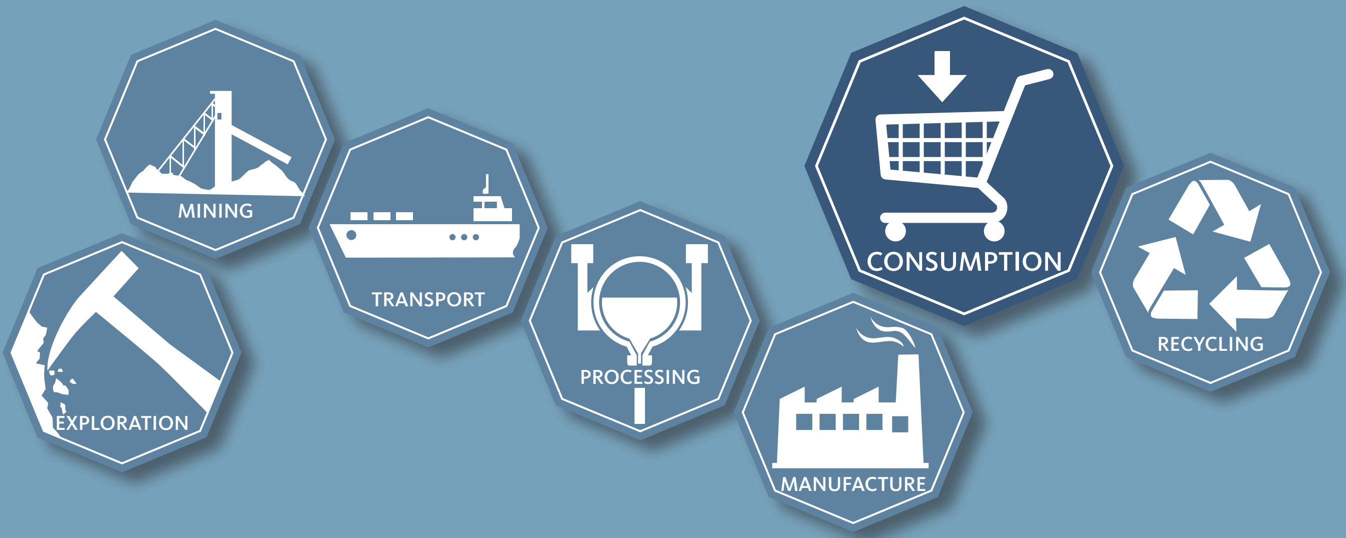
Rare Earth Elements (REE)

Geology, technologies, and forecasts

Per Kalvig

MiMa rapport 2022/1



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Definitions

Alkaline rocks	Geological designation for rocks that have relatively low silica and aluminium content and relatively high amounts of the alkali elements sodium and potassium.
Alloy	Materials consisting of a combination of metals to acquire the desired physical/chemical properties.
Basket price	The monetary worth (USD) of 1 kg REO based on the chemical compound found in the deposit.
Compounds	A combined product of all rare earth elements resulting in the dissolution of the mineral. Also known as Rare Earth Compound (REC) and Total Rare Earth Compound (TREC).
Didymium	A combination of the elements neodymium and praseodymium
Grade	The measure of the metal content of the ore. Normally measured as weight % of grams per tonne (equivalent to ppm) or as troy ounces per tonne. For REO, either % or ppm is used.
IA deposits	Ion adsorption (clay) deposits. The rare earth elements are adsorbed onto the surfaces of the clay particles.
Ore Value	The value of one tonne of the ore.
Mineral concentrate	A commodity consisting of a single mineral concentrated from the ore; the first product in the value chain.
Mischmetal	Alloy consisting of lanthanum, cerium, praseodymium, and neodymium. Manufactured as different alloys; cerium is always the primary element.
Tailings	Worthless minerals that are sorted from the sellable minerals in a mining facility during the ore processing. Tailings are usually a much larger quantity than the sellable minerals (the mineral concentrate) and are typically deposited in large basins near the mine.
Tolling	A company that performs a processing of the ore/raw material on contract.
Value chains	A business concept that describes all the activities necessary to manufacture a product. For the rare earth elements there are many value chains, often simply referred to as ’the value chain’.

The designation *rare earth elements* is used as a general description regardless of the degree of processing. If there is a need for a more precise designations, the chemical compositions are intended to be used, as is the purity of the products, if deemed relevant.

