken into angular fragments.

12 Skarn: a metamorphic rock that forms as a result of chemical alteration by hydrothermal and other fluids.

13 Pegmatite: a very coarse-grained igneous rock.

14 Carbonatite: a rock which contains more than 50 per cent carbonate minerals, thought to originate from carbon dioxide-rich and silica-poor magmas from the upper mantle.

15 Peralkaline: igneous rocks which have a higher molecular proportion of combined sodium and potassium than aluminium.

16 Metasomatism: chemical alteration of a rock by fluids.

17 Altered: hydrothermal or weathering induced changes to the chemical and mineralogical composition of a rock.

| Deposit type | Brief description | *Number documented | Typical grades and tonnage | Major examples |
|---|---|--------------------|---|--|
| Primary deposits | | | | |
| <i>Carbonatite-associated</i> | Deposits associated with carbonate-rich igneous rocks associated with alkaline igneous provinces and zones of major faulting | 107 | A few 10s thousands of tonnes to several hundred million tonnes, 0.1–10% REO e.g. Bayan Obo: 750 million tonnes at 4.1% REO | Mountain Pass, USA; Bayan Obo, China; Okorusu, Namibia; Amba Dongar, India; Barra do Itapirapuã, Brazil; Iron Hill, USA |
| <i>Associated with alkaline igneous rocks</i> | Deposits associated with igneous rocks characterised by abundant alkali minerals and enrichment in HFSE | 122 | Typically <100 million tonnes (Lovozero >1000 million tonnes), grade variable, typically <5% REO e.g. Thor Lake: 64.2 million tonnes at 1.96% REO | Ilimaussaq, Greenland; Khibina and Lovozero, Russia; Thor Lake and Strange Lake, Canada; Weishan, China; Brockman, Australia; Pajarito Mountain, USA |
| <i>Iron-REE deposits (iron oxide-copper-gold deposits)</i> | Copper-gold deposits rich in iron oxide and diverse in character and form | 4 | e.g. Olympic Dam: 2000 million tonnes at 0.3295% REO (Orris and Grauch, 2002) | Olympic Dam, Australia; Pea Ridge, USA |
| <i>Hydrothermal deposits (unrelated to alkaline igneous rocks)</i> | Typically quartz, fluorite, polymetallic veins and pegmatites of diverse origin | 63(a) | Typically <1 million tonnes, rarely up to 50 million tonnes, grade variable, typically 0.5–4.0%, rarely up to 12% REO e.g. Lemhi Pass: 39 million tonnes at 0.51% REO (Orris and Grauch 2002) | Karonge, Burundi; Naboomspruit and Steenkampskraal, South Africa; Lemhi Pass and Snowbird and Bear Lodge, USA; Hoidas Lake, Canada |
| Secondary deposits | | | | |
| <i>Marine placers (including coastal dune deposits formed by aeolian processes)</i> | Accumulations of resistant, heavy minerals, concentrated by coastal processes and found along or close to existing coastlines | 264(b) | Highly variable tonnage, commonly in the order of 10s to 1–3 hundred million tonnes, generally <0.1% monazite e.g. Jangardup 30 million tonnes at 0.046% Monazite (Orris and Grauch 2002) | Eneabba, Jangardup, Capel, WIM 150, North Stradbroke Island, Australia; Green Cove Springs, USA; Richards Bay, South Africa; Chavara, India |
| <i>Alluvial placers</i> | Concentrations of resistant, heavy minerals in river channels | 78(b) | 10s to <200 million tonnes, typically <0.1% monazite e.g. Horse Creek: 19 million tonnes at 0.041% monazite (Orris and Grauch 2002) | Perak, Malaysia; Chavara, India; Carolina monazite belt and Horse Creek, USA; Guangdong, China |
| <i>Paleoplacers</i> | Ancient placer deposits typically forming consolidated, cemented rocks | 13(b) | 10s million tonnes up to 100 million tonnes, typically (<0.1% REO | Elliot Lake, Canada; Bald Mountain, USA |
| <i>Lateritic deposits</i> | Residual surface deposits formed from intense chemical weathering of REE-enriched igneous rocks | 42(c) | A few 10s thousands of tonnes to several hundred million tonnes, 0.1–10% REO e.g. Mt Weld: 12.24 million tonnes at 9.7% REO (up to 40% REO) | Mount Weld, Australia; Araxá, Brazil; Kangankunde, Malawi |
| <i>Ion-adsorption clays</i> | Residual clay deposits formed from the weathering of REE-enriched granites | >100 | Most <10 000 tonnes, low-grade (0.03–0.35% REO) | Longnan, Xunwu, China |

Table 3 Key characteristics and examples of the major REE deposit types. Specific deposits listed may fall into more than one mineral deposit class. Number of documented occurrences, compiled from Orris and Grauch (2002), with the exception of ion-adsorption clays (Grauch and Mariano, 2008), are indicative of the distribution of known deposits across deposit types. The grades and tonnages of deposits vary considerably within each deposit class.*

Notes:

(a) Includes igneous-affiliated, metamorphic, other fluorite and lead deposits of Orris and Grauch (2002).

(b) Fourteen placers of 'uncertain origin' are excluded.

(c) Classified as 'carbonatites with residual enrichment' by Orris and Grauch (2002).

Rare Earth Elements

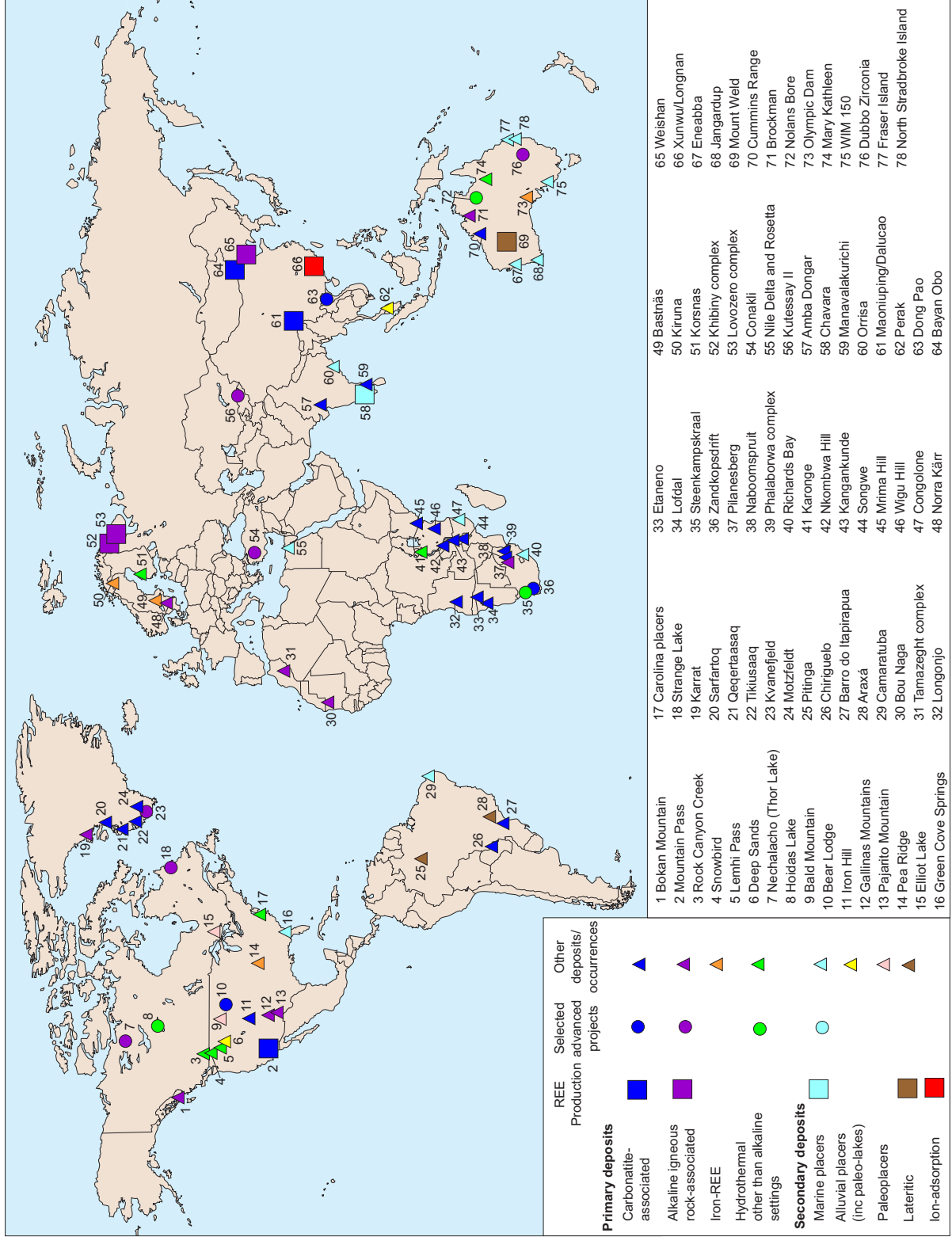


Figure 3 Map showing the global distribution of REE deposits.

desilicified¹⁸ zones, known as fenite, develop as a result of reaction with Na-K-rich fluids produced from the carbonatite intrusion. Carbonatites are characteristically enriched in a range of elements in addition to carbon dioxide, calcium, magnesium and iron, including REE, barium, strontium, fluorine, phosphorous, niobium, uranium and thorium (Rankin, 2004). The REE in carbonatites are almost entirely LREE which occur in minerals such as bastnäsite, allanite, apatite and monazite (Gupta and Krishnamurthy, 2005). REE minerals commonly develop in the late stages of carbonatite emplacement. This frequently makes it difficult to determine whether the minerals were precipitated directly from the carbonatite magma or from hydrothermal fluids (Wall and Mariano, 1996).

Although rare, economic concentrations of REE-bearing minerals can be concentrated by primary crystallisation processes alone (Rankin, 2004). As a carbonatite body crystallises the majority of the REE are incorporated into apatite and calcite. During later cooling, calcite can be partially replaced by other minerals, releasing REE. These can be subsequently incorporated in monazite and other REE minerals such as bastnäsite and parisite as they crystallise from the fluids (Möller, 1986). The Mountain Pass deposit in California, USA is an important example of a deposit formed by magmatic processes. The Mountain Pass carbonatite is a moderately dipping, tabular Precambrian¹⁹ intrusion into metamorphic rocks consisting of gneisses, granites and migmatites²⁰. The carbonatites are associated with potassium-rich igneous rocks of a similar age. The REE minerals occur in veins, with the ore typically containing 10–15 per cent bastnäsite, 65 per cent calcite or dolomite and 20–25 per cent baryte. Sulphide minerals are rare in the ore, although galena is locally common (Evans, 1993; Castor and Hedrick, 2006; Castor, 2008a).

More commonly, REE deposits are also associated with late-stage vein and replacement mineralisation either within carbonatites or the surrounding host rocks. The fluids can be largely derived from the carbonatite or significantly postdate the intrusion, resulting from subsequent processes including metamorphism and/or weathering. Hydrothermal REE mineralisation typically takes the form of fracture and cavity fillings or fine-grained disseminations overprinting earlier formed minerals. Subsequent alteration and breakdown of primary minerals by lower temperature fluids may release REE which

can potentially form secondary REE minerals (Wall and Mariano, 1996).

The Iron–REE–niobium deposit at Bayan Obo in Inner Mongolia, China is the world's largest REE deposit. The deposit is located on the northern margin of the North China craton, an extensional rifting environment in the mid-Proterozoic²¹. The Bayan Obo deposit consists of three main ore bodies (Main, East and West) lying along an east–west-trending zone, more than 18 km in length. The deposits are stratabound²² and hosted by mid-Proterozoic metasedimentary rocks of the Bayan Obo Group, largely within a dolomite marble (Wu, 2007). The mineralisation is thought to be largely Caledonian in age (420–555 Ma). Numerous carbonatite dykes are recognised in the district and several gabbros and alkali gabbros occur to the north and south of the ore bodies. Multiple mineralising stages are evident and over 170 minerals have been identified (Smith and Chengyu, 2000). REE principally occur as monazite and bastnäsite, although many other REE minerals are present including huanghoite, parisite and cebaite. REE-bearing niobium minerals are also common, the most widespread being columbite. The most important iron minerals are hematite and magnetite (Chao et al. 1997). The formation of the Bayan Obo deposit is the subject of considerable debate. Genetic models relating it to both carbonatite magmatism and hydrothermal iron oxide-copper-gold-(REE-uranium) mineralisation have been proposed. The origin of the dolomite hosting the deposit is disputed with some authors proposing a sedimentary origin whilst others suggest it is the result of carbonatite magmatism (Rankin, 2004). Recently published research concludes that carbonate minerals at Bayan Obo are derived from sedimentary carbonate rocks metasomatised by fluids likely to be derived from a carbonatite magma enriched in REE (Yang et al. 2009).

Less well known Chinese REE mineralisation, identified in the 1990s, is associated with the Himalayan carbonatite-alkaline complexes of western Sichuan, south-west China. The deposits contain total reserves in excess of three million tonnes LREE and occur along a 270 km long zone, measuring 15 km wide. The largest deposit is Maoniuping, China's second largest REE resource, followed by Dulucao and a number of small- to medium-sized REE deposits and occurrences. The REE mineralisation is related to carbonatite sills and dykes and associated syenites²³. Mineralisation is hosted in complex vein systems consisting

18 Desilicified: a rock in which silica has been released from the constituent minerals.

19 Precambrian: the period of time from the formation of the Earth, about 4500 million years ago to about 590 million years ago.

20 Migmatite: a very high-grade metamorphic rock intermediate between metamorphic and igneous.

21 Proterozoic: the geological eon extending from 2500 to 542 Ma.

22 Stratabound: an ore deposit that is confined to a single sedimentary bed or horizon.

23 Syenite: a coarse-grained intrusive igneous rock consisting predominantly of potassium feldspar and little or no quartz.

of pegmatites, carbonatite breccias, stockwork²⁴ zones and disseminated mineralisation. The ores are dominated by baryte, fluorite, aegirine-augite, calcite and bastnäsite (Hou et al. 2009). The Maoniuping deposit formed during the Cenozoic²⁵ orogeny²⁶ and consists of a vein system extending for some 2.6 km. REE in the original carbonatite are thought to have been enriched by hydrothermal fluids (Wang et al. 2008). The deposit is estimated to contain 1.2 million tonnes of ore averaging 2.89 per cent rare earth oxide (REO) (Hou et al. 2009).

The Lower Cretaceous²⁷ Chilwa Alkaline Province of southern Malawi lies at the southern end of the East African rift. It contains numerous mineralised carbonatitic and alkaline complexes, including the Kangankunde, Chilwa Island, Songwe and Tundulu complexes. Kangankunde is one of the largest carbonatites in the province and the richest in REE. It consists of approximately concentric zones of agglomerate, breccia, gneisses and fenite, surrounding a carbonatite core containing monazite, strontianite, fluorite and baryte. The monazite at Kangankunde is unusual for its high Ce levels and extremely low thorium and uranium content (Ministry of Energy and Mines, 2009). The REE-rich Okorusu fluorite deposit in northern Namibia developed from fluids expelled by the Cretaceous Okorusu carbonatite. A wide zone of brecciation and fenitization²⁸ surrounds the Okorusu complex. The fluorite mineralisation occurs at the outer edge of the zone of fenitization as either massive fluorite veins or replacement deposits (Buhn et al. 2002).

The Amba Dongar Carbonatite complex in western India consists of a carbonatite ring dyke and a number of syenite intrusions, hosted in late-Cretaceous sandstones. Hydrothermal activity has resulted in REE enrichment of the carbonatites and associated fluorite mineralisation (Doroshkevich et al. 2009).

The Early Cretaceous Barra do Itapirapuã carbonatites in southern Brazil are associated with REE mineralisation, resulting from hydrothermal overprinting of the original carbonatite. Hydrothermal alteration has resulted in the introduction of quartz, apatite, fluorite, REE fluorocarbonates, barytes and sulphide minerals. The REE were introduced during two stages of hydrothermal activity, probably related to magmatic fluids. The initial

stage representing the peak REE-mineralisation deposited fluorocarbonates with quartz and apatite. A subsequent hydrothermal stage resulted in LREE depletion and HREE enrichment relative to the earlier mineralisation (Andrade et al. 1999; Ruberti et al. 2008).

Deposits associated with alkaline igneous rocks

Alkaline igneous rocks form from magmas so enriched in alkalis that they precipitate sodium- and potassium bearing minerals (such as feldspathoids, alkali pyroxenes and amphiboles) not commonly found in other rock types. Alkaline igneous rocks vary widely in composition, from ultramafic²⁹ to felsic³⁰. Alkaline rocks can be further classified as peralkaline if they have a higher molecular proportion of combined sodium and potassium than aluminium. Importantly peralkaline rocks are commonly characterised by extreme enrichment in alkali metals (sodium, potassium), high-field strength elements³¹ (HFSE) such as zirconium, titanium, yttrium, niobium and REE. REE deposits associated with peralkaline rocks are typically relatively low-grade, although they are commonly enriched in yttrium and HREE (Castor and Hedrick, 2006).

The formation of HFSE mineralisation in alkaline rocks is poorly understood. It is generally agreed that the initial enrichment of HFSE results from magmatic processes. In some instances magmatic processes are entirely responsible for the mineralisation, as is evident from deposits in which REE mineral-rich layers form part of a cumulate³² sequence. In other examples hydrothermal processes have played the dominant role, upgrading initial magmatic concentrations. For example, in the fluorspar associated REE deposits of the Gallinas Mountains in New Mexico, USA the total REE concentration in the quartz-syenite intrusion, the suggested source of the mineralising fluids, is about 650 ppm, compared to the deposit which grades 1.5–2.5 wt. per cent REE, requiring hydrothermal enrichment of around 25 times (Salvi and Williams-Jones, 2004). Fluorspar, which commonly occurs in hydrothermal veins, is a potential source of REE which substitute for calcium in fluorite or occur as associated REE minerals.

The Ilimaussaq alkaline complex in southern Greenland contains potentially exploitable deposits of REE, zirconium

29 Ultramafic: composed chiefly of ferromagnesian (Fe-Mg) minerals, such as olivine and pyroxene.

30 Felsic: a rock consisting chiefly of feldspars, feldspathoids, quartz, and other light-coloured minerals.

31 High field strength element: elements which are not readily incorporated into the structures of common rock-forming silicate minerals during crystallisation of an igneous rock.

32 Cumulate: igneous rocks or mineral-rich layers formed by the settling of crystals in a magma chamber.

24 Stockwork: a network of many cross-cutting veins.

25 Cenozoic: the period of geological time from 65 million years ago to present.

26 Orogeny: a mountain building event resulting in folding and faulting of the Earth's crust.

27 Cretaceous — a geological period from circa 145 to 65 million years ago.

28 Fenitization — alkali chemical alteration of a rock resulting in enrichment in sodium and/or potassium.

and niobium in eudialyte-rich cumulate layers. Twenty-nine separate eudialyte-rich layers have been defined, with a total resource of about 2 million tonnes, grading 1.5 per cent REO. The Khibina and Lovozero complexes on the Kola Peninsula in Russia are some of the largest peralkaline igneous bodies in the world. The Khibina Complex hosts extensive nepheline syenite-associated apatite deposits thought to have crystallised from a magma. The apatite is enriched in yttrium amongst other elements. The Lovozero Complex is rich in zirconium, niobium, REE, yttrium, strontium, barium and phosphorus, which occur as eudialyte, loparite and apatite. Loparite has been mined periodically for about 50 years (Figure 4). Annual production is approximately 30 000 tonnes of loparite concentrate, containing 34 per cent REO (Salvi and Williams-Jones, 2004). The Strange Lake Complex in eastern Canada consists of several HFSE-enriched peralkaline³³ plutons. The dominant REE-bearing mineral is gittinsite, but other important minerals include bastnäsite, monazite, kinosite, thorite and gadolinite. The Thor Lake (Nechalacho) deposit in the Northwest Territories of Canada is hosted in a syenite and associated alkaline granite (Figure 5). The larger of two deposits delineated contains 642 million tonnes of ore grading 1.96 per cent REE, amongst other elements. Other significant examples of REE enrichment associated with alkaline rocks include the Tamazeght Complex, Morocco, and the Pilanesberg Complex, South Africa (Salvi and Williams-Jones, 2004). The Weishan REE deposit in Shangdong Province, China consists of bastnäsite-barite-carbonate veins associated with syenite intrusions (Castor and Hedrick, 2006).



Figure 4 Pinkish-red crystals of eudialyte in nepheline syenite and pegmatite from Lovozero, Kola Peninsula, Russia. BGS © NERC.

33 Peralkaline: igneous rocks with if they have a higher molecular proportion of combined sodium and potassium than aluminium.



Figure 5 REE-bearing bastnäsite, Thor Lake. © Clint Cox, The Anchor House, Inc. 2007.

Deposits unrelated to alkaline igneous rocks

A diverse group of REE deposits is not obviously related to alkaline igneous rocks. The most significant group is the iron-REE deposits, also termed iron-oxide-copper-gold (IOCG) deposits or Olympic Dam type, after the massive Olympic Dam copper-uranium-silver-gold deposit, in South Australia. Notably REE concentrations are not a defining characteristic of these deposits as they are absent from many examples. They are hosted by a variety of rocks ranging from intrusive³⁴ igneous to volcanic and a variety of sedimentary rocks. In these deposits iron minerals (magnetite and hematite) form a significant component of the mineralisation. Copper sulphides are commonly present and other minerals can include quartz, apatite, REE minerals (including bastnäsite, monazite, xenotime, allanite, parasite and apatite) uraninite and thorite.

Deposits of this group typically take the form of disseminated³⁵ to massive³⁶ replacement bodies, veins³⁷ and breccia zones. The introduction of REE is commonly associated with two stages of mineralisation. In the early stage of deposit formation the REE occur in apatite associated with magnetite mineralisation. From an economic perspective this stage of mineralisation is less significant because of the generally low abundance of apatite, which typically has a low REE content. However, the second stage is considerably more important. In the case of the Olympic Dam deposit, this mineralising stage consists of bastnäsite in association with hematite,

34 Intrusive: a body of igneous rock emplaced into pre-existing rocks.

35 Disseminated: small, fine-grained particles of ore mineral dispersed through a rock.

36 Massive: a homogenous structure.

37 Vein: minerals deposited in fractures in a rock.

quartz-sericite, bornite and baryte. Other REE-bearing minerals include florencite, monazite and xenotime (Samson and Wood, 2004). The Olympic Dam deposit consists of a funnel-shaped hydrothermal breccia body, within a granite, containing up to 95% hematite (Reynolds, 2001; Reeve et al. 1990). The breccia complex is strongly enriched in REE, averaging 3000–5000 ppm combined lanthanum and cerium (Reynolds, 2001). The ore typically contains about 0.5 per cent REO (Castor and Hedrick, 2006) and it is not currently economic to recover this from the deposit.

