REPORT

Geology of the Rare Earth Elements

Rare earth elements (REE) were once chemical curiosities, but have now become vital to a wide range of applications in electronics and energy systems, especially in high-strength magnets for car motors and turbine generators. They are essential materials in the manufacture of micro-electronics, with 2000 million smartphones currently produced each year, and they increase strength and heat reistance in aero engine alloys, and are vital for batteries in electric cars. New applications are being continually developed as materials-scientists experiment with the varied properties of these amazing elements.

REE are a group of elements with sequential increase in atomic number from lanthanum (57) to lutetium (71) that are correctly known as the lanthanide series. They sit together, all in one box, within the Periodic Table; scandium and yttrium (which lie in the same group within the Table) are usually considered with them due to their similar properties. They are all soft silvery metals. Recovery of individual elements is a difficult and costly process, partly because of their very similar chemistry and partly due to the environmental effects of the large amounts of radioactive and toxic waste products. That chemical similarity also makes REE next to impossible to recycle, and significant quantities are lost each year in the millions of replaced and abandoned smartphones.

REE are only produced in relatively small quantities; total world production in 2016 was about 135,000 tonnes. However, they have a wide range of physical properties that make them invaluable in multiple situations, commonly as alloys or additives in very small amounts that change or enhance the properties of the main material. They are classed as 'Critical Elements' in the Western world, partly due to their potential supply risk when around 95% of the world supply of REE is currently supplied by China.

Despite their name, REE are not particularly rare, as they have a crustal abundance that probably exceeds 100 ppm. This is comparable to that of copper, though that figure does apply to the total abundance of all 17 elements in the REE series, and some of the REEs are rarer than others. The first rare earths were discovered near Ytterby, near Stockholm in Sweden, which has given its name to four of the elements - yttrium, ytterbium, terbium and erbium. They are never found as native elements, but are generally combined in a variety of minerals. Furthermore, several REE commonly occur within the same mineral, which leads to difficulties in extracting the separate elements. It is not the crustal abundance that determines their values and resources, but the critical factors are how, where and by how much they have been concentrated by natural geological processes into ore deposits from which they can be economically extracted. There is then an extra factor in any resource value, depending on its content of associated radioactive elements and the environmental problems of their disposal.

The geology of REE orebodies

Most resources of REE are found as monazite (a phosphate of REE and thorium), bastnaesite (carbonate of REE) or xenotime (phosphate of yttrium and REE), and the phosphates are commonly intergrown with larger proportions of apatite (calcium phosphate). The principal orebodies of REE lie within four geological environments, though smaller quantities have been produced from various other sources, commonly as a by-product of uranium mining.

Carbonatites are by far the most important source. These unusual igneous rocks are composed largely of calcium and sodium carbonate but contain a wide range of other elements and minerals, notably iron, barium, uranium, thorium, fluorine and very variable amounts of REE (from several thousand ppm up to several percent). Their ultimate origin is obscure, but they are generally found away from current plate margins and are commonly associated with major rift systems, as in East Africa. Only a few of around 500 currently identified carbonatites contain REE that can be commercially extracted.

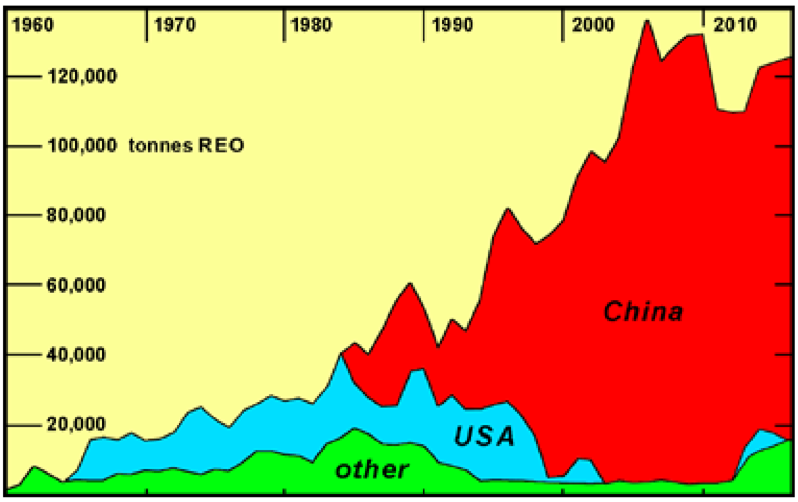

Figure 1. World production of REE (expressed as rare earth oxide equivalent) since 1960. China's production had been almost entirely from the huge Bayan Obo mine that primarily produces iron ore. The USA production has been largely from the Mountain Pass mine, which is currently closed. Other production has mainly been as a by-product of uranium mining, notably in Russia, Brazil and India, except for the increase since 2012 when the Mount Weld mine began producing ore.

__Figure 2__. The huge iron ore mine at Bayan Obo, in northern China, which is also the world's major supplier of REE at the present time.