Abbreviations

CAD	Canadian Dollar
CAPEX	Capital costs to the facility for infrastructure, mines, and processing plants.
CFL	Compact Fluorescent Lamp
CIF	Prices including insurance and shipping
CIS	Commonwealth of Independent States; also known as SNG
CRT	Cathode Ray Tube
DALY	Disability-Adjusted Life Years
DDWT	Direct Drive Wind Turbine
EPA	Environmental Protection Agency
ERA	Environmental Risk Assessment
ERMA	European Raw Materials Alliance (see Appendix VII)
EV	Electrical Vehicle
EXW	Ex Works. The vendor organises transport; the customer pays for the transport
FCC	Fluid Catalytic Cracking
FOB	Free on Board; the customer takes the responsibility and costs of the transport
FS	Feasibility Study
FTL	Fluorescent Tube Light
HDD	Hard Disk Drive
HEV	Hybrid Electric Vehicle
HREE	Heavy Rare Earth Elements (the group of heavy rare earth elements)
HREO	Heavy Rare Earth Oxides
HSLA	High-Strength Low-Alloy
IA	Ion Adsorption
IAC	Ion Adsorption Clay
IOCG	Iron Oxide Copper Gold
IP	Intellectual Property
ISL	In-situ leaching
IUPAC	Union of Pure and Applied Chemistry
IX	Ion Exchange
JOGMEC	Japan Oil, Gas Metals National Corporation
JORC	Joint Ore Reserves Committee Code; authorised Australian resource inventory method
kt	Kilo tonne (thousand tonnes)
LCD	Liquid Crystal Display
LED	Light Emitting Diode
LLE	Liquid-Liquid Extraction
LME	London Metal Exchange
LREE	Light Rare Earth Elements (the group of light rare earth elements)
M.	Million
MFA	Mass Flow Analysis
MIIT	Ministry of Industry and Information Technology of the People’s Republic of China
MiMa	Centre for Minerals and Materials
MoU	Memorandum of Understanding
MREC	Mixed Rare Earth Compound
MREE	Medium Rare Earth Elements (the medium group of rare earth elements)
MREO	Mixed Rare Earth Oxide
MRI	Magnetic Resonance Imaging (a scanner used in hospital equipment)
MRT	Molecular Recognition Technology
Mt	Megatonne (million tonnes)
NI 43-101	National Instrument 43-101; authorised Canadian resource inventory method

NORM	Naturally Occurring Radioactive Materials
PDP	Plasma Display Panel
PEA	Preliminary Economic Assessment
PFS	Pre-Feasibility Study
PLS	Pregnant Leach Solution (the liquid that is the product when the REE minerals have dissolved)
Ppm	Parts per million
REC	Rare Earth Compound: a combination product of rare earth elements that emerge after the mineral is dissolved and the rare earth elements are isolated from the mineral's other elements.
REE	Rare Earth Element
REE magnetic metals	Praseodymium, neodymium, terbium, and dysprosium
REIA	Rare Earth Industry Association
REM	Rare Earth Metal
REO	Rare Earth Oxide
RMB	Renminbi (yuan)
ROW	Rest of the World (used in the context: all countries except China)
SNG	Soduzhestvo Nezavisimykh Gosudarsty (Commonwealth of Independent States)
SSD	Solid State Drives
SX	Solvent Extraction
t/y	Tonnes per year
TREC	Total Rare Earth Compounds: The collective term 'compounds' of rare earth elements found in a mineral, resource, reserves, or product.
TREE	Total Rare Earth Element: The collective term for all rare earth elements found in a mineral, resource, reserves, or product.
TREO	Total Rare Earth Oxide: The collective term for oxides of all rare earth elements found in a mineral, resource, reserves, or product. The average conversion factor between TREE and TREO is about 0.8.
TWh	Terawatt per hour
USD	US Dollar
USGS	United States Geological Survey
WEEE	Waste from Electrical and Electronic Equipment
WTO	World Trade Organization
wt%	Weight percent
y	Year

Figure captions

Table captions

Introduction

Rare earth elements (REE) is the common name for a group of 17 special elements that over the last 20 years have seen increasing industrial significance, even to the extent that uncertainty regarding future supplies has caused geopolitical concern in the western countries. The rare earth elements are considered critical raw materials by several countries in the western countries. This issue is also relevant in a Danish context, both in relation to parts of the industry, (e.g. the wind turbine industry, which is a heavy consumer of rare earth elements), and because constrains in the raw materials supply chains abroad can spill over and consequently delay the green transition. Another consequence of international interest in these rare earth elements has resulted in large exploratory activities of Greenland's plentiful deposits of rare earth elements.

During the past 30 years, China has managed to develop all parts of the value chains relating to rare earth elements, from extraction of the primary raw materials to advanced finished products, and are today the dominant supplier and producer of raw materials with rare earth elements, raw materials of these special elements and exporter of products in which rare earth elements have crucial significance and can only be replaced by other raw materials with great difficulty. This development has been possible for China partly due to the USA and other western countries move of industrial production to Asia in the 1990s and 2000s to take advantage of the lower wage level. Hence, the West's development of infrastructure and know-how in the processing of these special raw materials stalled.

China's halt in exports of rare earth elements to Japan in 2010 was a wake-up call to politicians in the West, one which highlighted China's industrial strength and the West's own lack of secure supplies of mineral raw materials. Western countries had, over the previous 10 years, launched a series of political initiatives and private investment to develop their own supply chains that would liberate these countries from their dependence on China. On the other hand, China seeks to maintain its economically significant *de facto* monopoly through regulations and quota, tax, and duty systems. Overall, China's dominance remains unchanged despite 10 years of western efforts.

The value chains of rare earth elements differ in complexity from most other raw materials because it is a large group of elements found together in the minerals, but which have, to some extent, different uses and demands. These combinations require an infrastructure that includes many steps of complex technologies (some of which are even legally protected), as well as markets demanding the products.

It is, therefore, not easy to develop western supply chains that, in competition with Chinese companies, can deliver the important raw materials to, for instance, the green transition. The objective of this report is to highlight the complexity of such a task. Firstly, the report provides an overview of the value chains for rare earth elements from mineral exploration to finished product, as well as an account of the main industrial uses. Also, some of the reasons that the western world's supply challenges regarding the rare earth elements, now 10 years after the challenges were recognised, still haven't been resolved, are discussed. The report also provides an overview of the supply challenges the world may face heading towards 2030 with the increased focus on green technology, where the rare earth elements are included as key raw materials for several technology applications. In addition, the report touches upon the significant climate impact that the production of rare earth elements used in the green transition gives rise to.