At the Pea Ridge iron deposit in Missouri, USA high-grade REE mineralisation is associated with breccia pipes related to a granitic body. The deposit contains monazite and xenotime, and is dominated by LREE, but also contains significant HREE enrichment. The extensive magnetite and hematite deposits at Kiruna, Sweden are reported to be enriched in REE (Castor and Hedrick, 2006). Some researchers include the huge Bayan Obo iron-REE-niobium deposit, China in the Olympic Dam class because of the abundant iron oxides (1.5 billion tonnes containing 35 per cent Fe) (Samson and Wood, 2004; Smith and Chengyu, 2000).

There are a number of REE deposits which do not display characteristics of the iron-REE deposits and are not obviously associated with alkaline or carbonatite intrusions. Examples include the REE mineralisation hosted in sedimentary rocks of the Rocky Mountains in North America. Fluorite-associated REE mineralisation in sedimentary rocks occurs at Rock Canyon Creek in British Columbia, Canada and at the Snowbird deposit in Montana, USA. At Rock Canyon Creek mineralisation varies from finely disseminated to vein and breccia-hosted mineralisation associated with fluorite and baryte, REE minerals (synchysite and parisite dominate), quartz and carbonate. REE-thorium mineralisation occurs in sedimentary rock-hosted veins and breccia zones in the Lemhi Pass area along the Idaho-Montana border. The veins are rich in quartz, biotite and feldspar with hematite, monazite, thorite and apatite. The Hoidas Lake REE deposit in Saskatchewan, Canada is hosted by granitic³⁸ to dioritic³⁹, high-grade metamorphic rocks. The deposit is structurally controlled and lies close to a major fault zone. The mineralisation consists of a pyroxene- and apatite-rich vein system, containing allanite. The veins are controlled by north-east-trending faults

forming a 60 metre wide mineralised zone, extending for nearly 500 metres (Harvey et al. 2002). In Australia, the Mary Kathleen uranium-REE skarn deposit consists of numerous lenses and veins of massive allanite and apatite, hosted in high-grade metasedimentary⁴⁰ rocks close to an alkali granite intrusion (Samson and Wood, 2004).

Secondary deposits

Placer deposits

Placer deposits are concentrations of resistant, heavy minerals transported and deposited with sand and gravel by rivers and/or coastal processes. These detrital minerals can originate from a diverse range of primary sources and frequently include minerals rich in titanium, zirconium and REE. The most important placer deposits containing significant quantities of REE minerals are Tertiary⁴¹ or Quaternary⁴² in age. However, deposits as old as Precambrian, known as paleoplacers, are found in a few countries (Castor and Hedrick, 2006). Orris and Grauch (2002) identify more than 360 REE placer deposits worldwide. The most important REE-bearing mineral in placer deposits is monazite, with minor quantities of xenotime, fergusonite, euxenite, samarskite, allanite, knopite, pyrochlore and loparite (Möller, 1986).

The most important placer deposits are of marine origin, developed along, or in close proximity to, current shorelines. The heavy minerals in these deposits are concentrated by wave action, tides and currents. These deposits are largely exploited for their titanium and zirconium contents. During the 1980s monazite and xenotime produced from titanite-zircon beach placers in Australia were one of the most important sources of REE. Although historically important very little REE production is currently derived from monazite-bearing placers, owing to their typically high thorium content and associated high levels of radioactivity (Castor and Hedrick, 2006). Monazite generally forms a minor constituent of these deposits (typically less than 0.1 per cent) among the other heavy mineral phases and, as a result, REE production from placers was only economic because of the production of the other minerals. However, Australian deposits have local concentrations up to 1 per cent monazite and Indian ilmenite placer deposits can contain 1–2 per cent monazite (Möller, 1986).

38 Granite: an intrusive igneous rock dominated by quartz and feldspar.

39 Diorite: an intrusive igneous rock dominated by plagioclase feldspar, hornblende, pyroxene and little or no quartz.

40 Metasedimentary: sedimentary rock that shows evidence of having been subjected to metamorphism.

41 Tertiary: the period of geological time extending from about 65 to 2.6 million years ago.

42 Quaternary: the most recent period of geological time, spanning about 2.5 million years ago to present.

Extensive heavy mineral marine sand placer deposits occur along the Australian coastline. Fossil beach sand deposits occur both north and south of Perth in the south-west of Western Australia. Important fossil beach sand deposits also occur in the Murray Basin in central New South Wales and Victoria. Heavy mineral sand deposits also occur in the Eucla Basin of South Australia (Hoatson et al. 2011). The rutile-zircon-ilmenite deposits at Eneabba, north of Perth, historically produced about 2500 tonnes of monazite annually. The total heavy mineral content of the sands at Eneabba is about 6 per cent, with a monazite content between 0.5–7 per cent. These deposits formed in the late Tertiary to early Pleistocene⁴³ and are now located about 30 m above current sea level. The heavy minerals are thought to be derived from Archaean⁴⁴ metamorphic rocks which were incorporated in Mesozoic⁴⁵ sedimentary rocks before being reworked to form the placer deposits (Castor and Hedrick, 2006).

Other important marine placer deposits in Australia, representing large REE mineral resources, are the five WIM deposits, located inland in the southern Murray Basin of Victoria. These deposits represent fine-grained heavy mineral concentrations, deposited offshore in a shallow marine environment under low-energy conditions (Hoatson et al. 2011). One of these, the WIM 150 deposit, consists of a mid-Miocene⁴⁶, 14 metre thick sheet-like titanium and zirconium mineral sand body (Castor and Hedrick, 2006). Historic estimates suggest the WIM deposits contain approximately three million tonnes of REO in more than 200 million tonnes of heavy mineral concentrates (Hoatson et al. 2011).

Heavy mineral sand deposits also occur along the east coast of Australia, extending for about 1400 km from the Hawkesbury River in New South Wales to Fraser Island in Queensland. These are described as 'high dune sand deposits' by Hoatson et al. (2011), with the heavy mineral concentration resulted from the winnowing action of the wind. The heavy mineral concentration of these dune sands is generally low (<0.05 per cent), but locally reaches 1–2 per cent. Heavy mineral sand deposits at North Stradbroke Island, in Queensland are associated with a complex Pleistocene to Holocene⁴⁷ coastal sedimentary sequence. This consists of beach and dune sand deposits, with the majority of the heavy minerals sand resources occurring in the latter (Hoatson et al. 2011).

Monazite has been produced from placer deposits in a number of other countries. India has extensive beach sand deposits containing monazite in addition to other heavy minerals. The majority of the deposits occur along the present coastline and are estimated to contain 2.7 million tonnes of REO. In south-east Asia, monazite and xenotime occur in placer deposits worked for tin, zircon and titania. Alluvial tin deposits in Malaysia contain significant monazite and xenotime and Malaysia historically dominated yttrium production from xenotime. Monazite, in addition to other heavy minerals, was produced from Pleistocene marine sands at Green Cove Springs in Florida, USA. The USA has some historically important non-marine placer deposits. In these monazite typically occurs with ilmenite, zircon, magnetite and other minerals. Notable occurrences are the Carolina monazite belt and deposits in Idaho where monazite and euxenite were produced. (Gupta and Krishnamurthy, 2005; Castor and Hedrick, 2006).

A considerably older deposit containing REE-bearing minerals of possible placer origin occurs at Elliot Lake in Ontario, Canada. The deposit, formerly mined chiefly for uranium, consists of a metamorphosed early Proterozoic conglomerate containing REE in monazite, uraninite and brannerite. Metamorphism and hydrothermal activity may have subsequently enriched the heavy minerals (Castor, 2008b).

Residual weathering deposits

Laterites are in situ residual deposits derived from prolonged tropical weathering which leads to the breakdown of many rock-forming minerals, leaching of certain elements (e.g. calcium and magnesium) and residual enrichment of less mobile elements (e.g. iron and aluminium). Under certain conditions and where the parent rock is enriched in REE, such as in carbonatites, REE may be enriched to form an economic deposit. Chemical weathering of carbonatites causes dissolution of calcite, dolomite and apatite. REE released from these minerals can be incorporated in new supergene⁴⁸ minerals, commonly phosphates including monazite. The deposits are typically high-grade, containing 10–25 per cent REO. The major REE deposit at Mount Weld, Western Australia is developed in a thick laterite, above a Proterozoic⁴⁹ carbonatite intrusion. The deposit has exceptionally high REO contents of up to 40 per cent occurring mainly in REE phosphate minerals. The unweathered carbonatite contains 0.1–0.2 per cent REO and the extreme enrichment

43 Pleistocene: the geological epoch extending from about 2.5 million to 11 700 years ago.

44 Archaean: the period of geological that is older than 2500 million years ago.

45 Mesozoic: the geological era extending from about 250 to 65 million years ago.

46 Miocene: the geological epoch extending from about 23 to 5 million years ago.

47 Holocene: the geological epoch which began about 10 000 years ago.

48 Supergene: near-surface processes of leaching and transportation of metals followed by re-precipitation.

49 Proterozoic: the period of geological time extending from 2500–542 million years ago.

is thought to result from leaching and redeposition of REE by groundwater over a sustained period (Lottermoser, 1990; Castor and Hedrick, 2006).

A number of Brazilian carbonatites display supergene enrichment of various mineral commodities associated with lateritic zones. The Cretaceous Araxá carbonatite in Brazil is a ring complex about 4.5 kilometres in diameter. Deep weathering has created a laterite rich in phosphorus, REE and niobium. The REE largely occur in secondary phosphate minerals (Pirajno, 2009; Castor and Hedrick, 2006).

A relatively newly described class of REE deposits are residual deposits of REE-bearing clays, termed ion-adsorption clays in the majority of the literature or alternatively 'weathered crust elution-deposited rare earth ore' (Chi and Tian, 2008). These deposits, associated with weathered REE-enriched granites, occur throughout southern China, particularly in the provinces of Jiangxi, Guangdong, Hunan and Fujian (Grauch and Mariano, 2008). The weathered REE-rich zones range from 5–30 metres in thickness, but are typically in the range of 8–10 metres thick (Chi and Tian, 2008). These zones can be divided into four layers based on mineralogy: an upper layer dominated by soil (0–2 metres); a strongly weathered zone enriched in REE (5–10 metres); a semiweathered layer (3–5 metres); and a weakly weathered zone with the same minerals as the original rock (Castor and Hedrick, 2006; Kanazawa and Kamitani, 2006). Research suggests REE released during the weathering of the granites and the breakdown of primary minerals are absorbed by kaolin and other clay minerals such as halloysite in the form of hydrated ions or hydroxyl hydrate ions (Chi and Tian, 2008). These are small deposits, in the range of 3000–12 000 tonnes, with low grades between 0.03–0.35 per cent total REO (Grauch and Mariano, 2008). However, importantly they are particularly rich in the heavier REE and have extremely low content of radioactive elements (Chi and Tian, 2008).

Concentration of REE in other environments

REE accumulations are reported from a range of other geological settings and lithological associations not described above. Xenotime in the Killi Kill Hills, located in the Proterozoic Birrindudu Basin, in northern Australia is thought to be related to unconformity-associated uranium mineralisation, associated with fluids released during sandstone diagenesis (Vallini et al., 2007).

Phosphorites, sedimentary rocks of biochemical origin, which contain high amounts of phosphate-bearing minerals are commonly enriched in REE. Global phosphate

deposits are classified into three principal types: sedimentary phosphate deposits; apatite-rich igneous rocks and associated residual deposits; and modern and ancient guano accumulations. Marine phosphorites are the most significant in terms of global resources (Simandl et al., 2011). Extensive phosphorite deposits occur in the south-east US, extending from North Carolina to the centre of the Florida peninsula. The potential REE resource in these deposits has not been estimated, although yttrium and lanthanum are present (Long et al., 2010). Cambrian age REE-bearing phosphorites are described from Zhijin, Hinhua and Guizhuo deposits in south-west China (Jie et al., 2006).

Seafloor sediments have recently been proposed as a potential source of REE. Deep-sea muds (metalliferous sediment, zeolitic clay and pelagic red clay) in two regions, the eastern South Pacific and central North Pacific, are reported to contain high concentrations of REE. Sampling indicates that in the eastern South Pacific the REE-bearing mud contains 1000–2230 ppm total REE and 200–430 ppm HREE. The REE-bearing mud is deposited at the surface and is typically 3–10 metres thick. The REE-bearing muds in the central North Pacific are much thicker (typically more than 30 metres) and have lower REE contents in the range 400–1000 ppm. In addition to REE, the muds are enriched in other metals including vanadium, cobalt, nickel, copper, zinc and molybdenum. It is suggested that the REE enrichment is related to mid-ocean ridge hydrothermal activity, which has scavenged REE from seawater (Kato et al., 2011).

Extraction methods and processing

The diversity of REE-bearing deposits results in considerable variation in the mining and processing techniques used in their exploitation. Because REE are frequently exploited as by-products of other metals, these will frequently dictate the economics of the operation and the type of mining used.

Extraction methods

Surface mining

Surface mines are generally safer and more economic to operate than underground mines. Open-pit mining is most appropriate for near-surface deposits, typically less than 100 metres, which are lower-grade, steeply dipping or massive ore bodies. This method typically involves removing the overburden, digging the ore or blasting with explosives, then removing the ore by truck or conveyor belt for stockpiling prior to further processing. Surface and underground mining are sometimes combined at a single mine, and may take place simultaneously in order to

access shallow and deeper parts of an ore body. Hard rock deposits such as those containing bastnäsite are extracted using either open pit or underground methods. The Bayan Obo deposit in China is mined from two large open pits using a standard open-pit mining approach (Jackson and Christiansen, 1993). The Mountain Pass deposit in California was also mined as an open pit, which was 150 metres deep. Blast holes were drilled at 3–4 metre spacing and assayed for REO using X-ray fluorescence (Castor and Hedrick, 2006). The Mount Weld deposit in Western Australia is currently being mined using open-pit methods.

Mining methods for placer deposits are dependent on whether they are submerged in water or on land. Dry mining operations use scrapers, bulldozers and loaders to collect and transport the typically poorly consolidated ore to the processing plant (Figure 6). Dry mining is suitable where deposits are shallow, contain hard bands of rock or occur in a series of discontinuous ore bodies (Iluka, 2010). Drilling and blasting is not generally required except in limited areas where the sand has been cemented by ferruginous or calcareous precipitates (Jackson and Christiansen, 1993). When placer deposits are submerged in water or are affected by a high water table, extraction typically uses a dredger. Dredgers are floating vessels which either use a series of buckets or a suction device to recover material from the base of the water column. Dredgers are also used in artificial ponds, pumping ore in slurry form to a floating concentrator (Iluka, 2010).



Figure 6 Placer deposit mining © image courtesy of Iluka Resources.

In-situ mining

Ion adsorption deposits, such as those found in southern China, are relatively low grade but mining and processing is simpler than for other types of deposit due to their near-surface, unconsolidated nature. No drilling or blasting is required thus considerably reducing extraction costs

(Kanazawa and Kamitani, 2006). The deposits were initially mined using open-pit methods. The ore required no milling or dressing before processing, but the pond and pile leaching techniques used to treat the ore caused extensive environmental damage. In-situ mining techniques have subsequently been developed. The in-situ method is better suited to the softer ion adsorption clays that occur in areas like Longnan than the harder 'granite clay' areas in Guangdong.

The in-situ mining technique was developed by Jiangxi South Rare Earth Hi-Tech (SREC). The method involves drilling holes into the deposit. A reagent (ammonium sulphate) then leaches through the rock, before being collected through holes drilled at a lower level. This enables the stream of rare earth-rich reagent to be collected and channelled into tanks where ammonium carbonate is used as a precipitating agent.

It is estimated that over 90 per cent of the rare earths are recovered by leaching the ore with either an ammonium or salt-based solution. Oxalic acid is then added to precipitate the rare earths as oxalates. The oxalates are filtered and roasted then converted to rare earth oxides. This results in a concentrate with a total REO content of more than 90 per cent (Roskill, 2007).

Underground mining

Underground extraction uses a variety of standard mining methods depending on the characteristics of the ore body. Typically, these operations use labour-intensive drilling and blasting techniques, though attempts are being made to introduce more mechanisation into the workplace. Room and pillar is an underground mining method where mining progresses in a near horizontal direction by opening multiple stopes or rooms leaving pillars of solid material for roof support. Ore is blasted using explosives. It is then transported to the shaft using an underground rail system. Old workings may be backfilled with waste material to improve ventilation by forcing air to travel through only those areas that are being worked, as well as providing more roof support. Underground room and pillar methods were used at the Elliot Lake mine in Canada where REE were extracted as a by-product of uranium production (Harben, 2002). Loparite from the Lovozero complex in Russia is mined using both underground and open pit methods (Castor and Hedrick, 2006).

By-product production

REE are very rarely mined as the only or primary product of a mine, although Mountain Pass in California and Mount Weld in Western Australia are operated exclusively for the

recovery of REE. REE are extracted from Bayan Obo in China as a by-product of iron ore extraction. Loparite production in Russia is a by-product of titanium extraction and REE have been recovered from uranium mining operations in Canada. The Dubbo Zirconia operation in Australia will produce REE in addition to zirconium and niobium. REE in mineral sand deposits are generally by-products of titanium, zircon or tin extraction. Brazil is the only country where a mineral sand deposit has been worked exclusively for monazite. However, this was principally for the thorium content of the monazite rather than the REE (Gupta and Krishnamurthy, 2005).

Processing

After mining, the ores are processed to increase their REE content. Concentration is normally undertaken at, or close to, the mine site and involves crushing the ore and separating REE from the gangue minerals, using a range of physical and chemical processes.

Physical beneficiation

Hard rock deposits

Following mining, bastnäsite ore was crushed and screened. Prior to closure in 2002, ore at the Mountain Pass deposit in California was deposited in layers to form blending piles containing an average of seven per cent REE oxide. This material was subsequently conveyed to a ball mill where the particle size was reduced to approximately 0.1 mm. The material was then subjected to up to six conditioning treatments with steam and different reagents being added at each stage to produce a slurry containing 30–35 per cent solids. The slurry was processed by flotation to produce a bastnäsite concentrate (Figure 7). Froth flotation⁵⁰ is a selective process for separating minerals using water, chemicals and compressed air. Following grinding, water is added to the powdered ore to produce a suspension⁵¹. Air is blown upwards through the tanks. Chemicals are added which make specific minerals water repellent and cause air bubbles to stick to their surfaces. Consequently, these minerals collect in a froth at the surface and are removed. Reagents⁵² used for monazite flotation include fatty acids, hydroxamates⁵³ and dicarboxylic⁵⁴ acids. However, there are problems

with flotation separation as some of the common gangue minerals associated with bastnäsite, such as barite and calcite, have similar flotation properties (Gupta and Krishnamurthy, 2005).

Following flotation the ore is cleaned. At Mountain Pass a four stage cleaning method was devised producing a final concentrate of 60 per cent REE oxide with an overall recovery of 65 to 70 per cent (Gupta and Krishnamurthy, 2005).

Mountain Pass is unusual in that REE were the only product from the mine. Other operations generally produce REE as a by-product of other minerals and accordingly the beneficiation methods vary greatly. For example at the Bayan Obo deposit magnetite, hematite, fluorite and niobium oxide are also recovered and the beneficiation process is influenced by this requirement (Castor and Hedrick, 2006). The iron ore is separated by flotation and a bastnäsite concentrate and a mixed bastnäsite-monzite concentrate are produced (McKetta, 1994). Physical beneficiation of loparite in Russia uses a combination of gravity and electrostatic methods to produce a 95 per cent loparite concentrate (Castor and Hedrick, 2006).

Placer deposits

Since placer deposits show considerable variation in mineralogy and chemical composition the beneficiation methods vary greatly. In many cases gravity separation is used as it is particularly effective for separating minerals with significant differences in densities. The sediment is fed into a suspension, and the gangue particles, having a lower density, tend to float and are removed as waste. The higher density minerals of economic value sink and are also removed. Equipment including jigs, spiral and cone concentrators and shaking tables are used in gravity separation (Castor and Hedrick, 2006). In placer deposits the initial gravity separation is completed on the dredge during mining and unwanted tailings are discharged back into previously mined areas (McKetta, 1994). Higher grade deposits such as the Chavra sands in India contain 70–75 per cent heavy minerals and do not require this pre-concentration stage (Gupta and Krishnamurthy, 2005). However, monazite will normally only form 2–5 per cent of this heavy mineral concentrate.

The concentrate produced by gravity concentration is processed in a dry mill. Concentrates of ilmenite, rutile, leucoxene, zircon and monazite are produced using a combination of gravity, magnetic and electrostatic methods (Figure 8). Monazite, in contrast to ilmenite, rutile and many other heavy minerals found in placer deposits, is non-conductive and is separated, with zircon, by electro-

50 Froth flotation: a process for selectively separating hydrophobic (lacking affinity for water) materials from hydrophilic (having a strong affinity for water).

51 Suspension: a mixture in which fine particles are suspended in a fluid where they are supported by buoyancy.

52 Reagent: a substance or compound that is added to a system in order to bring about a chemical reaction.

53 Hydroxamate: a hydroxylamine (a reactive chemical with formula NH_2OH) compound containing a CONOH group.

54 Dicarboxylic acid: organic compounds that are substituted with two carboxyl functional groups (a carboxyl functional group consists of a carbon atom joined to an oxygen atom by a double bond and to a hydroxyl group, OH, by a single bond).

static methods. It is then separated from the zircon by electromagnetic or further gravity processing as it is moderately susceptible to magnetism and has a higher density. Xenotime is usually separated from monazite using precise gravity methods as they have very similar density and magnetic properties (McKetta, 1994). For finer grained deposits (between 15 and 100 microns) gravity separation is not an efficient method so flotation is used (Gupta and Krishnamurthy, 2005).

Chemical beneficiation

Following physical beneficiation to produce a REE mineral concentrate subsequent processing is required to extract the REE (Figure 9). The processes used for this have not developed considerably over the last 20 years and the processing route selected depends on the type of minerals and the economics of the operation (Chegwidden and Kingsnorth, 2002).

Hard rock deposits

At the Mountain Pass deposit the bastnäsite concentrate (about 60% REO) obtained from physical beneficiation was upgraded to about 70 per cent by leaching with hydrochloric acid to remove strontium and calcium carbonates. Calcination was then used to remove the carbon dioxide leaving an 85–90% REO concentrate

(Jackson and Christiansen, 1993). At Bayan Obo the mineral concentrate is baked with sulphuric acid at 300–600°C and leached with water, taking the REE into solution and precipitating other elements as waste (liquid-solid separation). The REE are then precipitated as double sulphates, converted to hydroxides and leached with hydrochloric acid for purification. Loparite concentrate in Russia is processed using gaseous chlorination at high temperatures in the presence of reducing agents. Titanium, niobium and tantalum are separated from REE chlorides and other elements which remain as a fusion cake. This cake is then dissolved in sulphuric acid in the presence of ammonium sulphate. Water is added to dilute the solution and sodium carbonate is used to precipitate the REE and thorium (Castor and Hedrick, 2006).