Pegmatites and skarns associated with alkaline granites are increasingly being recognised as significant resources of REE. The impact of metasomatism by late-stage fluids includes mineralised veins, breccias and disseminated ores, all with the exotic chemistry that typifies many pegmatites.

Heavy mineral sand deposits of ilmenite and zircon can also contain significant amounts of monazite, which have generally yielded REE as a mine by-product. These was formerly important sources of REE, but the typically high levels of radioactive thorium have now made them environmentally undesirable, and production from alluvial sands has been banned in Malaysia and Australia.

A resource recognised only more recently is in ion-absorption clays that have developed as weathering products of granites enriched in REE. These supergene ores are widespread in southern China, and present fewer problems in processing as many of the environmentally challenging elements, such as uranium, thorium and fluorine have been removed during weathering.

The world's current REE resources

Currently by far the largest source of REE is the Bayan Obo iron-REE-niobium deposit in northern China. It lies north of the city of Baotou, in semi-desert close to the border with Mongolia and some 500 km west of Beijing. Three huge orebodies extend along an 18 km strike length of metamorphosed Proterozoic dolomites that appear to have been metasomatised by a carbonatite intrusion, though there is still debate over the details of the genesis of this remarkable ore. It is worked primarily for iron, as it contains 1500M t (million tonnes) of hematite and magnetite ore, which provide the economic backbone of the mining operation. The REE was originally a rather welcome by-product, though it is now regarded as a very valuable co-product. Reported ore reserves are around 50M t at 6% REO (oxides of the rare earths, which is how the ores are normally evaluated) in monazite and bastnaesite. The Bayan Obo mine is also a huge producer of niobium, which is an essential component of high-strength steels, though 85% of the world's niobium now comes from the Araxa mines in southern Brazil's Minas Gerais.

Between 1965 and 1995, the Mountain Pass mine in California was the world's largest supplier of REE. It lies in a mountain range 80 km southwest of Las Vegas, right beside the freeway to Los Angeles, and not far south of Death Valley. An alkaline dyke swarm of carbonatites and vein networks are all derived from late-stage emanations from a Proterozoic syenite, and are rich in bastnaesite. Resources extended to 20M t of ore with 9% REO. The mine had to close in 1998 in the face of environmental and financial problems. Its pipeline, carrying toxic thorium in waste water, dispatched 20 km eastwards to evaporation ponds at Ivanpah Dry Lake, and then developed leaks that were environmentally unacceptable, and the mine's economics were undercut by the Chinese supply. The mine re-opened in 2012, but closed when it was declared bankrupt in 2015.

A newcomer now on stream is the Mount Weld mine, near Laverton, some 200 km north of Kalgoorlie in Western Australia. This is another Proterozoic carbonatite plug enriched with REE; it is 3 km in diameter and has weathered to create a cap of supergene ore with one of the world's highest grades, at 10.8 % REO through a reserve of nearly 10M t. The REE

__Figure 3__. Little activity at the Mountain Pass REE mine that is currently under care and maintenance in California.

Figure 4. *The open-pit REE mine at Mount Weld, already 50 metres deep into the red soils and laterites that characterise the Red Centre of Australia.*

now occur mainly as monazite in with the iron oxides forming the laterite profile that lies at depths of no more than 110 metres. Production from the shallow open-pit mine started in 2012, and the ore is shipped to a processing plant in Malaysia.

Perhaps the most exciting REE resource is Kvanefjeld in southern Greenland, which may rival Bayan Obo as the world's largest reserve of REE. It contains at least 6M t of REO, and also has massive reserves of uranium and zinc. Lying within the hills above the small town of Narsaq, it overlooks the fiord leading up to Bratahild, which was Erik the Red's first Greenland settlement in 982AD (and actually is in an area of good farming land and green fields far below the icecap). The magmatic ore is within an extraordinary complex of alkaline igneous rocks that were intruded into Proterozoic lavas. Kvanefjeld was recognised as a major uranium orebody in the 1950s, but its radioactive nature made it environmentally unacceptable in the pristine wilderness of Greenland, and the importance of its REE was not then appreciated. Restrictions on uranium mining were overturned by the Greenland government in 2013. Since then, the site's aura of radioactive hazard from its uranium has been cleverly replaced by a green halo of environmental goodness in supplying essential materials for the batteries of electric cars. The mine will be a large open pit, and production is likely to start within the next year or so.

A different type of REE ore has recently been recognised across a large swathe of the Jiangxi province in southern China, about 400 km north of Hong Kong. This occurs as ion-absorption clays within a residual blanket of laterite that is generally only about 10m thick. It source is the underlying granite, which contains about 400ppm REE in zircon and apatite, but the REE have been mobilised and precipitated as carbonates in a classic case of supergene enrichmnent. Though ore grades are generally less than 0.2% REO, they are low in thorium. Their potential mining therefore presents few of the environmental problems that are typical of ores where the REE are closely associated with radioactive thorium.