The report is based on published research articles and reports along with unpublished presentations, project websites, stock exchange announcements, newsletters, newspapers and material from industry and relevant organisations etc., combined with the knowledge that Centre for Mineral and Materials (MiMa) has built over many years taking part in multidisciplinary research projects related to rare earth elements' geology and international value chains. The report is based on data covering the period up to midio 2021. The report's analyses of global resources, global production, and the supply situation up until 2030 is, to a large extent, based on MiMa's database of western exploratory and mining projects, and draws on publicly available sources. The report's analyses are only meant as a guide, but they are considered solid and correct. Raw materials are a dynamic subject that can significantly affect conditions at a project level.

The report is intended for an audience of public and private decision makers and stakeholders and others who are connected to some of the areas associated with establishing western supply chains for rare earth elements.

As it is my expectation that the majority of readers' interest will be limited to only parts of this report, the chapters are designed so they can be read independently; however, the chapters on China's and the West's projects (Chapter 13) and future scenarios (Chapter 14), likely requires previous knowledge or reading of the chapters concerning supply chains (Chapter 5), and on the importance of geology (Chapter 9). The structure of this report hence implies that there are certain repetitions and cross-referencing.

This report is translated to English by Phil Rutter, based on the original Danish version (http://mima.geus.dk/wp-content/uploads/MiMa-Rapport_2021_02_Online_V2.pdf); minor revisions have been made August 2022.

Future perspectives

The report demonstrates that there are many, and large, deposits of rare earth elements across many countries in all parts of the world, and that there, unlike other raw materials, are known resources sufficient for several hundred years' consumption. However, the report also shows that the high increase in the consumption of rare earth elements for the planned expansion of wind power and electrification of the transport sector means that even by 2025, there is a risk of inadequate supplies of these raw materials, and that this supply problem will potentially grow heading towards 2030. A shortage of supplies of these important raw materials – including rare earth elements – can threaten the planned implementation of a green transition.

With a possible deepening supply crisis of rare earth elements already by 2025, an adjustment of national and regional mineral raw material strategies may be required, adopting a more global view of the industry, and recognizing that China's existing expertise is critical in securing supplies. Moreover, the strategies should reflect that raw material criticality is dynamic and complex; by solving one supply problem, e.g. the rare earth elements, it can create supply problems for other raw materials.

There are, as described in this report, many reasons for the West's futile attempts over more than 10 years to break China's *de facto* monopoly on the most important parts of the rare earth elements' value chains. Maybe part of the explanation can be found in the 30-year-old statement from Horst Damm at Canton Spring Fair in Guangzhou in 1991: *Our relationship with China is based on trust and understanding. They don't trust us and we don't understand them!*

Per Kalvig, Copenhagen, July 29, 2022

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Summary

Chapter 1: Rare earth elements are considered as critical raw materials
Raw materials considered of economic importance to a country or region, but which are also subject to actual or potential supply constraints, are defined as critical raw materials (CRM). Most industrial countries classify the rare earth elements (REE) as CRM's.

Chapter 2: What are Rare Earth Elements
The REE group includes seventeen elements: lanthanum, cerium, praseodymium, neodymium, promethium, samarium, europium, gadolinium, terbium, dysprosium, holmium, erbium, thulium, ytterbium, lutetium, yttrium and scandium, the latter of which is not dealt with. Commonly applied terms are light rare earth elements (LREE), including the first four of the elements listed above, and the heavy rare earth elements (HREE), including the rest. They are all metals and the misleading names 'rare' and 'earth' stem back to the first discoveries more than 200 years ago, reflecting a different understanding of chemistry and mineralogy.

The REE are widely used in industry, due to the specific chemical and physical properties of these elements. Although there are many similarities among the REE, the various industrial sectors only demand a few of them, due to their specific physical and chemical properties.

Chapter 3: Industrial Applications of Rare Earth Elements
The majority of the REE have industrial applications as for example: catalytic processes and as catalytic converters in the automobile industry, in batteries, permanent magnets, metallurgical processes, in the glass industry, phosphorescence, technical ceramics and optical polishing. Each of these sectors demands only a few specific elements and, in many cases, substitution is not an option. The global drive for green energy impacts in particular the demand for REE in the magnet industry, and consequently there is a substantial growth in demand for praseodymium, neodymium and dysprosium. Over the coming decade, this market is expected to play an important role for the development of global REE demand and supply.

Chapter 4: Trade and Prices
The majority of the REE raw materials and semi-finished products are traded bilaterally on long-term contracts. There are no recognised markets such as the London Metal Exchange (LME) that trade metals. Consequently, there is little information available in terms of volumes traded, dominant companies, specifications, and prices. Therefore, there are large variations in the available data on REE and, moreover, the products are also rarely well-defined, which makes analysis difficult.

Over the past 10 years the total consumption of REE's has grown by about 50 %. Lanthanum and cerium make up about 70 % of the traded tonnages and are thus the largest groups, followed by neodymium; however, the demand for neodymium is rising sharply due to the growing magnet market. In terms of value, the raw materials for market for permanent magnets are the most significant, accounting for about 80 % of the total turnover.

Trade in REE occurs at many stages along the value chains, from mine to finished product. The prices for various REE reflect the extensive and highly technical processing required to produce products that can meet the specific requirements of industry at every stage. The prices of mineral concentrates and other processed raw materials are therefore significantly below the published list prices for finished, refined products. REE-materials for the production of magnets belong to a group that requires particularly high specifications and therefore attracts consistently high prices. Price variations between the individual REE's also reflect differences due to their geological availability, such as lanthanum and cerium, which are often found in large quantities, and terbium and dysprosium, which are only found in small quantities.