Unconsolidated deposits

REE extraction from monazite and xenotime involves dissolution of the minerals in hot concentrated alkaline (caustic soda method) or acidic solutions (acid treatment). Acid treatment uses hot sulphuric acid digestion then leaching with water to remove the phosphate content. A dilution stage follows whereby a process of selective precipitation deposits thorium and REE as double sulphates (Castor and Hedrick, 2006). The sulphuric acid method has been used on a commercial basis in the past but it is no

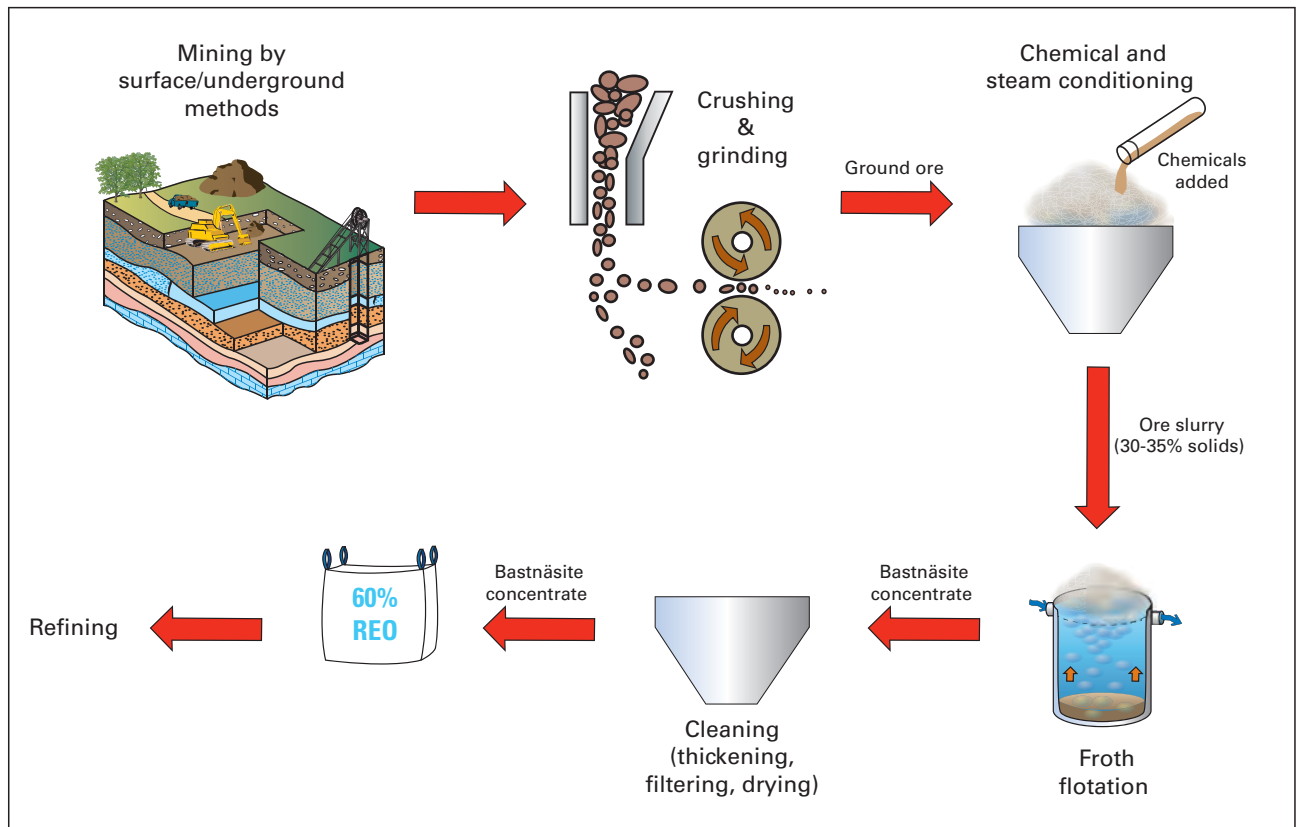


Figure 7 Generalised bastnäsite beneficiation flow diagram, based upon the former Mountain Pass operation.

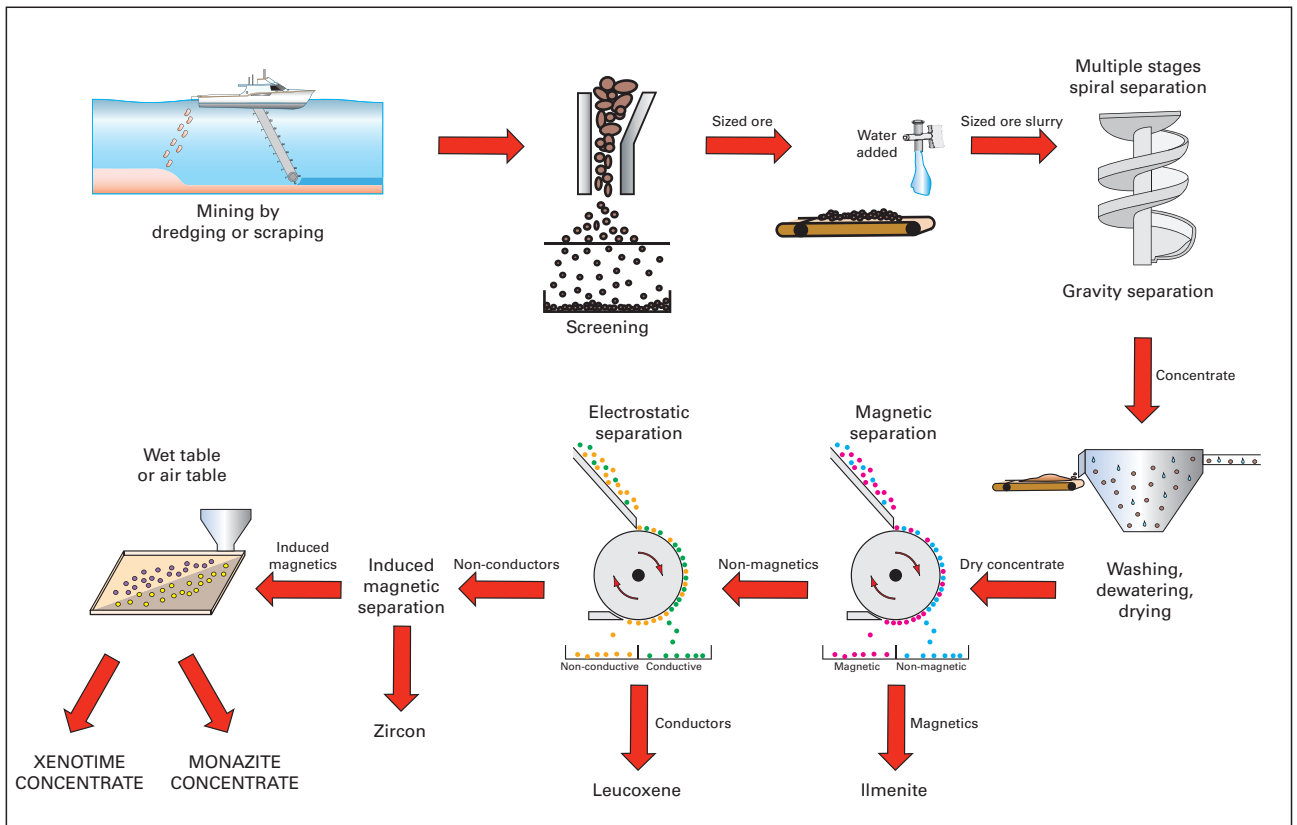


Figure 8 Generalised flow diagram for extraction of monazite and xenotime from placer deposits.

longer in use as it does not yield a pure product (Gupta and Krishnamurthy, 2005).

The caustic soda method involves dissolution of the minerals in a concentrated solution of sodium hydroxide, at 140–150°C, converting the REE and thorium to hydroxides. The phosphate compound is separated by dissolving in water and recovered as trisodium phosphate. REE are separated from thorium using partial dissolution in which REE are dissolved in concentrated hydrochloric acid whilst the undissolved material is filtered and forms thorium cake waste (Gupta and Krishnamurthy, 2005). The caustic soda method is used in India by Indian Rare Earths Ltd and was used in Malaysia at the Asian Rare Earth (ARE) plant until its closure in 1994 (Meor Yusoff and Latifah, 2002). This is the preferred process for chemical treatment as the phosphate can be recovered as a marketable by-product, whereas with acid treatment the phosphate is lost (Gupta and Krishnamurthy, 2005).

Processing of ion adsorption clays is relatively straightforward compared with other types of REE deposit as they do not require the processing of complex minerals that characterise hard rock deposits. A simple leaching process produces a solution containing REE from which a concentrate can be precipitated (Molycorp, 1993). This simple procedure means these types of deposits can be economically exploited

despite their relatively low grades (0.03 to 0.35% total REO) (Grauch and Mariano, 2008). Additional benefits include their low contents of cerium and radioactive minerals, and their enrichment in HREE and yttrium.

Separation of individual REE

The high value of REE depends on their effective separation into high purity compounds. Separating individual REE from concentrates is a very difficult process due to their similar chemical properties (Morais and Ciminelli, 2004). REE processing technology is most advanced in China, which can supply REE products at 99.9999 per cent purity, whilst French companies typically produce 99.99 per cent pure REE and Japanese sources 99.9 per cent REE (Zhongde, 2009).

Selective oxidation or reduction of certain REE can be useful in the separation process. In general REE are characteristically trivalent⁵⁵ but cerium, praseodymium and terbium can occur in the tetravalent⁵⁶ state as well as the trivalent state and samarium, europium and terbium display divalency⁵⁷. These differences in chemical behaviour can be exploited in the separation of individual

55 Trivalent: Having a valance of three.

56 Tetravalent: Having a valance of four.

57 Divalency: Having a valance of two (valency is a measure of the number of chemical bonds formed by the atoms of a given element).

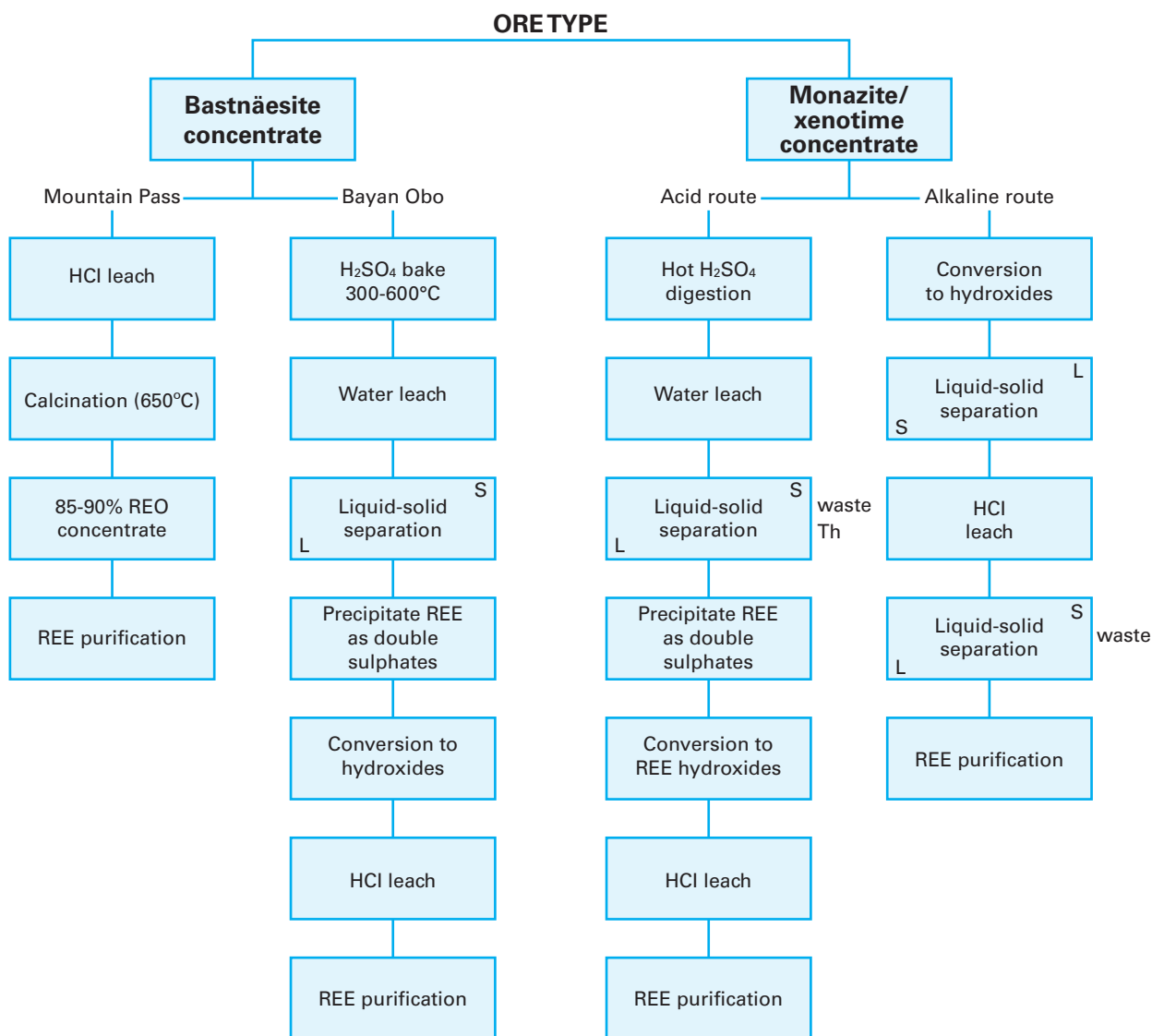


Figure 9 Examples of processing routes for the separation of individual REE from the major REE-bearing minerals. H_2SO_4 , sulphuric acid; HCl, hydrochloric acid (adapted from Chegwidan and Kingsnorth, 2002).

elements (Gupta and Krishnamurthy, 2005). Cerium and europium are generally separated by selective oxidation whilst other REE can be separated using fractional crystallisation⁵⁸, fractional precipitation⁵⁹, solvent extraction and ion exchange methods. These methods are based on the small differences in basicity⁶⁰, resulting from decreasing size in ionic radius from lanthanum to lutetium (Morais and Ciminelli, 2004). Until the early 1950s fractional precipitation and fractional crystallisation were the only techniques available for separating REE. These processes, however, are laborious and inefficient and

have consequently been superseded by more effective techniques like ion exchange and solvent extraction (Gupta and Krishnamurthy, 2005). The solvent extraction method is most appropriate for separating the LREE, with the HREE being more difficult to extract using this method (Moore, 2000).

Ion exchange is a process in which ions are exchanged between a solution and an insoluble (usually resinous) solid. The solution containing the REE is passed over the ion exchange resin. The REE displace the cations⁶¹ on the resin surface. This produces an aqueous waste containing the exchanged cations, with a mixture of REE deposited on the resin. Individual REE are then separated using a complexing agent which has different affinities

58 Fractional crystallisation: the process of separating the components of a solution on the basis of their different solubilities, by means of evaporating the solution until the least soluble component crystallises out.

59 Fractional precipitation: removal of some ions from solution by precipitation while leaving other ions with similar properties in solution.

60 Basicity: The degree to which a substance is basic or alkali.

61 Cation: a positively charged ion.

for the various REE (EPA, 2008). The ion exchange method produces highly pure REE in small quantities. However, it is a time consuming process and only a few HREE are purified commercially on a small scale using ion exchange.

For large scale production solvent extraction is the preferred route (Molycorp, 1993). Solvent extraction (SX), or liquid-liquid extraction, is a method used to separate compounds on the basis of their relative solubilities in two immiscible⁶² liquids, typically water and an organic solvent. This process relies on differences in the relative solubilities of REE in the liquid phases used.

On an industrial scale the SX process is carried out in a group of mixer settlers, called batteries. This allows repetitive fractionation during a continuously flowing process. Initially the process is relatively ineffective as the chemical properties of the REE ions in solution show only incremental variation with atomic number. However, when the process is repeated many times each REE is successfully separated from the others (Rhodia, 2009; Uda et al., 2000).

The end products of SX are usually solid-rare earth salts or oxides. An insoluble salt is precipitated from the solution obtained from the solvent extraction process. This is separated, dried or calcined at high temperatures and then ground (Rhodia, 2009). REE compounds with a purity of more than 99.99 per cent can be produced using this method (Castor and Hedrick, 2006).

Environmental implications

There are many environmental issues associated with REE production. These commonly result from insufficient environmental regulations and controls in the areas where REE are mined and processed. One of the most significant relates to the radioactivity of some ores. For example, xenotime in Malaysian placer deposits typically contains two per cent uranium and 0.7 per cent thorium. This was the main reason that the Malaysian processing industry failed and the plants were closed (Meor Yusoff and Latifah, 2002). Processing of beach sands containing monazite has been banned in Australia, China and Europe due to environmental concerns (Curtis, 2009).

A major advantage of the ion adsorption clay deposits in southern China is their low radioactive element content (Kanazawa and Kamitani, 2006). However, significant environmental issues are associated with exploiting

these deposits due chiefly to their illegal status and lack of adherence to environmental regulation. Although the in-situ mining techniques being applied are more environmentally friendly, there are some concerns regarding the long-term effects of injecting strong reagents into the ground. This led to a number of ion adsorption clay operations being suspended or closed down. However, improved environmental practices, enforced by legislation, have enabled many of these operations to resume production in the past few years (Roskill, 2007).

The regulated mines in southern China, as well as the mines working bastnäsite deposits in Batou, still pose significant hazards because of the chemicals used in processing. Reports indicate that the chemicals used in the refining process have been responsible for disease and occupational poisoning of local residents, water pollution and destruction of farmland (Hilsum, 2009). It has been reported that refining one tonne of REE oxide can potentially produce 60 000 m³ of waste gas containing sulphuric and hydrofluoric acid, 200 m³ of acidic water and 1.4 tonnes of radioactive waste (China Daily, 2010). It is suggested that the limited regulatory controls on China's REE industry has resulted in reduced costs to producers, contributing to its dominance of the market. However, there are indications that China is becoming increasingly aware of the environmental impacts of REE production. It has closed eighty REE production facilities in an attempt to improve efficiency and environmental performance, which is likely to impact on global supplies (Williams, 2009). In addition the Batou Institute of Rare Earths, the world's largest research institute for the industry, is undertaking seven projects aiming to make refining technology more efficient and less environmentally damaging (China Daily, 2010).

As with all extractive operations, REE production uses a considerable amount of energy, and in China most of this is supplied by coal-fired power stations. With increasing concerns about climate change and carbon emissions this may prove to be a significant factor influencing REE production. Conversely, REE products are increasingly used in environmental applications as they offer improvements in energy efficiency and can reduce carbon dioxide emissions. For example, using lanthanum in rechargeable batteries instead of nickel-cadmium, results in fewer environmental problems because, unlike most other types of rechargeable batteries, they do not contain cadmium or lead (Haxel et al., 2002). Use of REE in fluorescent lamps and gadolinium and thulium in magnetic refrigeration significantly reduce carbon dioxide emissions due to increased energy efficiency (Turner et al., 2007).

⁶² Immiscible: one (or more) liquids that are unmixable or insoluble with each other.

Specifications and uses

REE have been traded in a wide variety of forms since they were first exploited. Over the last 40 years the form of Chinese REE exports has changed considerably. In the 1970s exports were largely mineral concentrates, changing in the 1980s to predominantly mixed REE chemicals such as carbonates and chlorides. By the early 1990s separated REE oxides and metals were in greater demand, but by the end of the decade trade was dominated by REE magnets, phosphors and polishing powders. In the 2000s there is considerable trade in components and products containing REE such as magnets, computer hard drives, electric motors and liquid crystal displays (LCDs) (Kingsnorth, 2008a).

Specifications for REE mineral concentrates, compounds and metals vary depending on their end-use. Advances in processing techniques have removed the markets for lower specification products, for example a 90 per cent cerium oxide product used in the glass industry has been replaced by higher-grade cerium products with little or no price penalty (Castor and Hedrick, 2006).

REE are used in the widest range of consumer products of any group of elements (Castor and Hedrick, 2006). REE are indispensable in electronic, optical, magnetic and catalytic applications (Figures 10–12). In these applications REE play a vital role in environmental protection, improving energy efficiency and enabling digital technology, making them critical in a rapidly growing and developing world.

Catalysts

Catalysts⁶³ accounts for a significant share of the REE market by volume (19 per cent), but only five per cent of the total market value (Kingsnorth, 2009). REE are essential in automotive catalytic converters, which transform the primary pollutants in engine exhaust gases into non-toxic compounds. Cerium carbonate and cerium oxide are used in the catalyst substrate and as a component of the converter's oxidising catalyst system (Castor and Hedrick, 2006). The REE play a critical role in the chemical reactions within the autocatalyst and also enable it to run at high temperatures. They also increase the effectiveness and reduce the amount of platinum and other precious metals required, thereby decreasing costs (Lynas, 2010).

REE are also important in fluid cracking catalysts⁶⁴ which are used in the process of refining crude oil, transforming the heavy molecules into lighter compounds that make up petrol and other fuels such as gas, jet fuel and diesel. Lanthanum and cerium are used to stabilise the structure and chemistry of the high surface area zeolites used as a molecular filter in this application (Lynas, 2010).

Magnets

An increasingly important use of REE is in permanent magnets. This application was first developed in the 1960s when samarium alloyed with cobalt was used. By the mid 1980s neodymium–iron–boron magnets had been developed and have now largely replaced samarium–cobalt magnets, except in high temperature applications (Castor and Hedrick, 2006). Neodymium–iron–boron magnets possess a magnetic energy of up to 2.5 times greater than the samarium–cobalt versions. In addition the principal constituent is iron (84.4 per cent) which is significantly cheaper and more abundant than cobalt (Gupta and Krishnamurthy, 2005). Permanent magnets account for approximately 38 per cent of the REE market by value and 21 per cent by volume.

Because neodymium magnets are more powerful than alternatives, they provide improved performance for a smaller size which has led to many miniaturised applications. Tiny neodymium magnets are used in the speakers in earphones for consumer devices such as MP3 players, as well as in numerous other high performance speakers. This results in smaller, lighter devices with improved performance. Permanent magnets are also used in hard disk and DVD drives. The voice coil motor which controls the arm that reads and writes information onto the disk uses a neodymium-based magnet which gives improved control allowing thinner tracks and more data storage (Lynas, 2010).

Neodymium–iron–boron magnets are important in many 'green', carbon reducing technologies. It is estimated that wind turbines use in the range of 0.6–1.0 tonne of neodymium magnets per megawatt, of which approximately 30 per cent is REE (Avalon Rare Metals, 2010; Lifton, 2009a). In wind turbines electricity is generated in an alternator when magnets pass wire coils (Figure 13). One factor which determines the amount of electricity generated is the strength of the magnets used. The stronger the magnets, the higher the current generated, so strong neodymium magnets make considerably better alternators (Reuk, 2007).

⁶³ Catalyst: a substance that initiates or accelerates a chemical reaction without itself being affected.

⁶⁴ Fluid cracking catalyst: catalyst used in the transformation of heavy molecules into lighter compounds.