The future for REE resources

Since China's dominance and temporary manipulation of their REE exports in 2010, politically driven exploration programmes have found REE prospects all around the world. Some, any or all of these may come on stream within the next decade, as long as progress in technology continues to increase demand.

The Bear Lodge project in Wyoming, some 12 km east of Devil's Tower, is an almost conventional REE ore in Tertiary alkaline igneous rocks, with vein systems through volcanic vents that once produced both phonolite and trachyte. Drilling has already proven 3M t of reserves with 3.7% REO, and there are another 15M t of indicated reserves with 3% REO.

On the Laurentian Shield of eastern Canada, Strange Lake lies close to the northern part of the Labrador–Quebec border. Its alkaline granite has indicated reserves of 280M t at 0.9% REO, with higher values

Figure 5. *Small icebergs drift down a fiord cut into the Proterozoic complex of alkaline igneous rocks that contain the REE orebody at Kvanefjeld, in the southwestern corner of Greenland.*

within a zone of pegmatite only recently found. The ore is particularly valuable for its high levels of the rarer elements within the usual mixture of REE. There are plans for a large open-pit mine, but production is still some years into the future.

Another Australia project is based at Nolans Bore, 140 km northwest of Alice Springs. Again it has a Proterozoic carbonatite source, which fed pegmatitic fluids into veins and breccias within the granulite country rock. The ore mineral is fluorapataite, and resources extend to about 56M t with 2.6% REO. The deposit also contains significant amounts of uranium and thorium in associated minerals, and these will be stockpiled in on-site dumps until a market is found for them. Production of REE should start in 2019 with an open-pit mine that will eventually reach 200m deep.

Geologically rather different is the Round Top project in Texas, in the Sierra Blanca, 140 km southwest of El Paso and just 15 km from the Mexican border along the Rio Grande. This is based on a Tertiary rhyolite laccolith intruded into a Cretaceous sedimentary sequence. The rhyolite is enriched in REE, but the minerals are distributed uniformly through the intrusion. The bulk rock is high also in beryllium and fluorine, as is typical of pegmatite, suggesting that it was modified by late-stage fluids. Reserves amount to 500M t at 0.06% REO. An open-pit mine would be viable at this low value, but only because the rhyolite is susceptible to acid leaching; after crushing to gravel size, the REE could be extracted in solution, thereby avoiding any further mineral separation by expensive flotation.

Besides these, and more, workable REE orebodies already discovered, there are other, more obscure resources, that may have potential. Australia's gigantic Olympic Dam orebody contains huge amounts of REE, but at levels that are currently uneconomic to extract.

Sweden's enormous magnetite orebody at Kiruna contains apatite that has to be separated at the mine because the phosphate is a contaminant in iron ore. Until 1988, this was sold into the fertiliser industry, but since then it has been dumped on heaps adjacent to the mine. It has now been found to contain 1% REO, which could be extractable.

Ordinary coal seams, and their power-station ashes, are another potential resource (see Geobrowser in the 2016 *Mercian Geologist*).

And now ocean-floor muds have been found to contain up to 0.2% REE in beds up to 40 meters thick, notably on either side of the East Pacific Ridge along the Pacific–Nazca plate boundary; but scooping these from the ocean floor beneath 4000 metres of water is still far from being viable.

Politics of the REE sources

It is clear that the rare earth elements are not rare in geological terms. The problems in mining them come from a range of political, economic, technological and environmental factors. All is driven by the hugely increasing demands from industry, significantly with so much modern electronics technology, but with even larger potential in the future with REE being essential components in batteries for electric cars. Then, on top of all this, REE became a political weapon in 2010, when China briefly withheld supplies to Japan during a territorial dispute in the East China Sea. At that time, China held a near-monopoly of worldwide REE supplies, so this was a wake-up call to the Western world.

Figure 6. *Progress in systematic sampling across the REE prospect at Nolans Bore in central Australia.*

Since then, a veritable explosion of REE mineral exploration has been driven by both politics and simple economics. Fortunately, REE exploration is not that difficult, as carbonatites are easily recognised targets in various geophysical surveys, and many of the anomalies require only shallow drilling to evaluate as orebodies. But while new resources are being developed, Chinese companies have already widened their stake in REE by buying the Mountain Pass mine at its bankruptcy auction in June 2017, and are also major partners in the Kvanefjeld project. And with each new project the challenges inevitably follow where the normally-associated thorium waste is seen as a threat to the environment. The battle for REE resources continues as China *v*. the West, but is also threatening to become one of high-tech *v*. the environment.

Tim Colman and Tony Waltham

The geological resources and mining for REE is a youthful and fast-changing subject. Besides a few basic sources (including the useful summary at bgs.ac.uk/mineralsuk/statistics/mineralProfiles, and USGS Prof. Paper #261 on Mountain Pass), an on-line search for REE and any of the sites named above produces a wealth of data.