The prices of REE reflect the dynamic conditions of the world economy. Up until 2010, prices showed a predominantly downward trend. The political tensions between China and Japan exposed the West's supply challenges with China emerging as the dominant producer at all levels of the global value chain. After some violent fluctuations in 2011-2012, prices for many of the REE fell again; but for the raw materials used to make permanent magnets (in particular praseodymium, neodymium, dysprosium and terbium), prices have been rising. These 'magnet' REE now determine whether an exploration project is considered viable. High prices keep many of the exploration projects going; falling prices will see many projects abandoned.

Chapter 5: The Value Chain (Upper to Middle)

The value chains for all mineral raw materials start in principle with mineral exploration, of which, only a small number of projects are ultimately developed for mining and production of minerals that contain the desired commodity/element. For some elements, e.g., gold, the value chains are short and technically simple. For others – such as the REE – the chain is longer, with the need for extensive and technically complicated processing to produce the raw materials and compounds in accordance with the consumer's specifications. For these, the value chain often includes the following process steps: (1) Mining and production of mineral concentrates; (2) extraction of the REE from the minerals; (3) separation of the individual REE; (4) refining; (5) alloying, and (6) product/component manufacturing – and later (7) recycling. Step 1 is usually performed by the mining company; the subsequent steps are performed by companies specialising in each of the particular process steps and are most often located far from the mining site.

China dominates all steps of the REE supply chains, but with a declining share of the upper end of the supply chains. Despite the West's attempts to establish infrastructure at the other steps in the supply chain, western production still only accounts for a small, fairly insignificant part of this global chain. In particular, focus has been on developing more efficient methods for separating the individual REE (step 3), as the traditional methods are slow, require a lot of space for the many hundreds of separation columns, and as they are technically challenged, and IP-regulated, operations. Chinese companies control these productions, which constitute a significant bottleneck and is one of the main reasons why REE is considered as critical raw material.

Chapter 6: Recycling and Substitution

There is a growing recognition of the need to increase the volume of recycling of mineral raw materials in combination with the desire to reduce the environmental impact of primary production. This is coupled with the desire to detach western countries' reliance on China's REE production, thereby minimising supply risk. Overall, recycling currently contributes with less than 1 % of the global demand.

Efforts to increase recycling have mainly focused on production waste and discarded products such as magnets, batteries, lamps, and catalysts. The challenges for increased recycling are partly due to the fact that a large proportion of REE end up in physically small units, each of which contains only a small quantity of REE. Thus, it is difficult to collect and process this material efficiently. Large units with large quantities of REE, such as magnets from electric vehicles and wind turbines are only available after 10-15 years and 20-30 years of use respectively and can therefore not be included as a subsidy for existing needs. In addition, the technologies for recycling are under development. There is considerable material research going on targeted substitution of some of the high demand and expensive REE with others which are less in demand and thus cheaper.

Chapter 7: Environment, Health, and Climate Impact in the Upper Parts of the Value Chains
The production of refined REE raw materials takes place over a large number of process steps, which combined, have a significant CO_2 footprint, high water and energy consumption, as well as radioactive environmental impacts from e.g., associated content of uranium and thorium. The extent of these environmental impacts is particularly related to the type and quality of the ore and the technical methods used to exploit the specific REE required.

Chapter 8: Global Production of Rare Earth Elements
The global production of the raw materials containing REE in 2020 amounted to approximately 240.000 tonnes (USGS 2021). However, significant discrepancies between the global inventories occur, but all indicating the same fast-growing production trend, with about a 100 % growth in the period from 2015 to 2021. The growth reflects the global shift to fossil-free energy sources and electrification, for which neodymium, praseodymium and dysprosium in particular are in high demand. Primary production is supplied for the most part by 11 countries, of which China is by far the largest producer; but significant production also comes from e.g., USA, Myanmar, and Australia.

Global production statistics for the total REE are published annually by several institutions. To assess the supply-demand balance, the total figures are broken down to individual REE, and these estimates form the basis for the foresight scenarios are reported in Chapter 14.

Chapter 9: The Importance of Geology for the Supplies of Rare Earth Elements
REE are found in many different mineral and geological environments, occurring on all continents. Geologically, there are two main groups: (i) Magmatic types, divided into five subtypes, of which the alkaline and carbonatite subtypes constitute the largest deposits, and (ii) the secondary types, divided into heavy sand, laterite, and ion adsorption (IA) deposits, of which the latter is enriched with heavy REE (HREE). The mineralogy, and thus the distribution of the REE, is controlled by the geological environment it is related to. Given the fact that the natural distribution of REE does not match the market demand, some deposits are, however, more suitable than others, and consequently are economically more attractive.

Chapter 10: Resources and Reserves
The terms ‘resource’ and ‘reserve’ are used to describe the estimated volume and grade of a raw material being amenable to mining and the level of confidence in that estimate. Before mining can be initiated, the reserves must be documented at a very high level of confidence in order to convince investors that exploitation of a given resource is economically viable. It takes several years of high-risk and intensive mineral exploration to reach the stage where only minor uncertainties remain, and the risk has been minimised sufficiently for the major investment required to commence mining. The mining industry applies standardised terms and procedures set out in mining codes (fx. JORC, NI43-101, and CRIRSCO), to classify resources and reserves into various classes. A feasibility study based on mineral reserves, would need to see ‘’proven’ and ‘probable’ classes of mineral reserve; ‘measured’ resources would have been converted into either ‘proven’ or ‘probable’ mineral reserves through the application of various parameters. Rather few REE projects have reached this stage, despite many years of intensive exploration.