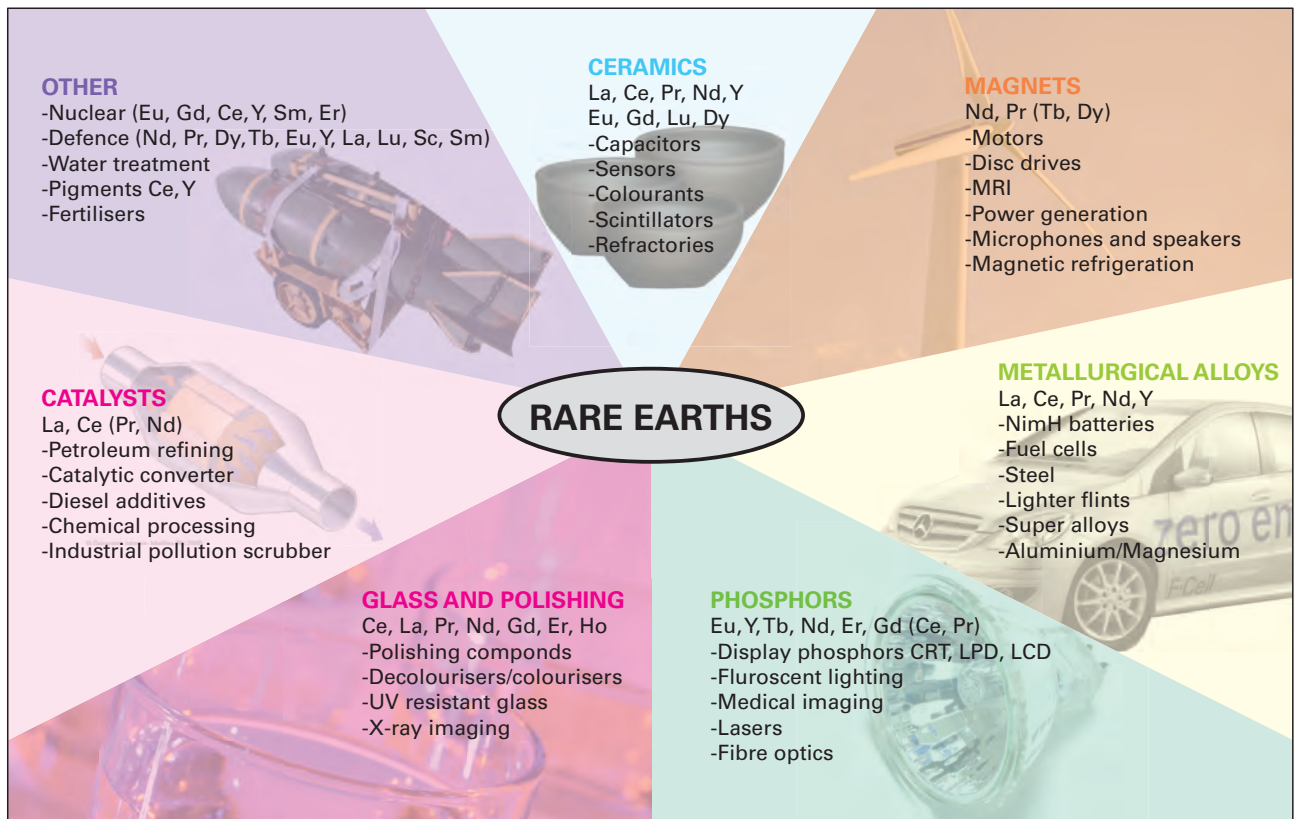


Figure 10 Applications of rare earths. Images courtesy of Johnson Matthey Plc, Mercedes-Benz and Ingrey Publishing.

Neodymium magnets are essential for hybrid cars such as the Toyota Prius. Hybrid cars reduce fossil fuel consumption by combining a petrol engine, battery-powered electric motors and brakes that capture energy during braking (Avalon Rare Metals, 2010). It has been suggested that the Prius is the largest consumer of REE of any individual product with each electric motor in a Prius requiring one kilogram of neodymium (Lifton, 2009b).

The use of REE magnets has the potential to increase the energy efficiency of many appliances. For example use of REE magnets in air conditioning systems can reduce power consumption by up to 50 per cent whilst retaining the same level of performance (London, 2009). Dysprosium and terbium are also used in magnets. Many magnets tend to lose their magnetism as they heat up, but the addition of dysprosium or terbium prevents this from happening at high temperatures (Venter, 2009).

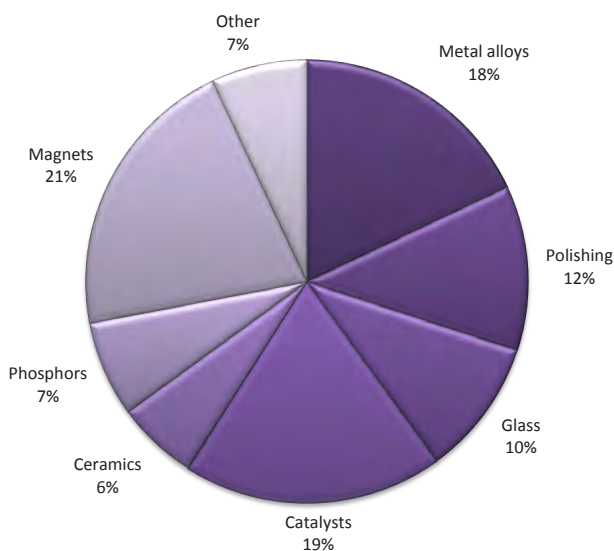


Figure 11 REE consumption by volume (Kingsnorth, 2009).

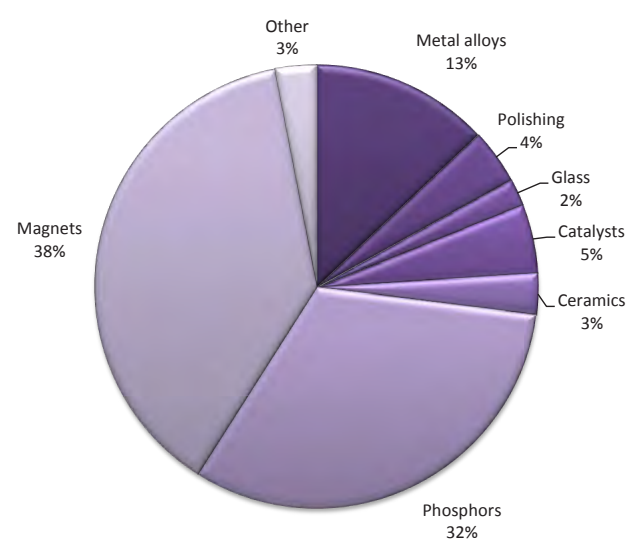


Figure 12 REE consumption by value (Kingsnorth, 2009).

Metallurgical alloys

REE have major applications in metallurgical alloys. In 2008 this use accounted for 18 per cent of global consumption by volume (Kingsnorth, 2008a). One of the oldest uses of REE as an alloy is in mischmetal, a pyrophoric⁶⁵ alloy containing only REE metals. The individual REE are present in the same proportions as they naturally occur in the bastnäsite concentrates (Gupta and Krishnamurthy, 2005). Typical composition is about 50 per cent cerium and 25 per cent lanthanum with small amounts of neodymium and praseodymium. The most common use of this alloy is in the flint ignition device of many lighters and torches, although for this purpose it is blended with iron oxide and magnesium oxide since the REE alloy alone is too soft (Venter, 2009). Mischmetal and cerium are commonly used as minor alloying additives for controlling inclusions in cast irons and steels. The cerium combines with the sulphide inclusions to form more rounded particles which are less likely to promote cracking (Lundin and Wilson, 2009).



Figure 13 Wind turbines use substantial quantities of neodymium–iron–boron magnets. BGS © NERC.

Superalloys are a class of heat resistant alloys used in applications involving intense, high-temperature oxidising environments such as in gas turbine engines and electric generators. Adding REE enhances the alloy's oxidation resistance. In M–chromium–aluminium–yttrium alloys

(where M is iron, nickel or cobalt), yttrium is the active component but lanthanum and cerium are also used in certain nickel and cobalt superalloy compositions. Less than one per cent of REE metal in a superalloy can dramatically improve its performance (Gupta and Krishnamurthy, 2005).

The use of REE as a method of storing hydrogen was identified in 1969 when it was discovered that the intermetallics⁶⁶ REM5 (where RE is the rare earth and M is iron, cobalt or nickel) could absorb a large amount of hydrogen at room temperature. Solid state storage of hydrogen is better than storage as cryogenic⁶⁷ and compressed gas in terms of safety, volume, weight, pressure and energy savings (Gupta and Krishnamurthy, 2005).

REE are used in nickel metal hydride (NiMH) rechargeable batteries that power many electronic products. A mixed rare earth metal alloy is used as the anode in the NiMH battery, representing about 26 per cent of the battery's weight. Lanthanum is the main REE used in the NiMH battery (Australian Rare Earths, 2010). These batteries in addition to many other REE-bearing components, are particularly important for hybrid cars such as the Toyota Prius (Figure 14). It has been calculated that each Toyota Prius battery uses 10 to 15 kilograms of lanthanum (Lifton, 2009b).

Phosphors

REE are commonly used in phosphors⁶⁸. This application accounted for 32 per cent of global consumption by value in 2008, although only seven per cent by volume (Kingsnorth, 2009). Phosphors are important in televisions, computer screens and any other visual display devices that requires cathode ray tube, liquid crystal display or plasma display panel technologies (GWMG, 2010). The colours seen on the display come from the use of europium–yttrium compounds for red, terbium–fluoride–zinc sulphide for green and cerium–strontium–sulphide for blue. These phosphors emit luminescence⁶⁹ when activated by photons⁷⁰ (Jackson and Christiansen, 1993). Plasma screens were developed with the aid of a new europium-based blue phosphor which retains brightness ten times longer than previous blue phosphors (Lynas, 2010).

⁶⁶ Intermetallic: solid state phases involving metals.

⁶⁷ Cryogenic gas: a gas that has been liquefied by lowering the temperature, usually to a temperature under about -100°C.

⁶⁸ Phosphor: a substance that exhibits the phenomenon of phosphorescence (sustained glowing after exposure to energized particles such as electrons or ultraviolet photons).

⁶⁹ Luminescence: any process in which energy is emitted from a material at a different wavelength from that at which it is absorbed.

⁷⁰ Photon: discrete bundle (or quantum) of electromagnetic (or light) energy.

⁶⁵ Pyrophoric: a material which can spontaneously ignite in air.

Figure 14 REE applications in a hybrid electric vehicle © Molycorp Inc. 2010.



Energy efficient lighting is a major application of REE phosphors. The compact fluorescent lamp (CFL) uses only a quarter of the power needed to produce the same amount of light as the standard incandescent light bulb (Lynas, 2010). More recently REE phosphors are being used for white LEDs (Figure 15). LEDs are 80 per cent more efficient than incandescent lighting, and 40 per cent more efficient than compact fluorescent bulbs (Avalon Rare Metals, 2010). REE are used in the manufacture of fibre optics and lasers. In lasers REE, typically neodymium, are used as an activator. Glass fibres containing REE can transmit data over exceptionally large distances without booster stations (Jackson and Christiansen, 1993). REE lasers are being increasingly used for medical and dentistry applications. This is one of the major applications for erbium. Erbium lasers are used in cosmetic treatments to ablate⁷¹ the epidermis⁷² revealing the smoother and younger looking underlying skin. In dentistry, the erbium lasers have proven safe and effective for the removal of tooth decay and cavity preparation in addition to many soft-tissue and hard-tissue surgical procedures (Margolis, 2006).

Glass and polishing

REE are commonly used in the glass industry. Glass and polishing applications accounted for 22 per cent of total REE consumption by volume in 2008, although only six per cent by value (Kingsnorth, 2009). The earliest commercial use of cerium was in 1896 when it was first used as a decolourising agent in glass. Decolourising is necessary as iron oxide is always present as an impurity in glass causing a yellow–green colour. Adding cerium oxidises the iron (Jackson and Christiansen, 1993).

REE are also used as dyes in glass. Small amounts of cerium will decolourise glass but about one per cent will turn it yellow and larger quantities brown. Neodymium colours glass red, praseodymium green and holmium blue. Erbium is used to colour glass pink and it is the only pink truly stable in glass melts. Other colours are obtained by mixing REE with other elements (Gupta and Krishnamurthy, 2005).

REE are important in glass due to their ability to absorb ultraviolet light. Cerium is used in glass bottles to protect the product and prevent browning of the glass due to radiation. Sunglasses contain cerium as well as neodymium and praseodymium to provide UV protection. Lanthanum is an integral part of camera lenses as low silica glass



Figure 15 LED bulb. Ingrey publishing.

71 Ablate: elimination of tissue from the body.
72 Epidermis: the thin, outermost layer of skin.

containing lanthanum oxide has a high refractive index⁷³ and low dispersion⁷⁴. Optical lenses containing gadolinium are used for magneto-optical and electro-optical systems (Gupta and Krishnamurthy, 2005). Praseodymium is used for anti-reflection coatings on lenses and as a constituent of tinted glass filters for selective light absorption (Jackson and Christiansen, 1993).

Substantial amounts of cerium concentrates and oxide are used to polish glass surfaces. Cerium is especially suitable as a polishing agent as it removes glass by both chemical dissolution and mechanical abrasion making it more efficient than other agents such as silica and zirconia. The majority of polished glass products, for example mirrors, television faceplates and cathode ray tubes are finished using cerium oxide (Haxel et al., 2002).

Ceramics

REE oxides are essential in ceramics. Both the strength and toughness of structural ceramics are improved by adding REO (yttrium oxide and cerium oxide in particular) as stabilisers and sintering⁷⁵ aids to reduce sintering temperature and production costs. REO are also important in functional ceramics such as semiconductor sensors, microwave dielectric⁷⁶ and piezoelectric⁷⁷ ceramics (Guanming et al., 2007). Ceramic applications accounted for six per cent of global consumption of REE in 2008 and three per cent by value (Kingsnorth, 2009).

Rare earth oxides are used in ceramic capacitors⁷⁸ to alter the temperature-compensating, dielectric and permeability properties of the various barium titanite ceramic dielectrics. Adding lanthanum, cerium, praseodymium and neodymium results in a stable dielectric constant and gives the capacitor a longer life span (Roskill, 1986).

Small amounts of rare earth oxides are used as colourants in ceramics. For example, praseodymium added to zirconia and silica makes a yellow pigment, yttrium gives an orange colour and neodymium a light purple. These pigments are stable at high temperatures so can be used in single and double firing processes (Gupta and Krishnamurthy, 2005).

73 Refractive index: a measure of how much the speed of a wave is reduced inside that medium compared to the speed of the wave in a reference medium.

74 Dispersion: the phenomenon in which the phase velocity of a wave depends on its frequency.

75 Sintering: a method for making objects from powder, by heating the material in a sintering furnace.

76 Dielectric: non-conducting or insulating material.

77 Piezoelectric: a substance that produces an electric charge when a mechanical stress is applied.

78 Capacitor: an electric device consisting of two electrical conductors isolated from one other by a dielectric material, capable of storing electrical energy for release at some predetermined time.

Refractories are materials that retain their strength at high temperatures and are commonly used to make crucibles. Yttrium oxide, and to a lesser extent cerium oxide, are used in crucibles to protect the principal refractory material, usually zirconia (Roskill, 1986).

Other applications

REE have a range of applications in nuclear energy due to their ability to absorb neutrons and remain stable at high temperatures (Jackson and Christiansen, 1993). Gadolinium is used as a 'burnable poison', especially in boiling water reactors, to even out the performance of the reactor over time. Gadolinium oxide is a neutron absorber which decays under neutron exposure, compensating for the progressive build up of other absorbers as the uranium oxide fuel is used up (World Nuclear Association, 2009). Europium is used for control rods to regulate reactor operation as it is a good neutron absorber (Gupta and Krishnamurthy, 2005).

REE are widely used in pigments and paints. Cerium compounds are used to coat lead chrome paints to make them more resistant to fading due to light exposure. Cerous acetate is used to treat titanium dioxide pigments to make them more durable and resistant to sunlight (Gupta and Krishnamurthy, 2005). Yttrium is used as a coating to provide corrosion resistance and a lead-free surface primer for paints (Hedrick, 2001).

The rare-earth elements (REE) have a wide variety of defence applications. Examples of defence technologies dependent in REE are optics, surveillance and protection, sonar transducers⁷⁹, microwave communication, power and communications, guidance and control, lasers and aircraft materials (Molycorp, 2009).

There are many medical applications of REE, for example gadolinium provides better imaging of tumours. Also RE magnets are important for medical applications, such as Magnetic Resonance Imaging (MRI) equipment. Permanent magnets are being used to replace expensive traditional systems of super cooling wire coils in liquid helium systems to reduce the electrical resistance in the wire coils. This enables the MRI machines to be wider and less claustrophobic for the patient (Avalon Rare Metals, 2010).

REE have been used in agriculture as a fertiliser, mainly in China. REE solutions or compounds are added during

79 Sonar transducer: a device used under water to convert electrical energy to sound energy and sound energy to electrical energy.

production of calcium superphosphate to create a rare earth phosphate fertiliser (REPF) containing between 0.04 and 0.16 per cent REE. Research has shown that this REPF can improve crop yields, decrease diseased plant rates and increase quality (Xiangsheng et al., 2006).

New technologies

As research and technology continues to advance many more applications for REE are being developed and discovered, especially in the areas of energy conservation and efficiency and environmental protection.

There are several applications for REE in new electronic technologies, for example, sub-light-speed computer processors, advanced satellite communication systems and advanced superconductors⁸⁰. As advances are made in materials science it is likely there will be further applications for REE, including in nano-particle technologies (Kennedy, 2010).

Magnetic refrigeration

Magnetic refrigeration is a new technology dependent on REE which is more environmentally friendly and efficient than standard refrigeration methods. Magnetic refrigeration is based on the magnetocaloric effect (MCE) which is the response of a magnetic solid to the application of a magnetic field. When the magnetic field is lowered the electrons⁸¹ within the material spin in a higher energy state⁸², absorbing heat from the material and causing the temperature to fall (Dieckmann et al., 2007). Gadolinium has been found to exhibit this effect strongly and has been suggested as the magnetic refrigerant. For the magnetic field source the most practical option in both household and transport applications is neodymium–iron–boron magnets (Gschneidner and Pecharsky, 2007).

Given the reliance of modern society on refrigeration, the advantages offered by magnetic refrigeration over conventional methods are considerable. It is also more environmentally friendly on account of its higher cooling efficiency. This higher energy efficiency results in less carbon dioxide being released. In addition no ozone-depleting or hazardous chemicals are involved (Brück et al., 2007). It has been calculated that REE magnets will make it possible to reduce up to 15 per cent of global fossil fuel consumption associated with cooling and refrigeration

while eliminating harmful chemical compounds currently used (Kennedy, 2010). There are still a number of issues to be resolved before the first commercial units can be released into the market. However, if commercialised, this technology could have a significant impact on REE demand (Gschneider and Pecharsky, 2007).

Fuel cells

REE are essential in solid oxide fuel cells (SOFC). These are a clean, low-pollution technology to electrochemically generate electricity at high efficiencies. The SOFC is one of the most promising fuel cell technologies. However, conventional SOFCs face challenges in commercialisation due to the high cost of the performance. Recent research has shown that electrolytes⁸³ made using industrial grade mixed lanthanum, cerium and praseodymium (LCP) carbonates are able to achieve excellent fuel cell performance at low temperature making them more cost effective. SOFCs are a potentially important future use of REE (Zhu et al., 2008).

A considerable amount of work has been undertaken in recent years to develop fuel cells as power generators for zero emission electric vehicles. As noble metals such as platinum or palladium are used as a catalyst, the high cost of fuel cells has always been a limiting factor. Research has examined the use of the REE-based AB₅-type hydrogen storage alloy⁸⁴ as a noble metal-free catalyst (Hu and Noréus, 2003). Although research to date is promising, currently no lower cost catalyst material has been found that will produce sufficient energy density⁸⁵ for transportation use (Frenette and Forthoffer, 2009).

Water treatment

New technologies are being developed which will use REE in water treatment. Molycorp, together with the United States army, have invented a portable device to purify water by selective adsorption. They have also developed this technology for use in the mining and smelting industries to remove arsenic by converting it to a concentrated and extremely stable compound for easy filtering and disposal. It is suggested that the process would consume just a fraction of the volume of raw materials required by conventional sequestration methods and would produce only one-third of the waste volume (Molycorp, 2009).

80 Superconductor: a material through which electricity flows with zero resistance.

81 Electron: a subatomic particle that carries a negative electric charge.

82 Energy state: definite stable energy that a physical system can have; used especially of the state of electrons in atoms or molecules.

83 Electrolyte: a solution that conducts electricity.

84 AB₅ alloys: commercial alloys usually of the type Mm(nickel, cobalt, aluminium, manganese)₅, containing typically 10 wt% Co. Mm denotes Mischmetal, a cost-effective mixture of the rare earths La, Ce, Pr and Nd.

85 Energy density: the amount of energy stored in a given system or region of space per unit volume, or per unit mass.

World resources and production

Resources

It is not possible to obtain an accurate figure for global rare earth resources⁸⁶ due to the quality and availability of data. USGS estimates total world reserves⁸⁷ of rare earth oxides to be about 114 million tonnes. China dominates world reserves with 48 per cent. China is followed by the Commonwealth of Independent States⁸⁸ with 17 per cent, the United States with 12 per cent, India with three per cent and Australia with one per cent. The remaining 19 per cent of reserves is divided between Canada, Malaysia, Brazil, Greenland, South Africa, Namibia, Kenya, Tanzania, Angola, Mauritania, Burundi, Malawi, Vietnam, Thailand, Indonesia, Finland, Sweden and Turkey (Table 4 and Figure 16; Cordier, 2011).

China

China has the most abundant REE resources in the world, possessing hard rock, placer and ion adsorption clay deposits. The Bayan Obo bastnäsite deposit is the largest deposit in the world and contains reported reserves of at least 48 million tonnes at 6 per cent REO (Kanazawa and Kamitani, 2006). A significant proportion of China's resources are contained in ion adsorption deposits. Importantly these deposits are rich in the less common HREE and they are thought to contain about 80 per cent of the world's resources of HREE (Vulcan, 2008). China's additional reserves occur as placer deposits, largely in the coastal areas of west Guangdong and Hainan Island and associated with alkaline igneous rocks, for example the Weishan deposit, in Shandong Province.

Commonwealth of Independent States

The REE resources of the CIS are dominated by loparite deposits (Kosynkin et al. 1993). Russia has significant REE resources in the apatite-nepheline ores of the Kola Peninsula (Khibina and Lovozero complexes) as well as extensive deposits in Sakha, Siberia (Naumov, 2008). The largest is the Tomtorskoye deposit, consisting of a pyrochlore-monazite-cradallite ore, containing 13–14 per cent REO (Vereschagin et al. 2006). Kyrgyzstan has significant reserves of REE estimated at 51 500 tonnes (Bogdetsky et al., 2005). Kazakhstan has significant REE resources associated with uranium mine tailings. Total reserves of the CIS are estimated at 19 million tonnes (Cordier, 2011).

86 Resources: A mineral resource is a concentration of minerals or body of rock that is, or may become, of potential economic interest for the extraction of a mineral commodity.