Exploration and mining companies report matters related to the resource/reserve to the authorities and markets, and, on the basis of this, the national resources/reserves are published. The USGS prepares annual global assessments. Since 2000, the global reserves for REE have amounted to around 114 Mt (TREO); at current rates of consumption, this is sufficient for several hundred years of production. But as consumption is increasing at a fast rate, the total life of the reserves decreases; however, this may well be offset by new discoveries as a result of exploration activity, new production methods and increasing supply from recycling.

Only annual data of the combined total amount of all REE are published. As such, inventories cannot generally be used for assessments of the reserves for the individual sectors. Estimates however have been prepared in this project for the reserves/resources for the individual REE, based on geological knowledge of the mines that produce them.

A 'bottom-up' analysis of the global resources/reserves has been carried out based on the estimates published for mining and exploration projects carried out as part of the project (Appendix I). From this analysis it appears that carbonatites and alkaline deposits constitute the largest proven and probable resources, respectively. It also appears that the largest proven reserves are found in China, USA, and Australia; the largest probable deposits are found in Greenland, Canada, and Russia.

Chapter 11: China's Strategies and Practice(s)

In 2002, the US abandoned production of REE after many years, leaving China to supply the world market. China was already a dominant producer, particularly due to the Bayan Obo and Sichuan mines (about 75 % of global production), ion adsorbed clay deposits in Southern and Eastern China (ca. 20 % of global production), as well as smaller amounts of heavy mineral sand deposits. After the year 2000, China expanded and diversified the value chains for REE, and exports of raw materials increased until 2010 when the political conflict between China and Japan resulted in a change in Chinese strategy, focusing on adding value to the products in China and not exporting raw materials. China has subsequently reduced production from ion adsorbed clay deposits to meet environmental criticism; this has caused a minor change in the overall LREE:HREE ratio, in favour of the former.

As part of China's diversification, the value chain has been expanded and a 'REE cartel' has been established, consisting of six large consortia, which are awarded licenses and half-yearly production quotas for both primary production and processing. Additionally, China has introduced a tax system, designed to make it more advantageous for Chinese companies to establish business links with domestic value chains, rather than foreign, with the overall aim to export the products to the West. Moreover, imported semi-products are taxed.

Chapter 12: China's Value Chains for Rare Earth Elements

China has developed highly diversified and complex value chains for REE, organised and structured to ensure that China can continuously maintain their monopolistic market dominance. In 2016, more than 400 companies across 23 provinces were involved in REE-related mining, raw material processing and trade; today the number is even higher.

The value chains are predominantly organised into six large groups (called The Big Six) and are organised on the basis of allocated production quotas for both mining and processing. Most members of The Big Six are vertically diversified, encompassing all necessary industries from mining to finished products, however, with a specialisation in the composition of the raw materials in LREE and HREE. The consolidation in The Big Six enables China to exploit the vast LREE resources at Baotou Bayan Obo, in Inner Mongolia, as well as the Sichuan Province to the West and Shandong Province to the East. The large contribution of HREE comes mainly from the exploitation of ion adsorption clay deposits in the southern provinces: Jiangxi, Ganzhou, Guangxi, Hunan, Fujian, Guangdong, and Yunnan.

Declining revenues and challenges in sourcing raw materials have contributed to rivalry between The Big Six. Considerations are therefore being given to reducing the number of groups from six to two. In addition to these challenges, the West's efforts to establish its own value chains mean increased competition for the magnet raw materials. Many western projects have Chinese partners, with whom favourable 'off-take' agreements can feed raw materials into the Chinese value chains, exemplified by the stakeholder relations between Shenghe Resources Holding and the Kvanefjeld Project, Greenland and Mountain Pass in the US.

Chapter 13: New Value Chains Outside China – Examples

Several western countries are active in the effort to establish independent value chains for REE, and a wide range of policy initiatives including research funding and business support schemes have been introduced. Additionally, hundreds of private exploration companies, especially after the price spike period in 2011, are undertaking exploration across the world. Some of these projects have now reached the advanced exploration stage and are faced with issues related to where and how to get the ore treated. In the absence of partners and sales opportunities in the West, most of the projects have established co-operation with Chinese partners, several of which are members or associated members of the Big Six, offering know-how, off-take commitments and often project financing as well. Some large, western-based companies do possess the required know-how and facilities related to the middle and lower parts of the value chains for the REE, however, several of these are also significantly engaged in REE activities in China. Thus, the international and lateral diversification of the large consortia makes it difficult to distinguish between 'Chinese' and 'the West'.

Chapter 14: Assessment of Supply challenges for the Green Transition

Over the past 20 years, technological development has increasingly involved the REE, resulting in a rapidly growing market, which is primarily dominated by China. However, the international focus in recent years on the need to develop CO_2-reducing technologies, especially in the transport and wind energy sectors, has resulted in the fast-growing need for a reliable supply of these REE, and this demand is expected to grow even faster over the next decade. In particular, the market will demand praseodymium, neodymium and dysprosium, and these commodities will determine the total production of the REE.

Rapidly growing consumption and lack of western development of relevant infrastructure for producing REE opens the possibility of supply shortage risks due to scarce primary production facilities. Scenarios have been made for the REE supply-demand balances in 2025 and 2030, respectively. The existing mines, as well as 26 advanced exploration projects, which to varying degrees are expected to contribute to production, are included. Demand is estimated based on three published foresight studies for the development of the electric vehicle market up to 2030.

The scenarios indicate a supply deficit of around 10 % in 2025 for both praseodymium and neodymium if the expected demand for electric vehicles is sustained and the production of raw materials follows the stipulated low-level scenario. Applying the same assumptions for 2030, the outcome of the scenarios is a significant deficit of about 50 % for each of these two raw materials. This serious supply challenge is not solved solely by establishing new mines in the West, nor with low-capacity level for mid- and downstream industries. Conclusively, it appears unlikely that the West will be able to achieve self-sufficient status for REE by 2030.

1. Rare Earth Elements Considered as Critical Raw Materials

A mineral raw material is defined as critical if it has both industrial/economic significance and the raw material supplies are diminishing. Lack of critical, processed raw materials for the industrial sector forces businesses that are dependent on these raw materials to reduce or close production causing economic repercussions on a national scale.

It is nothing new for there to be political and academic interest in the significance of raw materials in a social context. 200 years ago, there were concerns about whether it was possible to produce enough foodstuffs for a growing population. This concern was replaced in the 1960s with the worry that industrialisation would deplete nature's mineral raw material reserves. Today, there are two opposing concerns: On one side, the knowledge that the world's mineral resources are finite, and the introduction of sustainability principles regarding the use of raw materials are necessary if there are to be resources for future generations. On the other side, the concern as to whether it is possible to increase raw material supplies at the necessary rate to meet the demands of a growing and increasingly wealthy and consumption-focused global population. For example, copper usage is expected to have tripled by 2100 (90 million tonnes) compared to 2020 (Schipper *et al.* 2018). Implementation of the green transition, where the availability of large quantities of specialty metals is a prerequisite, has put raw material supplies under additional pressure.

There are many reasons for the current challenges regarding supplies, and they are different from raw material to raw material as well as between the different industrial sectors. There is, however, one constant in that private and national monopolisation of raw material supplies are responsible for many of these challenges, with China's raw material dominance as the most frequently cited reason (Schulz *et al.* 2017; Federal Register 2021; Government UK 2021). It is the latter of these concerns that is associated with the rare earth elements, as well as many other critical raw materials. Concerns about unstable raw materials supplies are not just a western phenomenon. China, as part of a five-year plan, is also preparing lists of raw materials that should receive special priority, often referred to as 'strategic raw materials'; in the plan for 2016-2020, the rare earth elements were placed on this list (Andersson *et al.* 2018).

Since the 2000s, a number of criticality analyses have been undertaken as part of national and regional monitoring of the raw materials supply situation. They have taken place on different scales (e.g. regional scale (the EU, North America etc.), national scale and at a more local level), and with a variety of methodical approaches, which has led to insights that reflect the various dynamics and business structures. In 2010, the EU Commission prepared the first criticality analysis, which has since then been revised and expanded in 2014, 2017, and 2020 (Figure 1-1) (European Commission 2020). In all the EU's analyses, the rare earth elements are characterised as 'particularly critical' as a result of China's total value chains from mining, processing, refining and usage to the manufacturing of export goods, which gives the country a *de facto* monopoly. The combination of China's *de facto* monopoly and the fast-growing industrial importance of these rare earth elements to technologies regarding the green transition, consumer electronics and defence systems are the reason that rare earth elements are considered critical within the EU.

The criticality analyses, however, include two weak points: (i) Trade statistical data makes it only possible to track traded raw materials (including the rare earth elements) as raw materials;

contents of rare earth elements in components and products cannot be tracked. As the vast majority of Danish industry imports products and components, it is therefore not possible to estimate in what way the rare earth elements are critical for Denmark; (ii) Criticality analyses are calculated on the basis of trade statistical data, meaning they can only refer to past data, so it is not possible to estimate the raw material supply situation of the future.