87 Reserves: A mineral reserve is the part of the resource which has been fully geologically evaluated and is commercially and legally mineable with current technology.

88 Commonwealth of Independent States: A loose collection of sovereign states that includes most, but not all, of the countries that comprised the former Soviet Union.

| Country | Reserves (tonnes) |
|------------------------------------|--------------------|
| China | 50 000 000 |
| Commonwealth of Independent States | 19 000 000 |
| United States of America | 13 000 000 |
| India | 3 100 000 |
| Australia | 1 600 000 |
| Other Countries | 22 100 000 |
| World Total | 113 800 000 |

Table 4 Estimated world REO reserves (reserves are defined by USGS as that part of the reserve base which could be economically extracted or produced at the time of determination. The term reserves need not signify that extraction facilities are in place and operative. Reserves include only recoverable materials (Cordier, 2011).

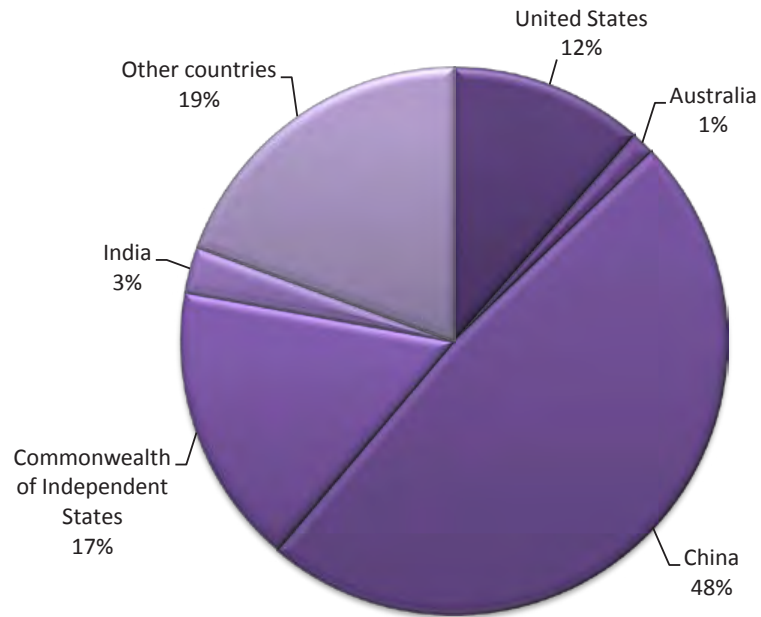
USA

The United States hosts significant REE reserves of an estimated 13 million tonnes. The largest deposit is Mountain Pass in California which was exploited until 2002 and which Molycorp plans to bring back into production by 2012. The deposit is reported to contain 1.12 million tonnes of proven and probable REO reserves (Molycorp, 2010). Another important resource is at the Bear Lodge project in Wyoming which is currently being explored by Rare Element Resources Ltd. Exploration by Ucore rare metals at the Bokan Mountain uranium project in Alaska indicates potentially significant concentrations of light and heavy rare earth elements associated with the uranium mineralisation (Ucore Uranium, 2010). A historic resource estimate produced by the USGS indicates 170 000 tonnes of REO at Bokan Mountain (Hiyate, 2010). Exploration by Great Western Metals Group on the Deep Sands heavy mineral sands deposit in Utah has revealed potentially extensive REE mineralisation (Figure 17). Exploration has suggested however that it is not economic and no further exploration will be undertaken. REE resources are also present in Idaho, Montana and Missouri (Hedrick, 2008).

Australia

Elevated concentrations of REE in Australia have been identified in various heavy mineral sand deposits (beach,

Figure 16 Global distribution of REO reserves (Cordier, 2011).



dune, offshore marine and channel), carbonatite intrusions, peralkaline igneous rocks, iron-oxide breccias complexes, calc-silicate rocks (skarns), fluorapatite veins, pegmatites, phosphorites, fluvial sandstones, unconformity-related uranium deposits and lignites. The most commercially significant of these are related to magmatic and weathering processes associated with carbonatites and alkaline igneous rocks, and secondary placer deposits, such as heavy-mineral sand deposits (Hoatson et al., 2011). The Mount Weld deposit in Western Australia, notable for the high grade of the mineralisation, has a total resource of 17.49 million tonnes at a grade of 8.1 per cent REO (Lynas, 2011). The polymetallic Olympic Dam deposit in South Australia is estimated to contain 45 million tonnes of REO. However, the material is of too low grade (0.5 per cent REO) to be currently exploited. Australian has significant REE reserves (3.4 million tonnes) in heavy mineral sands containing monazite, but these are not worked due to radioactivity issues (Lambert et al., 2008). Other Australian resources of note include the Dubbo Zirconia project (owned by Alkane Resources), Nolans Bore (owned Arafura Resources), Cummins Range (owned by Navigator Resources) and WIM 150 (owned by Australian Zircon).

Canada

Canada has substantial undeveloped REE resources. The Hoidas Lake project (owned by Great Western Minerals Group) is the most advanced, with reserves of 2.6 million tonnes at 2.43 REO (Billingsley, 2010). A further significant resource occurs at Thor Lake (owned by Avalon Rare Metals). The deposit contains total inferred mineral resources of 107.6 million tonnes at 1.35 per cent REO

(Avalon Rare Metals, 2011). A number of other projects are being evaluated in Canada.

Greenland

It has been suggested that Greenland contains REE resources which could potentially meet about 25 per cent of global demand (Lewis, 2009a). The Kvanefjeld deposit in the Ilimaussaq intrusion is estimated to contain of 4.91 million tonnes REO. Greenland Minerals and Energy have completed an interim report from the feasibility study



Figure 17 Rare earth element bearing sands, Deep Sands, Utah. © Great Western Minerals Group Ltd.

suggesting that the mine will have an annual output of more than 43 000 tonnes REO (Batten, 2010). Other projects currently being explored in Greenland include the Karrat REE deposit (Avannaq Resources), the Sarfartoq REE project (Hudson Resources) and the Motzfeldt Ta-Nb-REE project (Ram Resources).

Africa

South Africa has what is claimed to be the highest grade REE deposit in the world, the Steenkampskraal monazite deposit, with an average grade of 17 per cent REO and a reserve of 29 400 tonnes REO (GWMG, 2011). A further notable resource in South Africa is Frontier Minerals' Zandkopsdrift carbonatite deposit. The Kangankunde deposit (owned by Lynas Corp) in Malawi is estimated to contain an inferred resource of 107 000 tonnes REO (Curtis, 2011). The Tantalus project in Madagascar is estimated to contain 14.4 million tonnes of material grading 1.52 per cent REO (Industrial Minerals, 2009a). A monazite-rich laterite overlying a carbonatite at Mrima Hill in Kenya is reported to contain 32 million tonnes of material at about 3.1 per cent REO (Pacific Wildcat Resources, 2011). Montero Mining's Wigu Hill project in Tanzania has grades of up to 27.25 per cent REO in bastnasite-rich sheeted dykes (Montero Mining, 2011). A major carbonatite-associated deposit occurs at Etaneno in Namibia and is estimated to contain 20 million tonnes of REO. The Longonjo carbonatite in Angola is currently being explored for rare earths by Black Fire Minerals (Black Fire Minerals, 2011). Other resources in Africa include: the Karonge hard rock bastnäsite deposits in Burundi; the hard rock monazite Bou Naga deposit in Mauritania; the Congolone heavy mineral sands in Mozambique; and the Nile Delta and Rosetta placer monazite in Egypt (Gupta and Krishnamurthy, 2005).

Europe

European rare earth projects are located in Scandinavia and Turkey. Tasman Metals is currently investigating two projects in Sweden, Norra Kärr and Bastnäs, and one in Finland, Korsnäs. Norra Kärr is a zirconium and rare earth element enriched peralkaline nepheline syenite intrusion with an inferred resource of 60.5 million tonnes grading 0.54 per cent REO, 53 per cent of which is HREO (Figure 18). The target at Bastnäs is high grade vein and breccia style REE and gold mineralisation associated with iron ore. Korsnäs is a REE and lead enriched skarn which was mined by Outokumpu Oy as a mixed open pit and underground operation from 1959 to 1972 (Tasman Metals, 2011a). The Norra Kärr project has been declared a project of 'National Interest' under the Swedish Environment Act. This classification will protect Norra Kärr from any land

use that may compete with future mining (Tasman Metals, 2011b).

REE resources are associated with the Kiruna and Mamberget iron ore mines in Sweden (Parak, 1973). LKAB has recently reported large quantities of REE-bearing apatite in their tailings ponds and plan to conduct a study to investigate the viability of extracting them (LKAB, 2011). Depending on the success of this study it is suggested that the operation could produce about 6 000 tonnes of REE annually. AMR Resources has discovered REE mineralisation associated with pyroclastic tuff formed by lamproitic volcanism of mantle origin at Canakli in south-central Turkey. It has been estimated the deposit contains about 700 000 tonnes REO (AMR Resources, 2011).



Figure 18 Eudialyte rich pegmatite, Norra Kärr, Sweden. © Tasman Metals Ltd.

South and east Asia

India contains both hard rock and placer deposits and the USGS estimates that the country has 3.1 million tonnes of reserves (Cordier, 2011). Vietnam is known to have rare earth deposits, both in heavy mineral sands and carbonatites. The Dong Pao deposit is the most significant with reserves of 7.45 million tonnes at 5.33 per cent REO (Watanabe, 2010). Heavy mineral sand REE reserves are also present in Thailand, Indonesia and Malaysia (Gupta and Krishnamurthy, 2005).

South America

Brazilian REE reserves are estimated at 48 000 tonnes (Cordier, 2011). These reserves include placer and hard rock deposits (Jackson and Christiansen, 1993). The Araxá carbonatite complex in Brazil is reported to contain 800 000 tonnes of laterite resources averaging 13.5 per cent REO (Castor and Hedrick, 2006). Important REE resources also occur in Argentina and Uruguay.

Production

Historical production

REE were initially produced in minor quantities from granite pegmatites, the first geological environment in which they were identified (Castor and Hedrick, 2006). India and Brazil were the world's main sources of REE from these deposits until the 1940s when Australia and Malaysia began production primarily of monazite from placer deposits. Between the 1960s and 1980s bastnäsite carbonatite deposits were exploited and the United States was the principal producer (largely from Mountain Pass) followed by Australia (Naumov, 2008). During the 1980s China began to produce REE, mainly from the Bayan Obo deposit, overtaking the United States to become the world's largest producer by 1988 (Gupta and Krishnamurthy, 2005).

China now dominates world production of REE, accounting for 97 per cent of supply in 2010. Producers

in other countries were generally unable to compete with low priced Chinese exports. The exception was the Mountain Pass mine in California which remained active until 2002 when environmental issues resulted in its closure. REE prices at this time were relatively low and no new deposits have since come on stream, resulting in the current situation of virtually no REE mines outside China.

Current production

The only countries known to be actively mining REE are China, Russia, India, Brazil and Malaysia. In addition REE minerals may be produced in Kazakhstan, Democratic P.R. of Korea, Republic of Korea, Kyrgyzstan, and Vietnam but reliable estimates of quantities are difficult to obtain. Total estimated world production of REO in 2010 was approximately 122 500 tonnes, eight per cent less than the estimated 2009 production of 132 500 tonnes. World production has more than doubled in the last 20 years (Figure 19). Peak production was in 2006 with over 137 000 tonnes REO.

Chinese production increased steadily until 2006 when an estimated peak of 133 000 tonnes was produced. Thereafter production decreased with about 125 000 tonnes in 2007, 128 000 tonnes in 2008 and 129 000 tonnes in 2009. Production decreased slightly in 2010 with estimated production of 119 000 tonnes, accounting for more than 97 per cent of global production (Figure 19).

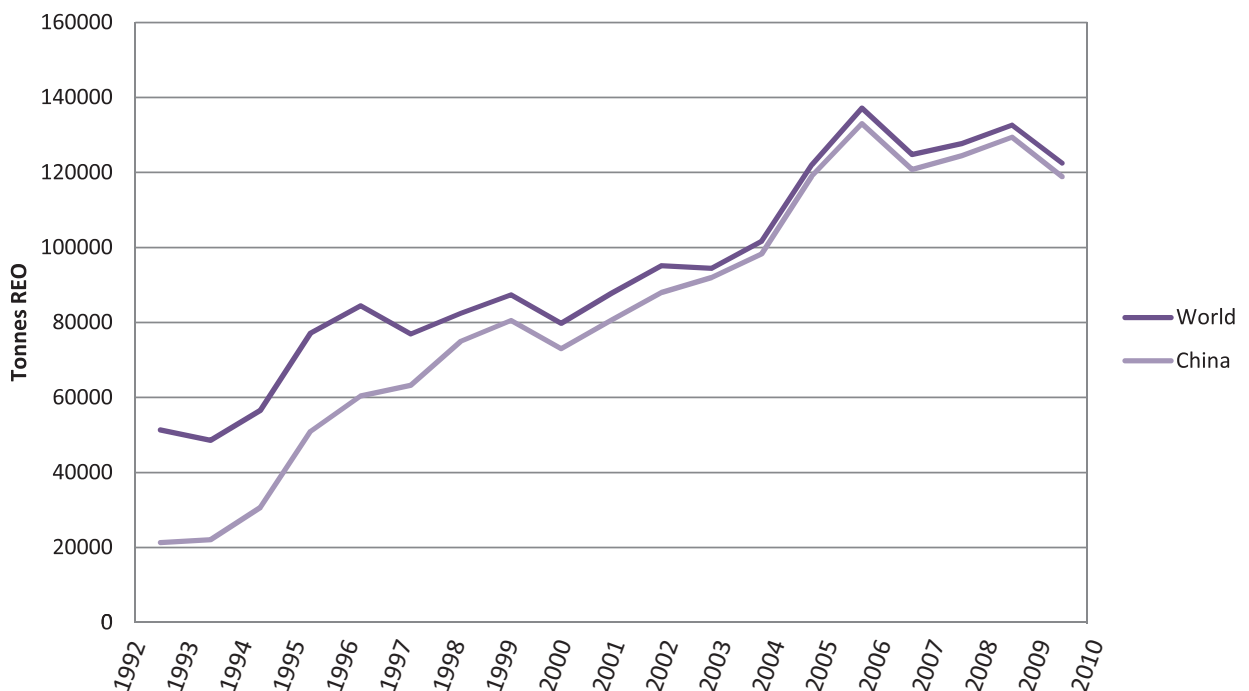


Figure 19 Chinese and world production of REO between 1992–2010 (World Minerals Statistics Database, BGS).

Chinese production is primarily from Bayan Obo as a by-product of iron ore mining, but also from Sichuan and South China (Long et al., 2010).

Russia accounts for the only other significant rare earth mine production outside China, with an output of about 2500 tonnes REO in 2010. The Lovozerskaya Mining Company extracts loparite ore from the Kola Peninsula which is processed to rare earth chlorides and rare earth carbonates by Solikamsk Magnesium Works (SMW) (Chegwidden, pers comm).

Rare earths are produced in Brazil from heavy mineral sands by Indústrias Nucleares do Brasil (INB) with an estimated production of 200 tonnes of REO in 2010. There are also plans to produce REE as a by-product from the Taboca Pitinga tin mine in a joint venture between Canada's Neo Material Technologies Inc. (NMT) and Japan's Mitsubishi Corp (Industrial Minerals, 2009b).

Malaysia currently produces monazite as a by-product of tin extraction and has historically produced xenotime. Production fluctuates each year and in 2010 was about 480 tonnes REO compared to only 20 tonnes in 2009. Lynas Corp, the company developing the Mount Weld deposit in Australia, has built its concentration plant and Advanced Materials Plant (LAMP) in Malaysia with commercial production planned for the end of 2011 (Curtis, 2011).

Indian Rare Earths Ltd (IRE), a subsidiary of the Nuclear Power Corporation of India (NPCIL), extracts monazite from beach sand deposits. This is primarily for the uranium and thorium content but minor amounts of rare earth chlorides are produced as a by-product. About 2000 tonnes of monazite is extracted annually, but REO production is generally less than 50 tonnes. Toyota Tsusho Corp plans to construct a manufacturing plant for processing REO in the state of Orissa using raw materials provided by IRE (Toyota, 2011).

Since the closure of Mountain Pass mine in 2002, the USA has not been mining REE ore but Molycorp, who acquired the deposit from Chevron Mining in 2008, has been producing about 2000 tonnes of REO per year using stockpiled material. Mining restarted in December 2010 and milling operations are expected to resume in early 2012.

Kyrgyzstan was a major producer of REE in the 1980s providing a significant proportion of the former USSR's REE in addition to exporting to Japan, South Korea and Germany. The REE mines are no longer operational

although the country is still producing REE from stockpiles (Bogdetsky et al., 2005).

Projects under development

Global concerns are growing over the long-term availability of secure and adequate supplies of minerals and metals needed by society. Of particular concern are the 'critical metals', so called because of their growing economic importance and high risk of supply shortage. Demand for many of these metals is increasing in response to development of low carbon technologies, such as renewable energy and electric vehicles. The UK and EU are almost wholly dependent on imported supplies of these metals. Furthermore, many of the critical metals are not readily substitutable in many applications and recycling rates are commonly less than 1 per cent (UNEP, 2011).

Recent studies in the EU, USA, Japan, UK and elsewhere have attempted to identify 'critical' metals and minerals. REE are among those identified as most 'critical', by the European Commission (EC). This means that the EC considers there to be a potential risk of supply shortage with an associated impact on the EU economy. Strategies are being considered to mitigate against these supply risks. These include the promotion of sustainable development practices, improved resource efficiency and increased recycling. The EU does not currently produce any REE.

Concerns regarding security of REE supply principally result from China's near monopoly of production. The increasing demand for REE and supply concerns has prompted considerable exploration for this commodity group and a proliferation of companies exploring for REE. As of July 2011, there were 393 individual rare earth development projects at various stages. These were led by 244 companies in 35 different countries (Hatch, 2011b).

In terms of the most advanced projects, following the expected 2012 completion of Phase 1 of its modernisation and expansion efforts at its processing facility, Molycorp plans to produce approximately 19 050 metric tons of REO equivalent annually. Annual production is expected to increase to approximately 40 000 metric tons of REO equivalent once Phase 2 of its expansion is completed at the end of 2013. The company intends to market a range of rare earth products, including high-purity oxides, metals, alloys, and permanent magnets (Molycorp, 2011).

Lynas Corporation Ltd. began mining the Mount Weld bastnäsite deposit in 2007 and has stockpiled about 773 000 tonnes of ore (Figure 20; Curtis, 2009b). A concentration plant at Mount Weld has been completed and the Lynas Advanced Material Plant (LAMP) in Malaysia is on schedule for completion by the end of 2011. The company initially plans to produce 11 000 tonnes of REO annually, which will be ramped up to 22 000 tonnes by 2012 (Curtis, 2011). This is subject to the government granting the company a pre-operating licence and allowing it to import ore into the country for processing.

Other advanced projects in Australia include Alkane Resources' Dubbo project in New South Wales and Arafura Resources' Nolans Bore in Northern Territory. Alkane Resources has been operating a demonstration pilot plant for processing the ore since 2008 and in August 2010 announced that it had started larger-scale production of an yttrium-heavy rare earth concentrate from its new rare earth circuit (Alkane Resources, 2010). The company plans to produce 6500 tonnes REO annually from the second quarter of 2013 (Alkane, 2011). Arafura Resources' plans to begin construction on Nolans Bore in 2012, with production planned in the fourth quarter of 2013 at an annual rate of 20 000 tonnes REO (Arafura, 2011).

Japan, as the world's largest importer of REO and metals, has been investing in a number of projects outside China to secure supplies. Summit Atom Rare Earth Co. (Sareco), a joint venture between Japanese Sumitomo Corp and Kazakhstan's state-owned nuclear company Kazatomprom, plans to extract rare earths from uranium mine tailings in Kazakhstan. A pilot plant is planned to start at the end of 2011. The company anticipates annual production of 15 000 tonnes of REO by 2015 (Suleymanov, 2010).

Toyota Tsusho Corp and Sojitz Corporation in a joint venture with the Korean government are developing the Dong Pao deposit in Vietnam. Annual production of 2000 to 3000 tonnes of REO is planned by 2012, increasing to 5000 tonnes (Chegwidden and Kingsnorth, 2010). Sumitomo Corp and Mitsui are also considering investing in the Sakha rare earth deposits in Siberia, Russia. According to the Russian government these deposits were not scheduled to be developed until 2030 but due to supply shortages and increasing prices a revised plan is being considered (Russia Briefing, 2011).

Great Western Minerals Group (GWMG) is currently developing the Steenkampskraal deposit in South Africa. GWMG has a 'mine to market' strategy with a plan to mine and process rare earths. GWMG plans to be the first

fully integrated supplier outside China. Annual production of 5000 tonnes REO is planned by 2013 (GWMG, 2011).

Frontier Rare Earths commenced a pre-feasibility study on its Zandkopsdrift deposit in South Africa at the beginning for 2011. The deposit has total indicated resources of 22.92 million tonnes grading 2.32 per cent REO. Production is planned to commence in 2015 with a target of 20 000 tonnes per year (Frontier Rare Earths, 2011).

If the projects discussed above come on stream as planned, total new 'rest of world' (i.e. non-Chinese) production could exceed 50 000 tonnes REO by 2013 and more than double by 2015 (Table 5).

There are also several projects in advanced stages of exploration although target start-up dates are unavailable (Table 6).

Stans Energy Corp has acquired an exploration licence for the REE-bearing Aktyuz Ore Field in Kyrgyzstan, as well as the Kutessay II mine, once the Soviet Union's primary source of REE. The company commenced a re-sampling programme at Kutessay II in 2010 in order to confirm the results of historical geological sampling and validate historical reserve estimates. This was completed in December 2010 (Stans Energy, 2010).

Greenland Minerals and Energy Ltd (GMEL) received approval by the government of Greenland to fully evaluate the Kvanefjeld multi-element project at the end of 2010 and is the first company in Greenland to receive permitting for the evaluation of a project that contains uranium. The deposit has total indicated and inferred resources of 457 million tonnes at 1.07 percent REO with a cut off grade of 0.015 U₃O₈ (GWMG, 2011).

There are several advanced rare earth projects in Canada: Zeus (Matamec Explorations), Hoidas Lake (GWMG), Nechalacho (Avalon Rare metals) and Strange Lake (Quest Rare Minerals). Avalon plans to build its own processing plant for REO and aims to be in production by 2016 (Lismore, 2011). Rare Element Resources is currently exploring the Bear Lodge deposit in the USA. The property has an inferred resource of more than 600 000 tonnes REO as well as 947 000 ounces of gold (Rare Element Resources, 2011).

Despite the existence of plentiful REE resources globally, it has been suggested that alternative sources may struggle to compete with China. With the current monopoly position, China could manipulate REE pricing to the

| New REO sources | | Projected REO production (tonnes) | | |
|---|--|-----------------------------------|---------------|----------------|
| | | 2011 | 2013 | 2015 |
| Lynas Corp | Mount Weld, Western Australia | 2750 | 22 000 | 22 000 |
| Molycorp Minerals | Mountain Pass, California | 3000 ¹ | 19 050 | 40 000 |
| Alkane Resources | Dubbo, New South Wales, Australia | 0 | 3250 | 6500 |
| Arafura Resources | Nolans Bore, Northern Territory, Australia | 0 | 0 | 20 000 |
| Great Western Minerals Group | Steenkampskraal, South Africa | 0 | 5000 | 5000 |
| Toyot Tsushu Corp/Sojitz, Vietnamese government | Dong Pao, Vietnam | 0 | 2000–3000 | 5000 |
| Sumitomo/Kazatomprom | Uranium tailings, Kazakhstan | 0 | 3000 | 15 000 |
| Frontier Rare Earths | Zandkopsdrift, South Africa | 0 | 0 | 10 000 |
| AMR Resources | Canakli, Turkey | 0 | 2000 | 5500 |
| Total potential new production | | 5750 | 56 800 | 129 000 |

Table 5 Potential new production of REO outside China. Estimated production forecasts based on company reports. 1 — Production from stockpiles.

detriment of competitors (Kennedy, 2010). Furthermore, Chinese production is relatively low cost as a significant proportion is derived as a by-product of iron ore mining and the ion adsorption clay deposits are reportedly easy to process (Cox, 2009). However, China's domestic demand for rare earths is rapidly increasing — it is predicted to be more than 100 000 tonnes by 2015 compared to about 70 000 tonnes in 2010 (Curtis, 2011). Further, China's domestic supply is being restricted as a result of decreasing production quotas and increasing government legislation covering illegal mining. Consequently, there would appear to be plenty of opportunities for new producers. It has even been suggested that, due to these supply issues, China may become a net importer of the heavy rare earths by 2015 (Chen, 2011).

World trade

The current value of the REE market is estimated to be in the range of \$2–3 billion (Kingsnorth, 2011), relatively small compared with many other minerals. The REE market is more complicated than many others because of the large number of elements and their broad range of applications for which demand fluctuates over time, largely as a result of technological developments. The market has a history of abrupt and dramatic changes. Demand for the individual REE has fluctuated markedly in recent decades. For example, when the colour television was introduced demand for europium increased sharply. However, by the 1960s the production of samarium-cobalt magnets resulted in samarium becoming the main REE used by industry.



Figure 20 Mt Weld open pit. © Clint Cox, The Anchor House, Inc. 2010.

| Deposit | Company | REO reserves (million tonnes) | Ore reserves (million tonnes) | Grade (% REO) | Target start up date |
|-------------------------------|--|-------------------------------|-------------------------------|---------------|--|
| Mountain Pass, USA | Molycorp Minerals | 1.12 | 13.59 | 8.24 | Start up Q4 2012, initial production 19 050 tpa |
| Mount Weld, Australia | Lynas Corp | 1.42 | 17.49 | 8.1 | Start up Q3 2011, initial production 11 000 tpa |
| Mount Weld, Australia | Lynas Corp | 1.42 | 17.49 | 8.1 | Start up Q3 2011, initial production 11 000 tpa |
| Nolans Bore, Australia | Arafura Resources | 0.85 | 30.3 | 2.8 | Start up Q4 2013, initial production 20 000 tpa |
| Steenkampskraal, South Africa | Great Western Minerals Group | 0.03* | 0.25* | 17* | Start up by 2013, initial production 2700 tpa |
| Dong Pao, Vietnam | Toyot Tsushu Corp/ Sojitz, Vietnamese government | 0.40 | 7.5 | 5.33 | Start up by 2012, initial production of 2000 to 3000 tpa |
| Uranium tailings, Kazakhstan | Sumitomo/ Kazatomprom | | | | Start up in 2011, initial production of 3000 tpa |
| Conakli, Turkey | AMR Resources | 0.70 | | | Start up by 2012, initial production of 2000 tpa |
| Zandkopsdrift, South Africa | Frontier Rare Earths | 0.53 | 22.92 | 2.32 | Start up by 2015 with target production of 20 000 tpa |
| Hoidas Lake, Canada | Great Western Minerals Group | 0.057 | 2.85 | 2.0 | Aimed to be in production by 2015 |
| Strange Lake, Canada | Quest Rare Minerals | 0.42 | 36.53 | 1.16 | Start up by 2016 |
| Bear Lodge, USA | Rare Element Resources | 0.18 | 4.9 | 3.77 | Unknown |
| Kvaneffjeld, Greenland | Greenland Minerals and Energy | 4.91 | 457 | 1.07 | Unknown |
| Kutessay II, Kyrgyzstan | Stans Energy Corp | 0.043 | 16.27 | 0.264 | Unknown |
| Nechalacho, Canada | Avalon Rare Metals | 0.90 | 57.49 | 1.56 | Unknown |
| Zeus (Kipawa), Canada | Matamec Explorations | 0.06 | 12.47 | 0.51 | Unknown |

Table 6 The size and status of selected advanced rare earth projects outside China.

In the 1980s neodymium magnets became widely used resulting in considerable demand for this element. Recent technological innovations have led to increased demand for dysprosium and terbium (Cox, 2009).

Historically the balance of demand and supply in the world rare earth market has been fairly stable. However, in recent years the market has changed substantially from a position of oversupply to demand shortages. Total REO demand in 2008 was 124 000 tonnes, an increase of 45 per cent compared to 2003 when demand was only 85 000 tonnes (Avalon Rare Metals Inc., 2009). Total

demand is predicted to reach 190 000–210 000 tonnes by 2015. Significant growth is forecast in most sectors of REE consumption, particularly for magnets and metal alloys which have a predicted consumption of up to 50 000 tonnes and 55 000 tonnes respectively by 2015 (Table 7; Kingsnorth, 2010).

Supply constraints in recent years have led to considerable reliance on illegal supply from China. Statistics indicate that about a third of the 39 000 tonnes of REE exported from China in 2008 was smuggled (O'Driscoll, 2009). Illicit exports are typically in the form

| Application | Consumption REO (tonnes) | | Market share 2015 % |
|------------------------|--------------------------|--------------------|---------------------|
| | 2008 actual | 2015 forecast | |
| Catalysts | 25 000 | 30–34 000 | 16 |
| Glass | 12 000 | 20–22 000 | 6.5 |
| Polishing | 15 000 | 50–55 000 | 11 |
| Metal alloys | 22 250 | 45–50 000 | 26 |
| Magnets | 26 250 | 39–43 000 | 23 |
| Phosphors and pigments | 9000 | 12–14 000 | 6.5 |
| Ceramics | 7000 | 8–10 000 | 5 |
| Other | 7500 | 10–12 000 | 6 |
| Total/range | 124 000 | 190–210 000 | |

Table 7 Global demand for REE in 2008 and 2015 (Kingsnorth, 2010).

of REE mixed with steel, exported as steel composites, making them hard to detect. The process is reversed in the importing country, recovering the REE (Bradsher, 2009). An official at the Ministry of Economy, Trade and Industry suggested that Japanese industry, the world's largest importer of REE, has become reliant on illicitly imported metals (Lewis, 2009b).

Imports and exports

Imports of REE compounds and metals are dominated by Japan, USA, Germany, France and Austria. The largest importer of REE compounds in 2009 was USA at nearly 16 500 tonnes. Japan was the second largest with imports of just under 13 500 tonnes. These two countries were followed by Germany importing 8200 tonnes, France (7000 tonnes) and Austria (4500 tonnes). Estonia, China, the Republic of Korea, Brazil and Russia are also significant importers of REE compounds (UN Comtrade; Figure 21). Japan is the largest importer of REE metals at 4800 tonnes. Japan is followed by France with 400 tonnes, Belgium, India and Austria, each importing about 300 tonnes and Brazil, the USA and China Hong Kong SAR⁸⁹ importing about 200 tonnes each (UN Comtrade, 2011).

China exported 38 500 tonnes of REE compounds in 2009, nearly four times as much as the next largest

exporter, Austria, which is not a primary producer of REE. The Austrian-based company Treibacher AG exports a diverse range of REE products, including oxides of all the REE, ferrocerium/lighter flint alloys, hydrogen storage alloys, individual REE metals, mischmetal and fifteen cerium compounds and solutions (Hedrick, 2002). Austria exported over 10 000 tonnes of REE compounds in 2009. The third largest exporter was Japan at nearly 6000 tonnes, followed by Russia with 4600 tonnes. Other significant exporters of REE compounds in 2008 were the USA, Estonia, France, Kazakhstan, Sri Lanka and Germany (Figure 22). Rare earth compounds are exported from Estonia by AS Silmet, one of only two rare earth processing facilities in Europe. This company was recently bought by Molycorp Minerals who plan to increase the plant's capacity from 3000 to 6000 tonnes. Rhodia in France, the other rare earth processing facility in Europe, separates REE to very high purity levels then formulates the resulting concentrate into high-technology materials for various applications (Rhodia, 2011).

China was also the largest exporter of REE metals, with a total of 5300 tonnes. It was closely followed by the USA (4100 tonnes), China Hong Kong SAR (460 tonnes), Belgium (270 tonnes) and Austria (240 tonnes). The other countries shown in Figure 12 all exported between about 50 and 100 tonnes (UN comtrade, 2010).

China's rare earth industry

Chinese leaders have long emphasised the importance of REE. As the late Chinese patriarch Deng Xiaoping stated 'The Middle East has oil, and China has rare earths'. Not only is China dominant in the mining and refining of REE it also leads in the production of REE alloys, magnetic parts and components. It is not unusual for a country to want to develop value-added production and exports and clearly China is no longer content to merely supply Western supply chains. It aims to increase its own manufacture of high-value products, in line with ambitious plans to reduce energy intensity and carbon emissions. It would appear the underlying rationale is to bring more of the manufacturing chain into China to maximise the benefits to its economy.

Rare earths have been a 'protected and strategic' mineral in China since 1990. This prohibits foreign investors from mining rare earths and participating in smelting and separation projects unless they are in a joint venture with a Chinese company. The Chinese government has put a number of measures in place in attempt to protect and regulate the REE industry.

⁸⁹ SAR: Special Administrative Region, a provincial-level administrative division in the People's Republic of China.

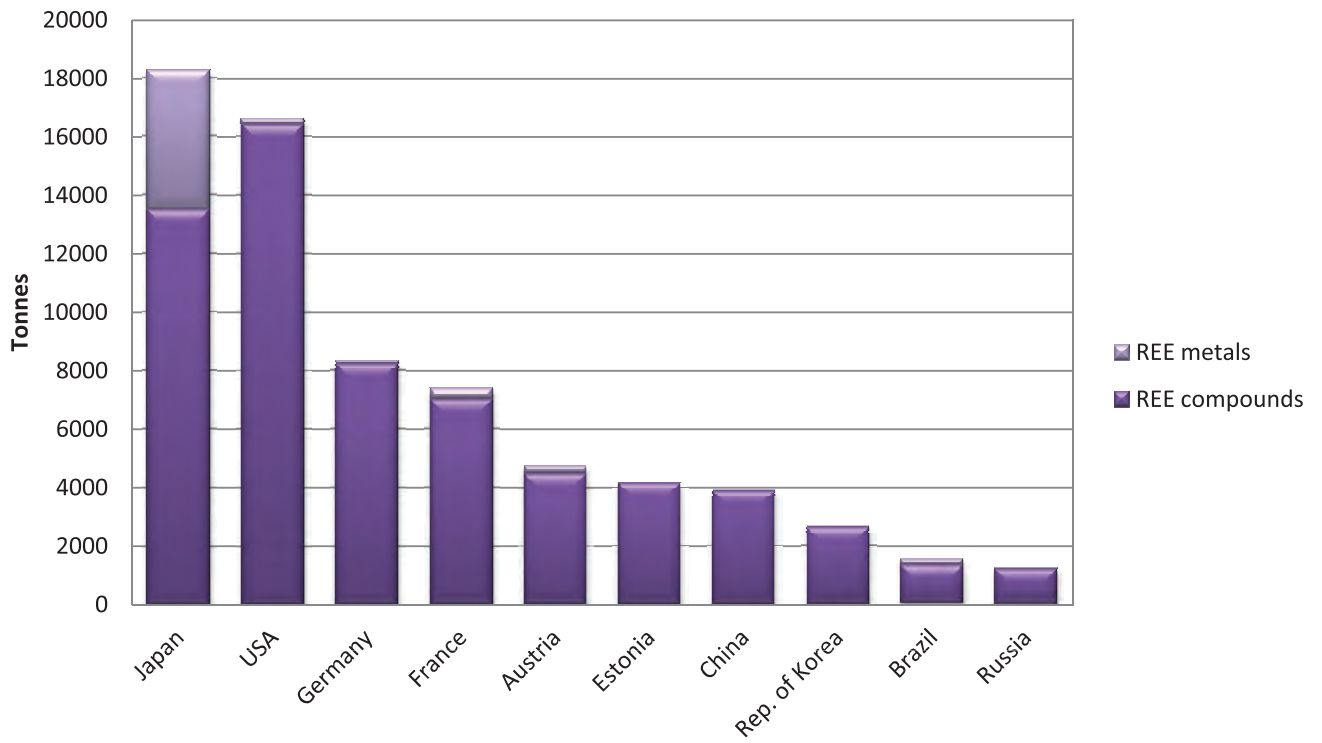


Figure 21 Major importers of REE compounds and metals in 2009. Source United Nations Commodity Trade Statistics Database (UN Comtrade).

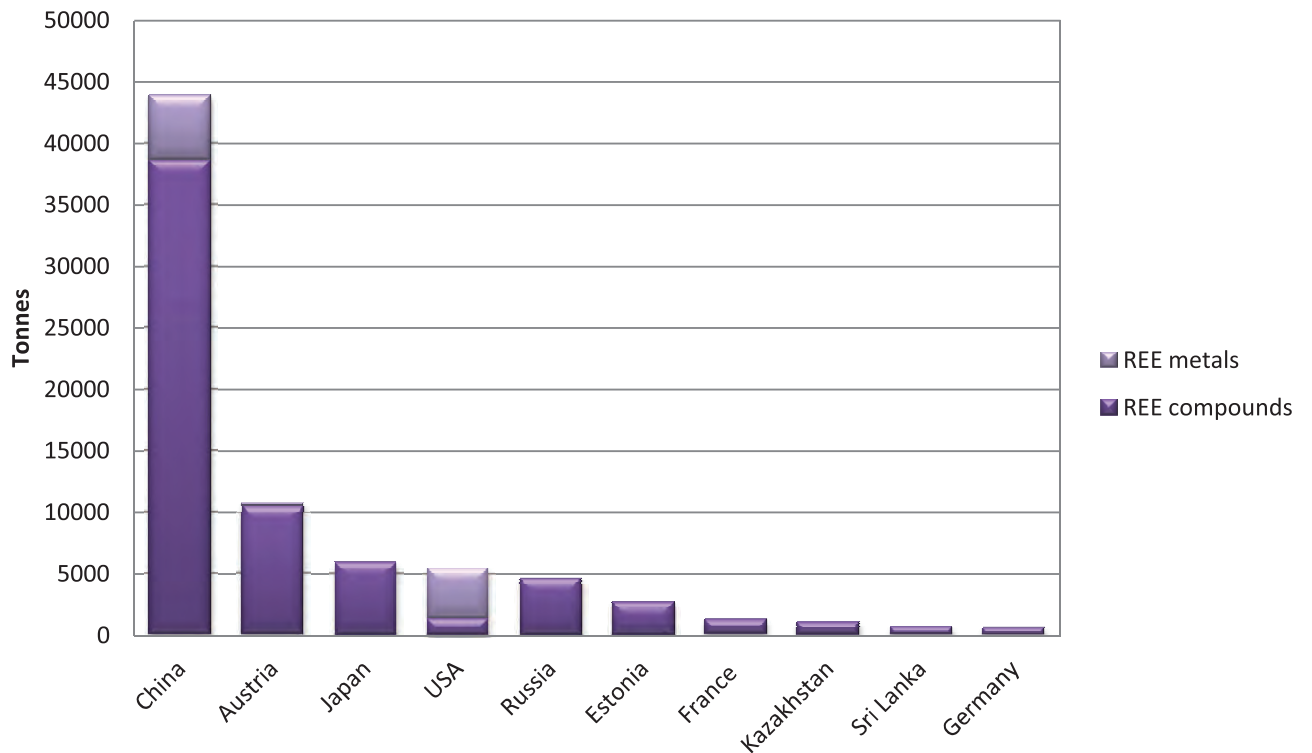


Figure 22 Major exporters of REE compounds and metals in 2009. Source United Nations Commodity Trade Statistics Database (UN Comtrade).

As with other strategic commodities in China, the Ministry of Land and Resources (MLR) is responsible for developing production plans for rare earths. This includes setting an

overall annual production and export quota (Tse, 2011). China's actual production has been higher than the quotas in recent years, as shown by Figure 23. This is partly due

to illegal mining, particularly from the ion adsorption clays in southern China. The production quota for 2011 has been set at 93 800 tonnes, a five per cent increase compared to 2010.

In addition to quotas for total production, China also sets quotas on the export of REE. Export quotas are released annually in two phases and specific export quotas are set for domestic REE producers and traders and for Sino-foreign joint-venture producers, who export products under a licence system (Tse, 2011). These quotas are further divided with widely varying allocations to individual exporting companies. Total Chinese REE export quotas have been steadily declining since 2005 when they were more than 65 000 tonnes. The decline is principally in response to increasing domestic demand. The total export quota in 2009 was 48 155 tonnes, with 31 310 tonnes allocated to domestic producers and traders and 16 845 tonnes allocated to Sino-foreign joint-ventures. In 2010 the total export quota decreased by 37 per cent to 30 258 tonnes, with the decline for Sino-foreign joint-ventures exceeding 50 per cent (Tse, 2011). In 2011 the Government set the REE export quota at 14 508 tonnes for the first half of the year and 15 738 tonnes for the second half giving a total of 30 246 tonnes (Hatch, 2011a) (Figure 23). Although the export quota for 2011 appears only marginally lower than in 2010, the figures are not directly comparable to the previous years because for the

first time these quotas include REE ferro-alloy alloys. It has been suggested that this will result in a 20 per cent net decline in the amount of REE metal and oxide being exported (Burton, 2011).

China also imposes export duty on REE leaving the country. Neodymium, yttrium, europium, dysprosium, terbium and scandium have an export tariff rate of 25 per cent, whilst the other REE have a 15 per cent levy. Dysprosium- and neodymium-alloys are subject to a 20 per cent export tariff (Global Trade Alert, 2011). Furthermore, in 2007 China removed the refund of VAT (16 per cent) on exports of 'unimproved' REE, whilst it remained in place for higher value-added exports including magnets and phosphors. The OECD estimates that this decision, combined with the export duty, results in REE processors outside China, e.g. magnet manufactures, paying 31 per cent more (before transport and storage costs) for REE raw material, than Chinese companies (Korinek and Kim (2010). This price differential could force REE processors to move manufacturing enterprises to China.

In parallel with these trade instruments, China is increasing regulation and consolidation of its REE industry. There has been a trend of closing smaller operations, while merging larger producers and restricting mining operations to state-owned companies (Levkowitz, 2010). China's Ministry of Land and Resources has cited environmental concerns,

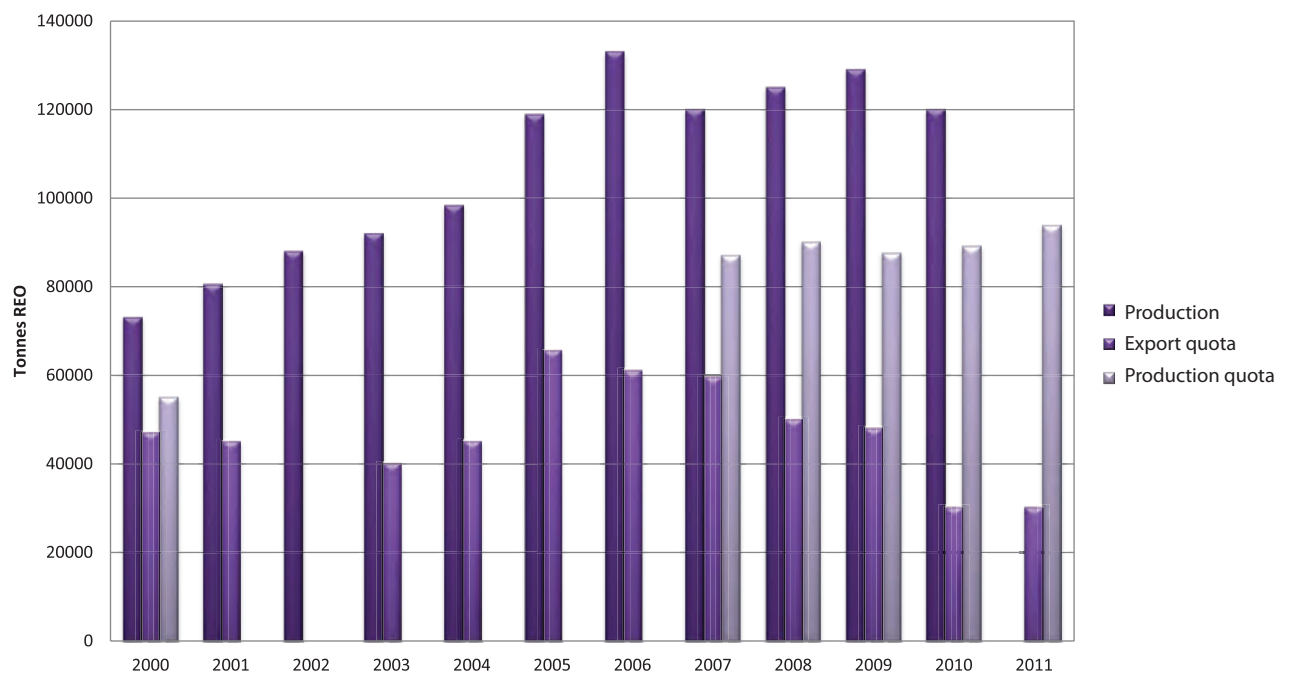


Figure 23 China's REO production, production quotas and export quotas 2000–2011. Export quotas include quotas for both domestic producers and traders as well as Sino-foreign joint ventures except for 2000–2004 where data is not available for Sino-foreign ventures (World Minerals Statistics Database, BGS; Tse, 2011).

protection of finite resources and reduction of illegal mining as the principal reasons for these actions.

It has been recently estimated that as much as 50 per cent of HREE production and 14 per cent of LREE production are illegal (Nicoletopoulos, 2011). In 2006 there were 47 domestic REE producers and traders and 12 Sino-foreign ones which were allowed to export REE products. By 2011 the number had reduced to 22 domestic REE producers and traders and 9 Sino-foreign ones (Tse, 2011). China's Ministry for Industry and Trade has consolidated the 35 REE producers in the Inner Mongolia region into a single state-owned company, the Baotou Steel Rare Earth, which will handle all mining, processing and trading (Hawes, 2011a). Similar consolidation appears to be happening in the south of China with the establishment of Chinalco Rare Earth Company, combining five smelting plants and one trading firm in the Jiangsu Province (Hawes, 2011b).