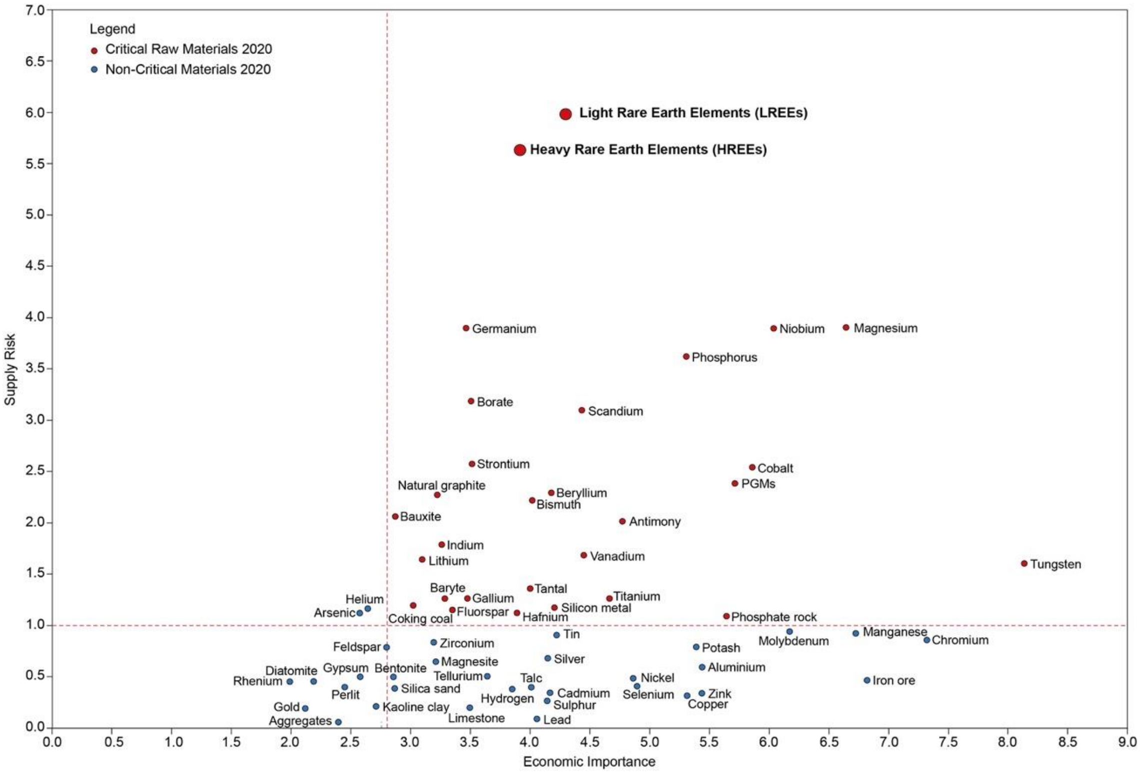


Figure 1-1 *Overview of raw materials evaluated in the EU Commission's criticality assessment; red* symbols *are raw materials assessed as critical for industries in the EU; blue symbols are assessed as non-critical. PGM – platinum group metals. Source: European Commission (2020).*

This report shows that the most important reasons for the current supply risks concerning rare earth elements cannot be a lack of geological availability, though the name implies otherwise, nor that there are only a few mines in countries outside of China. The main reason must be attributed to China's dominance and development of the wide-ranging and highly technological value chains, which convert the minerals for industrial use, and in the raw materials in highest demand (Figure 1-2). The report shows that in a 5-10 years period there is the risk that the causes for criticality will change to – also – include the upper parts of the value chains.

The insecure supply situation for rare earth elements, and the geopolitical challenges associated with it, was exposed in September 2010 when China, as a result of territorial disputes with Japan over the islands of Senkaku and Diaoyudao in the East China Sea, stopped exporting rare earth elements to Japan (see section 4.3.2). The incident resulted in political action plans, research programs and private actions in order to break China's monopoly, unfortunately without success. The western world has not experienced a shortage of these raw materials in the intervening period.

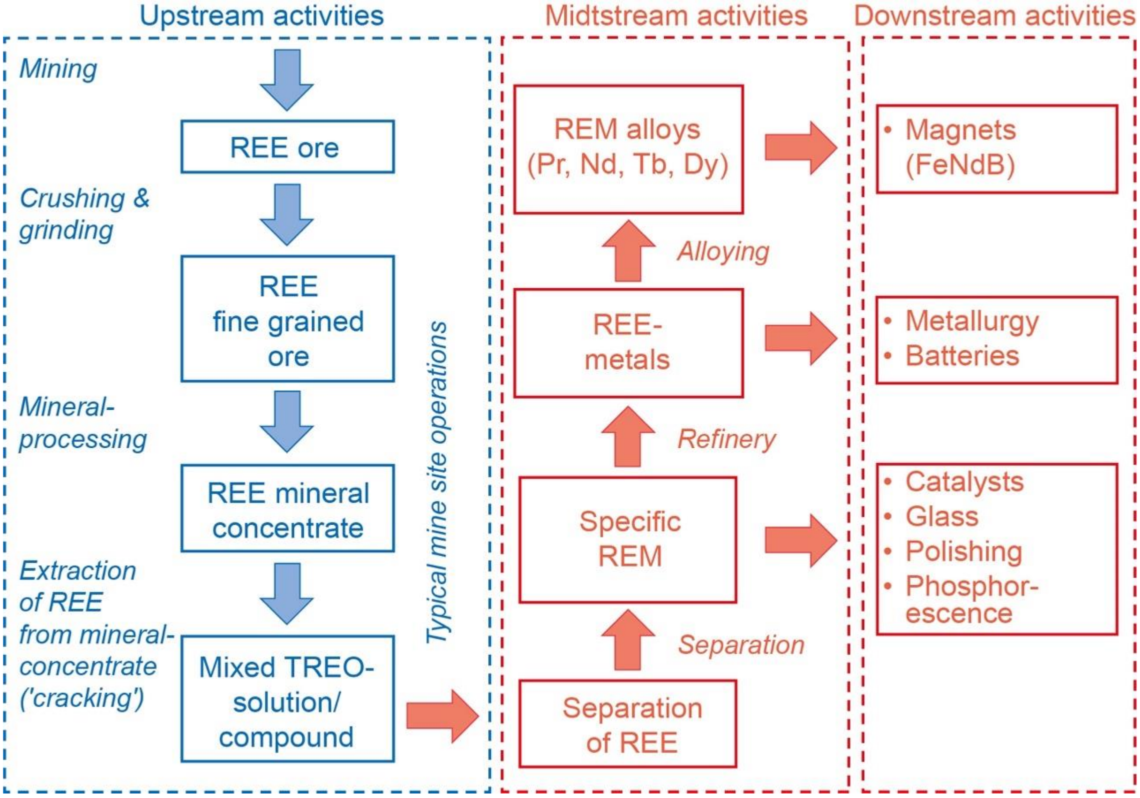


Figure 1-2 *Generic diagram of the value chains of rare earth elements from mine to finished product. The blue steps are generally performed in or near the mining facility based on traditional technologies. The red steps include high-tech processing phases, each undertaken by companies specialising in each specific step. The red steps are completely dominated by Chinese companies.*

2. What are Rare Earth Elements?

The designation *rare earth elements* is a paradox because they are neither rare nor earth (i.e. soils). This paradoxical name came about as they were first discovered as late as 1787 when yttrium was detected, which made it the first of the 17 elements that are designated today as rare earth elements. At that time, the discoveries suggested a conclusion that it must be rare, which we know today is incorrect. The other part of the paradoxical name, *earth (i.e. soils)*, is also incorrect as the 17 elements are metals; but the word earth was used at that time for all the smallest constituents found in nature. The designation rare earth elements have, however, stuck, and are often referred to as *rare earths*, and the English abbreviation REE (Rare Earth Elements) is used. Unless otherwise stated, this report will apply the term *rare earth elements* as a collective name regardless of the chemical form in which they occur.