The Ministry has also indicated that it will not grant any new mining licences for rare earth prospecting before June 2012. Consolidation of the industry is likely to provide the remaining major companies with greater control over pricing and the Chinese Government has announced plans to implement a unified pricing mechanism. It is proposed that two of China's largest mining companies will publish a set price for certain REE on a monthly basis (Yan, 2010).

China has indicated that it is building a REE strategic reserve base in northern China. Baotou Steel Rare Earth is reported to be developing storage facilities to hold up to 200 000 tonnes of REO and using 9 per cent of its production in 2010 (55 000 tonnes) to build this (Yam, 2011). Development of a stockpile system may allow China to better balance market needs for specific elements and store currently lower priced elements for the future.

As with other commodities there are indications that Chinese companies are seeking to secure rare earth resources outside China by taking positions in potential new producers. In 2009 Jiangsu Eastern China Non-Ferrous Metals Investment Holding Co. acquired a 25 per cent stake in Arafura Resource Ltd, which is developing the Nolan's Bore deposit in Australia (Arafura, 2009). However, a move in 2009 by state-owned China Non-Ferrous Metal Mining Co. to acquire a 51.6 per cent stake in Lynas Corp., which is developing the Mt Weld deposit in Australia, was blocked by Australia's Foreign Investment Review Board (Keenan, 2011).

Although China bans foreign companies from investing in REE mining it does allow them to enter the more profitable downstream processing sectors with Chinese companies. About 50 foreign companies are reported to be operating in the 'Baotou Rare Earth Hi-Tech Zone' (Wall Street Journal, 2010).

In 2009 the EU, Mexico and USA filed complaints to the World Trade Organisation (WTO) related to export restraints China imposes on certain mineral exports. In 2011 the WTO concluded 'that China's export duties were inconsistent with the commitments that China had agreed to' and with 'WTO rules'. In its defence China had argued that some of its export duties and quotas were justified 'because they related to the conservation of exhaustible natural resources for some of the raw materials'. However, 'China was not able to demonstrate that it imposed these restrictions in conjunction with restrictions on domestic production or consumption of the raw materials so as to conserve the raw materials.' (WTO, 2011). Although not specifically included in this dispute it has been suggested that the judgement could have implications for Chinese REE exports. The Chinese Ministry of Commerce has now indicated that it 'will take steps forward in rare earth export management, according to the relevant laws and World Trade Organization rules' (Reuters, 2011).

Industry commentators have suggested that there are sufficient reserves elsewhere in the world to not only compensate for the reduction in China's REE supplies, but to ultimately supply any domestic Chinese shortfall (Lifton, 2009a). This view is supported by the USGS which indicates that undiscovered resources are thought to be very large relative to expected demand (Hedrick, 2010). In reality the supply-demand balance is likely to vary considerably over time for individual elements and between the LREE and HREE (Table 8). Detailed analysis of global supply and demand, assessing a number of scenarios and projected sources of individual REO, ranks the following REE in order of risk to supply: dysprosium, yttrium, terbium, europium and neodymium (Hatch, 2011b). An earlier criticality study (based on a combination of importance to the clean energy economy and risk of supply disruption) by the US Department of Energy ranked dysprosium as the most critical REE in both the short (0–5 years) and medium-term (5–15 years). Neodymium, terbium and yttrium were ranked next in the short term, followed by europium. In the medium-term neodymium and terbium were ranked below dysprosium, followed by europium and yttrium (Bauer et al. 2010).

| | Demand | | Supply/production | | |
|-------------------|---------------|-------------|-------------------|-------------|-----------------|
| | REO tonnes | % | REO tonnes | % | Surplus/deficit |
| Lanthanum | 51050 | 28.4 | 54092 | 26.5 | 3042 |
| Cerium | 65750 | 36.5 | 79156 | 38.9 | 13406 |
| Praseodymium | 7950 | 4.4 | 9909 | 4.9 | 1959 |
| Neodymium | 34900 | 19.4 | 33665 | 16.5 | -1235 |
| Samarium | 1390 | 0.8 | 4596 | 2.3 | 3206 |
| Europium | 815 | 0.5 | 659 | 0.3 | -156 |
| Gadolinium | 2300 | 1.3 | 3575 | 1.8 | 1275 |
| Terbium | 565 | 0.3 | 512 | 0.2 | -53 |
| Dysprosium | 2040 | 1.1 | 1830 | 0.9 | -210 |
| Erbium | 940 | 0.5 | 1181 | 0.6 | 241 |
| Yttrium | 12100 | 6.7 | 12735 | 6.3 | 635 |
| Ho, Tm, Yb, Lu | 200 | 0.1 | 1592 | 0.8 | 1392 |
| Total | 180000 | 100 | 203502 | 100 | |

Table 8 Forecast supply/demand by element in 2014 ($\pm 15\%$) Those shown in bold are predicted to be in deficit by 2014 (IMCOA, 2009).

Prices

As with many minor metals, there are no exchanges on which REE metals are traded. Both the metals and their oxides are sold by specialist REE-trading companies (Vulcan, 2008). REO are typically supplied on long-term confidential contracts and prices are set by producers.

There are significant differences between the price of individual REE metals and oxides (Table 9 and Figure 24). Currently cerium oxide trades at about US\$150 per kilogram whereas europium oxide is sold for US\$5880 per kilogram. HREE are typically more expensive than lighter LREE due to their lower abundance in most deposits. The relative difficulty and associated expense in extracting each element is another factor which influences the price. The price of individual elements is also affected by demand patterns which vary with time. Furthermore REE prices are affected by the purity level of the product which is dictated by specific end-user requirements. Higher purities and other value-added properties attract higher prices (Lynas, 2009).

REE prices have fluctuated significantly since the 1950s, largely as a result of the supply/demand balance, related

to environmental legislation and economic factors such as inflation and energy costs (Hedrick 1997).

Between 1958 and 1971 prices decreased largely as a result of the opening of the Mountain Pass Mine in California and widespread use of REE compounds and metals in commercial applications. Supplies continued to increase in the 1970s and demand kept pace. By the late 1970s operating costs had increased due to inflation and rising energy costs leading to an increase in prices. Prices were stable during the early 1980s. However, by 1985 a change in the petroleum industry to fluid cracking catalysts (due to environmental legislation) which use less REE resulted in decreased demand. Mine production decreased in response, leading to a rise in prices the following year (Hedrick 1997).

REE prices have been artificially low since the 1990s as a result of the Chinese REE industry growing so rapidly that supply exceeded demand. By 1995 demand for REE had increased considerably, causing concern over supply and placing upward pressure on prices. China reacted by increasing production, which caused prices to fall the following year (Naumov, 2008).

By 2000 demand for neodymium and dysprosium had increased dramatically due to their use in Nd-Fe-B magnets and China responded by increasing production of both metals and oxides. Because REE cannot be selectively mined this led to over-production of other REE and a

| REE | Price (US\$ per kg) | |
|--------------|---------------------|-----------|
| | Metal | Oxide |
| Cerium | 168–170 | 149–151 |
| Dysprosium | 3400–3420 | 2580–2600 |
| Europium | 6600–6620 | 5860–5880 |
| Gadolinium | 223–228 | 200–210 |
| Lanthanum | 165–167 | 149–151 |
| Neodymium | 465–470 | 335–340 |
| Praseodymium | 280–282 | 247–250 |
| Samarium | 189–192 | 127–130 |
| Terbium | 5100–5120 | 4500–4520 |
| Yttrium | 205–215 | 180–185 |

Table 9 REO and metal prices on August 16th 2011. Prices shown are for a minimum 99% purity and are quoted in US\$ per kilogram on an FOB China basis (Metal-pages, 2011).

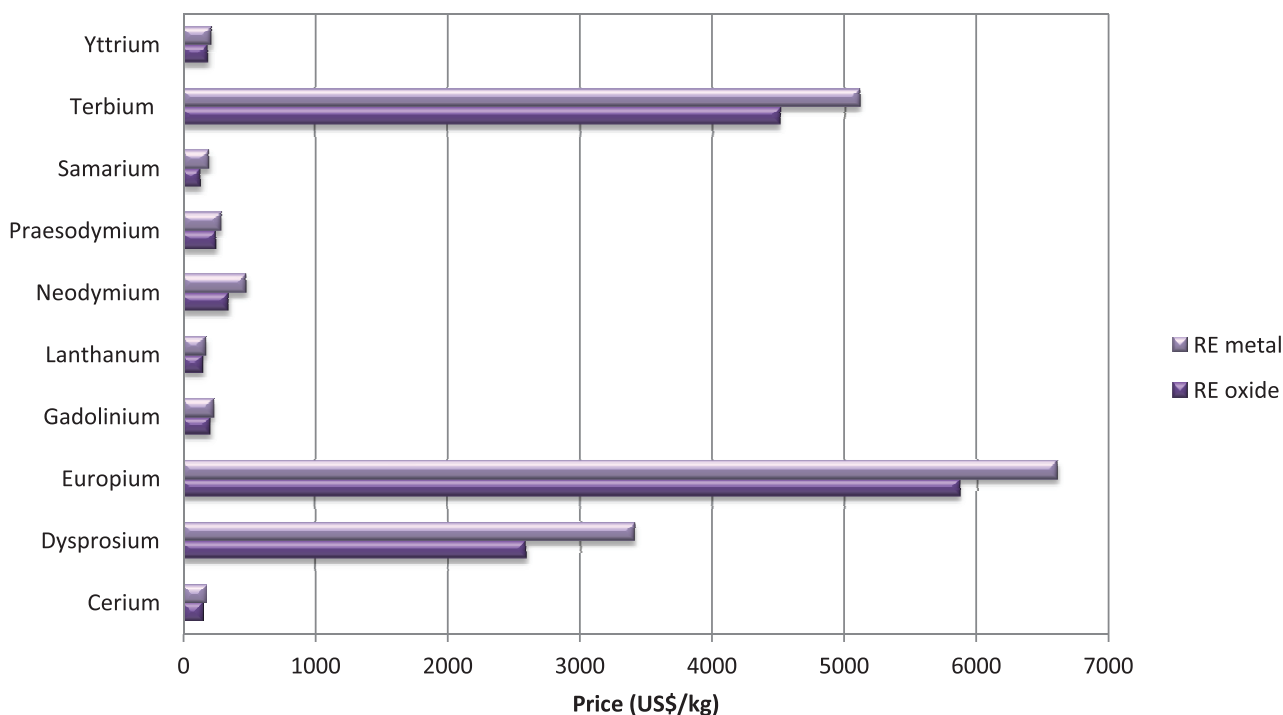


Figure 24 REO and metal prices on August 16th 2011 (Metal-pages, 2011).

decrease in prices. In an attempt to combat this and help prices recover China decreased production. However, this failed due to a decrease in demand for telecommunication

equipment and computers during the first half of 2001 resulting in supplies continuing to exceed demand (Naumov, 2008).

| REO (purity 99% min) | Price (\$ per kg) | | | | | | | |
|---------------------------|-------------------|-------|-------|-------|-------|-------|-------|-------|
| | La | Ce | Nd | Pr | Sm | Dy | Eu | Tb |
| 2002 | 2.3 | 2.3 | 4.4 | 3.9 | 3.0 | 20.0 | 240.0 | 170.0 |
| 2003 | 1.5 | 1.7 | 4.4 | 4.2 | 2.7 | 14.6 | 235.4 | 170.0 |
| 2004 | 1.6 | 1.6 | 5.8 | 8.0 | 2.7 | 30.3 | 310.5 | 398.0 |
| 2005 | 1.5 | 1.4 | 6.1 | 7.6 | 2.6 | 36.4 | 286.2 | 300.0 |
| 2006 | 2.2 | 1.7 | 11.1 | 10.7 | 2.4 | 70.4 | 240.0 | 434.0 |
| 2007 | 3.4 | 3.0 | 30.2 | 29.1 | 3.6 | 89.1 | 323.9 | 590.4 |
| 2008 | 8.7 | 4.6 | 31.9 | 29.5 | 5.2 | 118.5 | 481.9 | 720.8 |
| 2009 | 4.9 | 3.9 | 19.1 | 18.0 | 3.4 | 115.7 | 492.9 | 361.7 |
| 2010 | 22.4 | 21.6 | 49.5 | 48.0 | 14.4 | 231.6 | 559.8 | 557.8 |
| Q1 2011 | 75.9 | 77.5 | 130.2 | 119.7 | 72.8 | 412.9 | 719.2 | 717.6 |
| Q2 2011 | 135 | 138.3 | 256.2 | 220.1 | 125.6 | 921.2 | 1830 | 1659 |
| % change 2002–2008 | 279 | 98 | 625 | 656 | 73 | 492 | 101 | 324 |
| % change 2009–2010 | 359 | 457 | 159 | 166 | 324 | 100 | 14 | 54 |

Table 10 REO price trends 2002–2011 (Lynas Corp, 2011b; Metal-pages, 2011).

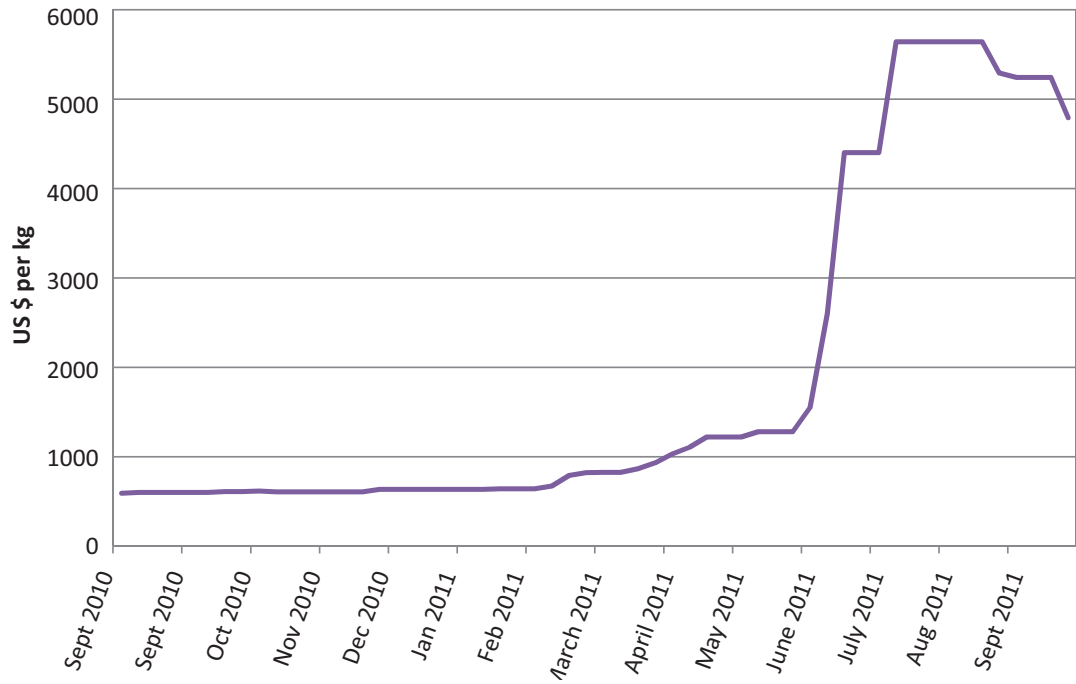


Figure 25 Price trends for europium oxide from September 2010 to September 2011 (Industrial Minerals, 2011).

Prices for most REO fell to low levels between 2002 and 2003 before gradually increasing until 2006. The rate of increase subsequently accelerated, peaking in the first half of 2008. Of the LREE oxides praseodymium and neodymium showed the largest rises, both increasing in price by over

600 per cent between 2002 and 2008. In addition to being rarer, the HREE became increasingly important in industry during the 2000s with the prices of dysprosium oxide and terbium oxide increasing by 500 and 300 per cent respectively between 2002 and 2008 (Table 10).

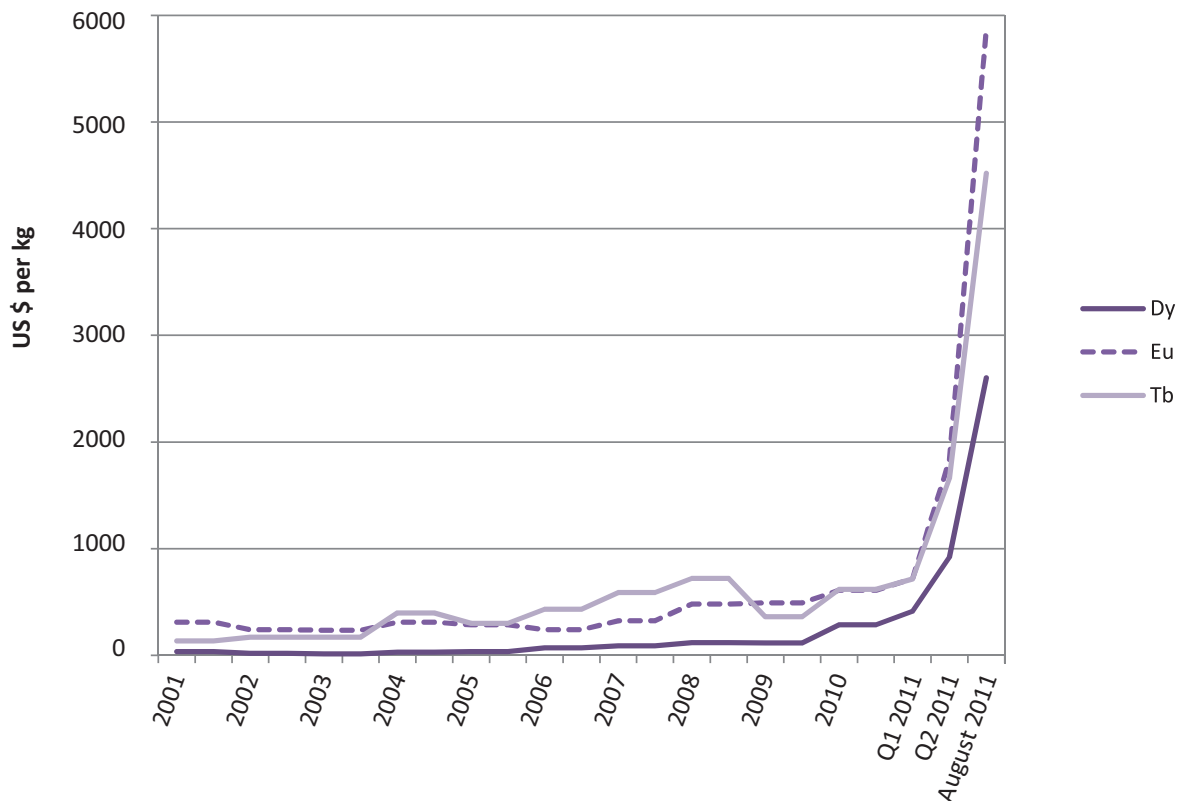


Figure 26 Price trends for selected HREE from 2001 to 2011 (Lynas, 2011b).

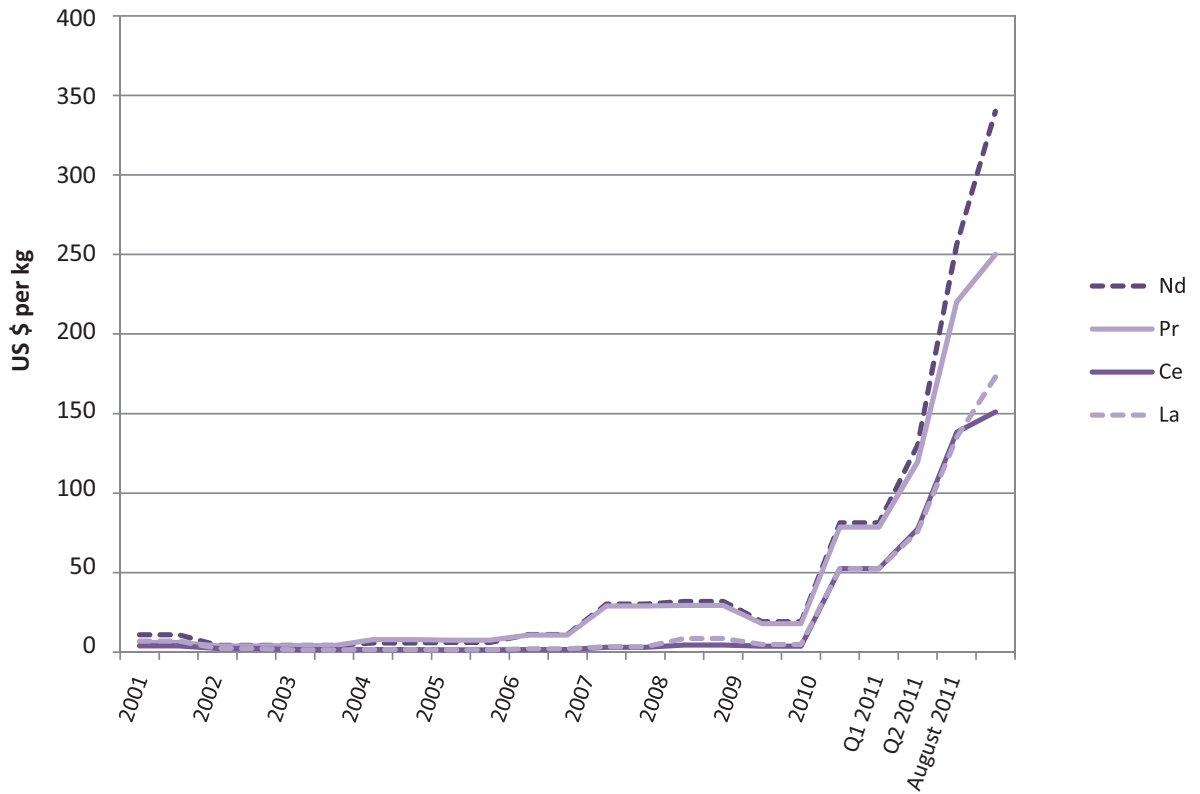


Figure 27 Price trends for selected LREE from 2001 to 2011 (Lynas, 2011b).

As with many resource-based sectors the REE industry was deeply affected by the global recession. During the second half of 2008 many industries began to use existing inventories to lower costs. This caused REE prices to decrease significantly; for example terbium fell to US\$360 per kilogram, a decrease of more than 50 per cent from its peak of US\$740 per kilogram in 2008. Praseodymium and neodymium prices also both fell dramatically in the second half of 2008 before stabilising at that level for most of 2009. REE prices began to recover during the last quarter of 2009 but were still a long way off pre-recession prices by the end of 2009.

Prices for all REO increased during the first half of 2010, largely driven by an increase in Japanese imports and growing demand for permanent magnet applications. The biggest increases were for neodymium, praseodymium, dysprosium and terbium (Watts, 2010a).

In July 2010, China announced that it would be reducing its export quotas for rare earths by 70 per cent for the second half of 2010 to 7976 tonnes, taking the total to 30 258 tonnes for the year (Watts, 2010b). This sparked a dramatic price increase for all REO and metals. Prices for the lower value LREE, especially cerium and lanthanum, were most affected. Chinese producers have to pay for export quotas and therefore have focused on selling the high value heavy rare earths in order to maximise profits.

This created a supply squeeze for the LREE (Industrial Minerals, 2010a). Between the end of July and beginning of September, cerium oxide prices rose from US\$6.7 per kilogram to US\$35 per kilogram, an increase of over 400 per cent. Prices continued to rise during the rest of 2010 but more gradually than earlier in the year.

Prices for all the REE escalated at the beginning of 2011, particularly for the LREE, as China announced a reduction of 35 per cent in its export quotas for the first half of 2011 and global demand remained strong. Cerium oxide prices, for example, increased from US\$57 per kilogram to US\$101 per kilogram by the end of the first quarter. HREE prices did not rise at the same rate as the LREE at the beginning of 2011 as exporters initially used their quotas to export the higher value HREE. However, these soon became in short supply both domestically and outside China (Industrial Minerals, 2011a).

LREE prices largely stabilised in May and June compared to the huge increases seen at the beginning of the year. The exception was neodymium which jumped from US\$230 per kilogram at the end of May to US\$365 per kilogram at the end of June. This was due to continuing strong demand for Nd-Fe-B magnets (Industrial Minerals, 2011b).

HREE prices rose dramatically from the end of June 2011 as China continued to regulate ion adsorption clay mining

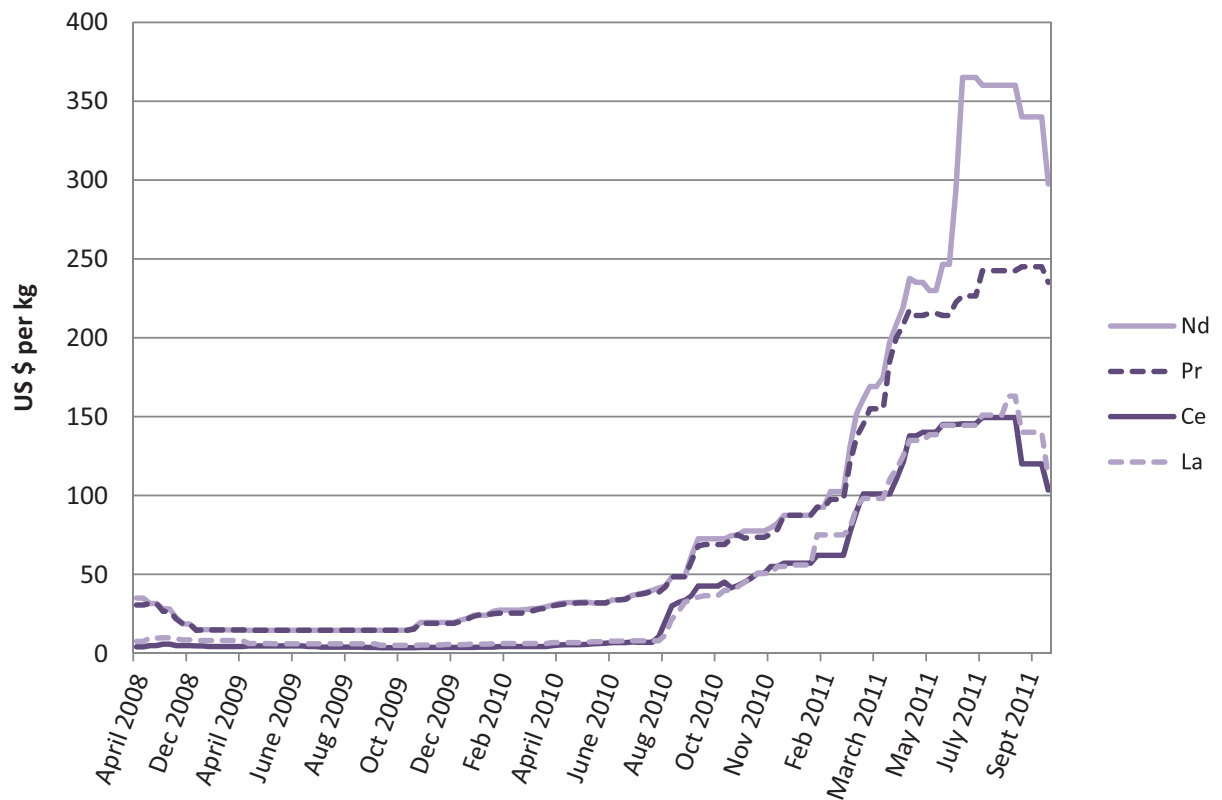


Figure 28 Price trends for selected REO from April 2008 to September 2011 (Industrial Minerals, 2011).

operations in the southern provinces. The government is carrying out inspections to enforce environmental and safety standards which is leading to a slow down in production and fears over supply shortages (Watts, 2011). For example, europium oxide prices more than quadrupled between June and August from US\$1550 to US\$5640 per kilogram (Figure 25).

Prices for all REE increased dramatically from the beginning of July. For example, terbium oxide which was trading at just over US\$700 per kilogram in the first quarter of 2011 had reached US\$4520 per kilogram by the beginning of August and neodymium oxide increased from US\$130 to US\$352 per kilogram during the same time period (Figures 26 and 27; Lynas, 2011b).

A sharp correction occurred in early August with cerium oxide prices decreasing nearly US\$50 per kilogram between the beginning of August and end of September (Figure 28). Despite this decrease, prices are still significantly higher than those in the first quarter of 2011 (Industrial Minerals, 2011d).

A consequence of the escalating rare earth prices has been the subsequent increase in the price of end products made from REE. Companies producing these products have complained about the soaring costs and

little or no guarantee over availability (Nicoletopoulos, 2011). Companies are also reacting by finding substitute materials, recycling and investing in rare earth projects outside China (Watts, 2011).

Recycling and substitution

In recent years the REE market has been in over-supply and as a result there has been little incentive to investigate recycling technologies and substitutes. However, with rising prices and concerns about security of supply, secondary sources and recycling could reduce pressure on primary production. Improving efficiency in rare earth use is another approach which could reduce pressure on rare earth supplies. Research and development is necessary in all fields of application and is also required on the primary supply side to enable greater efficiencies in mining, beneficiation and processing (Schüler et al., 2011).

Substitutes

Many of the applications of REE are highly specific and substitutes are either unknown or provide inferior performance (Haxel et al., 2002). Where substitutes exist they are commonly another REE or a more expensive material such as platinum-group elements. These for example can be used in petroleum cracking in place of REE (Bonel and Chapman, 2005).

In many cases substitution requires a totally new product design. For example rare earths are important in wind turbines with a gear-less design. A supply shortage of rare earths could lead to a shift to alternative geared drive systems which are less reliant on rare earths. Rare earth magnets are used in the motors of hybrid electric vehicles and electric vehicles and although substitutions based on alternative electric motor designs are available more research and development is required (Schüler et al., 2011).

For approximately 20 years scientists have been trying to find alternatives for the neodymium-iron-boron magnet with no success (Smith, 2009b). Europium, used in the colour cathode ray tube and LCD⁹⁰ in computer monitors, has a relatively low abundance, high demand and no substitute.

Substitution of REE by materials other than rare earths may be possible where metallurgical and magnetic properties are involved. However, in those applications based on specific optical, chemical and certain special magnetic properties substitution is less likely (Table 11). Consequently, for the foreseeable future it is assumed that REE will be required in polishing applications, catalysts, phosphors, magnets and optical glass components, colouring and decolouring glass, pigments and as intensifiers of x-rays (Gupta and Krishnamurthy, 2005).

Recycling

Until the last few years, rare earth prices have been so depressed that rare earths could not be cost-effectively recovered through recycling. Rising prices will be the principal incentive for encouraging recycling in addition to stimulating research activity into recycling technology. The majority of REE recycling technologies are in the research stage and may not reach commercialisation (EPOW, 2011).

Only small quantities of REE-bearing scrap are currently recycled: it has been estimated that less than one per cent of REEs were recycled from scrap in 2009. This was primarily from permanent magnets (Kara et al., 2010). The recycling processes for the rare earths are quite complex and both physical and chemical treatments are necessary. Most of the current recycling procedures are energy-intensive processes (Schüler et al., 2011).

Rare earths can be recycled from the scrap produced in the manufacture of neodymium-iron-boron magnets.

Manufacture of magnets increases annually and generates a significant amount of scrap so an effective means of recycling neodymium from this source would be highly beneficial. However recycling neodymium from scrap is very difficult as it forms extremely stable compounds with several elements (Takeda et al., 2006). Several processes have been proposed for recycling REE magnets but they have not been developed commercially as magnets made from recycled materials do not have the same performance as those prepared from primary raw materials. This quality issue is due to contamination by impurities, largely carbon and oxygen, in recycled magnets (Itakura et al., 2006). Studies have also been undertaken to investigate recovering REE from optical lenses and polishing sludges (Saito et al., 2006).

The Japanese government is investing in rare earth recycling projects and many companies are examining the development of efficient recycling technologies for rare earths. For example, the Japanese company Hitachi has recently developed a method for recycling rare earth magnets from hard disk drives, motors, air conditioners and other compressors. REE magnets are separated and collected from end-of-life products by specifically developed machinery and the rare earths are extracted from the magnets using an experimental dry process. Hitachi aims to commence full recycling operations by 2013 (Hitachi, 2010). In other REE applications, Mitsui Metal Mining Co is to recycle REE from NiMH batteries and General Electric is examining recycling of REE from lights phosphors and magnets.

Although recycling of rare earths used in many applications is challenging, reusing them is a further option. The lifetime of permanent magnets is longer than that of the device in which it is used in many applications. For example, disc drives only last a few years and are generally disposed of containing functional magnets (Trout, 2007). The reuse of products containing rare earths from the main applications, for example electric motors, hard disks and other electronic components, would require intensive dismantling. An efficient collection system would also be required, coupled with sufficiently high prices to make this viable (Schüler et al., 2011). However, certain products, such as electric vehicles and wind turbines, have a considerably longer lifetime and it could be ten to twenty years before they enter the recycling economy (Schüler et al., 2011).

Establishing a source of rare earths from recycling would be beneficial in many ways. Europe currently has no primary production of rare earths but, as one of the

⁹⁰ LCD: liquid crystal display.

| Application | Rare Earth Material | Alternative |
|-------------------------|------------------------|----------------------------------|
| Metallurgy | | |
| Nodular iron | Misch metal | Magnesium |
| Steel | REE silicide | Calcium |
| Nuclear energy | | |
| Control rod | Europium | Hafnium |
| Hydrogen storage | Lanthanum nickel alloy | Iron titanium alloy |
| Glass | | |
| Polishing | Cerium oxide | Plate glass (Pilkington) process |
| Ceramics | | |
| Glazed ceramic tiles | Cerium | Tin, zirconium |

Table 11 Alternatives to REE in some applications. (Gupta and Krishnamurthy, 2005).

largest consumers, an increasing amount of waste is generated in the manufacture of final products. Recycling this waste would decrease dependency on foreign resources. Recycling would also be advantageous from an environmental perspective. Rare earth extraction and processing uses significant amounts of energy and chemicals and recycling would generally be more energy efficient. Furthermore, processing secondary sources of rare earths would not have the radioactivity issues associated with the mining of some of primary deposits (Schüler et al., 2011).

Focus on Britain

There has been no systematic, comprehensive evaluation of REE resources in Britain. However REE are known to occur in a number of geological settings:

- Nodular monazite in Lower Palaeozoic sedimentary rocks of south-central Wales and Exmoor
- REE-bearing minerals associated with the alkaline intrusive complexes of north-west Scotland
- Various REE-bearing minerals from the British Tertiary Igneous Province⁹¹

⁹¹ British Tertiary Igneous Province: Area of the north-west British Isles where intense igneous activity occurred during the Palaeocene and early Eocene (about 63 to 52 Ma) as a

- Synchysite and other REE minerals associated with lead-zinc-barytes mineralisation in the Alston Block of the North Pennines (Figure 31).

Most of these are small occurrences with no demonstrated economic potential, although the nodular monazite in Wales is widely distributed with high contents of La and Ce reported in alluvial sediments.

Nodular monazite

Monazite nodules are present in the Lower Palaeozoic sedimentary rocks of the Welsh Basin and also occur in certain horizons within the Variscan⁹² sedimentary succession of south-west England. These monazite occurrences were identified by BGS geochemical drainage surveys which showed high levels of REE (>5000 ppm cerium) in panned stream sediment concentrates from Wales and south-west England. These anomalies result from the presence of a distinctive form of nodular monazite. The most extensive area containing high cerium levels is in south-central Wales, from catchments draining Ordovician and Silurian sedimentary rocks of the Welsh Basin (Cooper and Read, 1983).

The physical appearance of this type of monazite is very different from normal detrital monazite, which is largely derived from granitic sources. The nodules are grey, flattened, ellipsoidal, 0.05 to 2 mm in diameter with an inclusion fabric which is indistinguishable from that of the host rock (Cooper et al., 1983). The nodules show zonation of light and heavy REE and a strong differentiation between the core and rim of single grains (Read et al., 1987). It is thought that the nodules formed by the migration of REE upwards from turbidite⁹³ muds into the organic-rich hemipelagic⁹⁴ layers where they nucleated and grew during diagenesis and compactional dewatering (Milodowski and Zalaciewicz 1991).

An assessment was undertaken in 1994 to investigate the economic potential of the Welsh nodular monazites. The nodules are low in thorium which increases their economic attractiveness as it reduces the radioactive hazard associated with working them. In addition levels of europium, one of the more valuable HREE, are higher than average for placer deposits. The study concluded that

result of continental separation and lithospheric attenuation during the early stages of the opening of the North Atlantic.

⁹² Variscan: orogeny caused by Late Palaeozoic continental collision between Euramerica (Laurussia) and Gondwana to form the supercontinent of Pangaea.

⁹³ Turbidite: type of sedimentary rock composed of layered particles that grade upward from coarser to finer sizes and are thought to have originated from ancient turbidity currents in the oceans.

⁹⁴ Hemipelagic sediment: deep-sea, muddy sediment formed close to continental margins by the settling of fine particles, in which biogenic material comprises 5–75% of the total volume and more than 40 per cent of the terrigenous material is silt.

the bedrock deposits, which are the source of the REE, do not contain sufficient monazite to be economic and further work would be required to assess the true potential of the placer concentrations (Smith et al., 1994).

Alkaline igneous rocks

Ongoing, but as yet unpublished, studies by BGS on the Caledonian alkaline igneous intrusions of the north-west Highlands of Scotland have identified high concentrations of REE. Values of about 2 per cent total REE have been reported in the Cnoc nan Cuilean intrusion of the Loch Loyal Complex in Sutherland. REE minerals including allanite, ancylite⁹⁵, betafite⁹⁶ and rhabdophane⁹⁷ have also been identified in the Ben Loyal area (Shaw and Gunn, 1993). Pyroxenites⁹⁸ of the southern margin of the Loch Borralan Complex in the Assynt District contain REE values up to 739 ppm Ce, 1764 ppm Ce and 986 ppm Y associated with up to 2 per cent apatite. 0.7 per cent La+Ce was reported from syenite in the Loch Ailsh Complex on the eastern margin of the Assynt culmination (Shaw and Gunn, 1993).



Figure 29 Prismatic gadolinite-(Y) in a miarolitic cavity within the Northern Arran granite, Strathclyde, Scotland
Photograph: Fergus MacTaggart, BGS © NERC.

95 Ancylite: hydrated strontium–cerium–carbonate hydroxide. Formula: $\text{SrCe}(\text{CO}_3)_2(\text{OH}) \cdot \text{H}_2\text{O}$.

96 Betafite: Calcium Sodium Uranium Titanium Niobium Tantalum Oxide. Formula: $(\text{Ca}, \text{Na}, \text{U})_2(\text{Ti}, \text{Nb}, \text{Ta})_2\text{O}_6(\text{OH}, \text{F})$.

97 Rhabdophane: hydrated neodymium-dominant phosphate. Formula: $(\text{Nd}, \text{Ce}, \text{La})\text{PO}_4 \cdot \text{H}_2\text{O}$.

98 Pyroxenite: ultramafic igneous rock consisting essentially of minerals of the pyroxene group.

Tertiary granites

Several minor occurrences of REE-bearing minerals have been identified within the granites of the British Tertiary Igneous Province, an area of the north-west British Isles where intense igneous activity occurred during the Palaeocene and early Eocene. The Mourne Mountains and Arran granites represent the southern sector of the province with the lower silica Mull and Skye granites making up the northern sector (Hyslop et al., 1999). Fergusonite and gadolinite associated with other REE element-bearing minerals including allanite and zircon have been identified within miarolitic cavities of the northern Arran granite (Figures 29 and 30; Hyslop et al., 1999). The fergusonite and gadolinite are found associated with, and growing on, albite and orthoclase. The fergusonite, which occurs as prismatic acicular crystals up to 2 mm long, is dominated by neodymium and yttrium and the gadolinite by yttrium. The gadolinite occurs as dark green, vitreous, turbid, prismatic crystals up to 2.5 mm long (Hyslop et al., 1999).

Gadolinite and an unusual honey-brown coloured type of monazite, have been reported in vugs⁹⁹ in the Mourne Mountains granite of Northern Ireland (Hyslop et al., 1999, Green et al., 2005). Three minerals with significant REE



Figure 30 Euhedral crystal of zircon on an albite surface
Photograph: Fergus MacTaggart, BGS © NERC.

99 Vug: a small to medium sized cavity in a rock or vein.

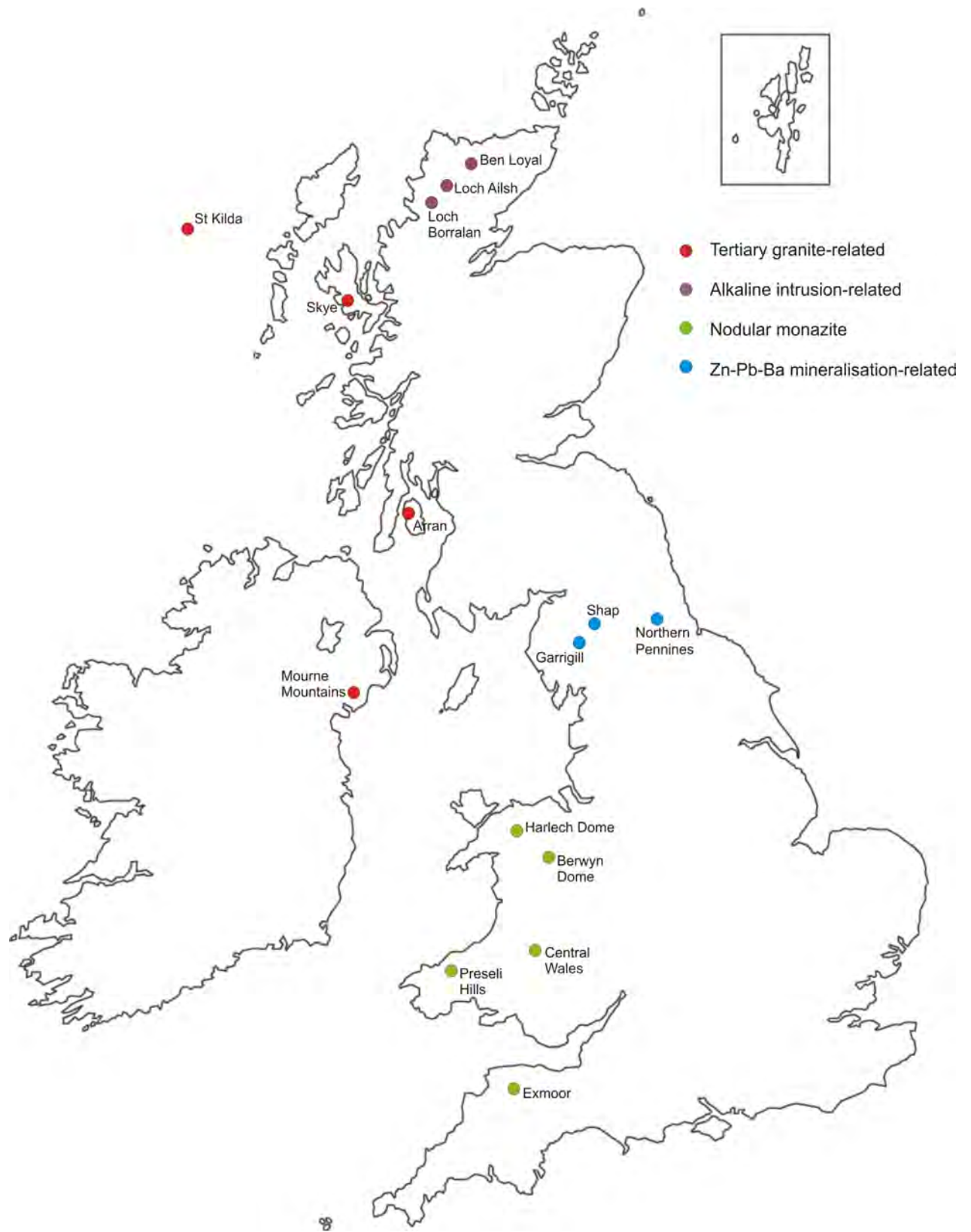


Figure 31 REE mineral occurrences in Britain (Mountain High Map frontiers™ © 1998 Digital Wisdom).

content, allanite, chevkinite¹⁰⁰ and zirkelite¹⁰¹, have been identified in the granites of St Kilda, in the Outer Hebrides. Chevkinite is the most common and can contain up to 41 per cent total REE. However, the REE minerals make up less than one per cent of the host rock (Harding et al., 1982).

Various REE-enriched accessory minerals have been identified in the granites of Skye. Allanites and sphenes¹⁰² are particularly LREE enriched with analyses returning an average of 25 and 46 weight per cent REO respectively (Exley, 1980). Gadolinite and kinosite have also been identified in miarolitic cavities within the granites on Skye (Green and McCallum, 2005).

Lead-zinc-fluorite-barite mineralisation

Small quantities of synchysite and other REE minerals have been identified associated with lead-zinc-fluorite-barite mineralisation in the Northern Pennine Orefield (NPO) of the Alston Block. Bismuthinite-bearing quartz veins near Stanhope and Rookhope contain synchysite, and more rarely monazite, xenotime and adularia, intergrown with bismuthinite (Ixer et al., 1996).

Synchysite has also been identified at the Tynebottom Mine, near Garrigill. The synchysite is associated with an assemblage which is believed to be part of the earliest, highest temperature mineralisation of the Alston Block (Ixer and Stanley, 1987).

Various studies have also shown that the fluorite in the NPO is enriched in REE. Values of up to 1888 ppm Ce+La+Y have been identified and the enrichment is thought to be derived from the underlying Weardale granite or as a result of inclusions of REE-bearing minerals within fluorite (Smith, 1974; Shepherd et al., 1982; Plant and Jones, 1999; Walters, 2011).

100 Chevkinite: cerium–titanium–iron silicate. Formula: $Ce_4(Ti, Fe_{2+}, Fe_{3+})_6O_8(Si_2O_7)_2$.

101 Zirkelite: titanium–zirconium–iron–yttrium–calcium oxide. Formula: $(Ca,Th,Ce)Zr(Zr,Ti)_2O_7$.

102 Sphene: calcium–titanium silicate. Formula: $CaTiSiO_5$.

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