2.1 Rare earth elements – chemical perspective

Today, according to the International Union of Pure and Applied Chemistry (IUPAC), chemists define rare earth elements as the 17 elements comprised of the *group 3* transition metals scandium (21) and yttrium (39) together with the 15 lanthanides, which are the elements from lanthanum (57) to lutetium (71) (Figure 2-1). They are all naturally occurring elements, with the exception of promethium (61), which is a radioactive daughter isotope from the uranium isotope U-235.

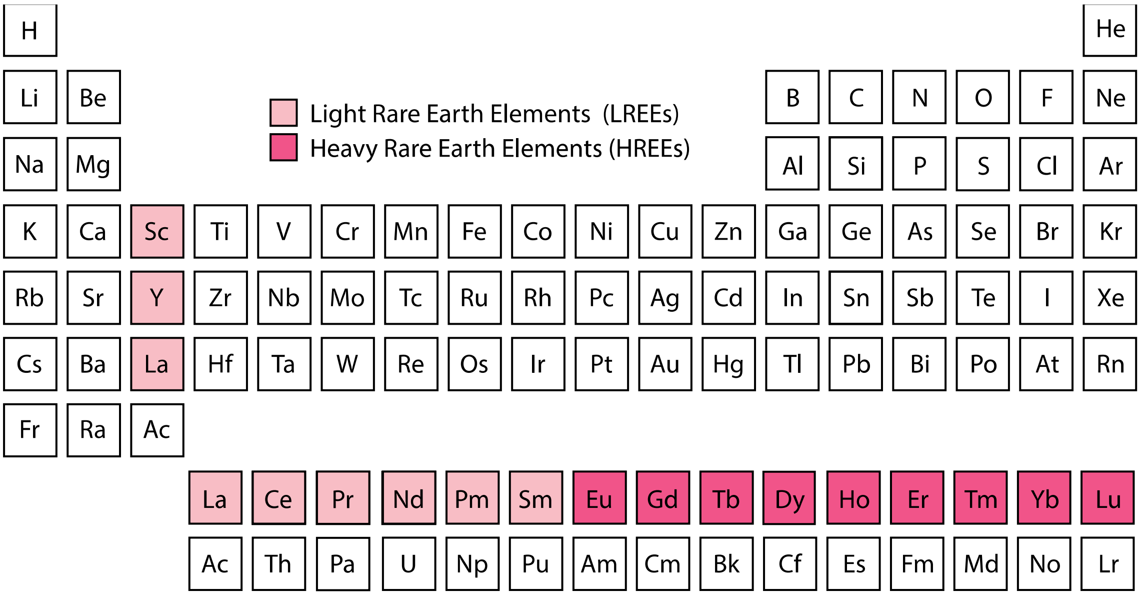


Figure 2-1 *The periodic table of elements with an indication of the rare earth elements that include the lanthanides; lanthanum (La), cerium (Ce), praseodymium (Pr), neodymium (Nd), promethium (Pr), samarium (Sm), europium (Eu), gadolinium (Gd), terbium (Tb), dysprosium (Dy), holmium (Ho), erbium (Er), thulium (Tm), ytterbium (Yb), lutetium (Lu) and the transition metals yttrium (Y) and scandium (Sc). Different designations of LREE and HREE are also shown (see Figure 2-2).*

Geologists do normally not include scandium as one of the rare earth elements due to its smaller ion radius causing it to react differently, and it is predominantly recovered as a by-product of the production of aluminium from bauxite, making scandium to have its own value chains. Scandium is therefore not dealt with in this report.

The rare earth elements are all soft, silver-coloured metals with many physical and chemical characteristics in common. In nature, they are usually found alongside non-metals in oxidation step 3+ and typically form oxides with the formula REE_2O_3; however, cerium (Ce) can also be found with a valence of 4+ and europium (Eu) with a valence of 2+. Some of the physical and chemical similarities between the individual rare earth elements gradually change in the range from lanthanum (La) to lutetium (Lu), for example, the cation size decreases (Table 2-1). The decreasing cation size causes small chemical differences between the individual rare earth elements, meaning they are applied to different industrial purposes.

Table 2-1 *Selected chemical and physical specifications for rare earth elements. Source: Atwood (2012).*

Name	Chemical symbol	Atomic number	Electron configuration	Trivalent ion radius		Atomic weight	Melting point
				CN6	CN8		°C
Lanthanum	La	57	$[Xe]5d^16s^2$	1.032	1.160	138.91	920
Cerium	Ce	58	$[Xe]4f^1\ 5d^16s^2$	1.010	1.143	140.12	799
Praseodymium	Pr	59	$[Xe]4f^3\ 6s^2$	0.990	1.126	140.91	931
Neodymium	Nd	60	$[Xe]4f^4\ 6s^2$	0.983	1.109	144.24	1,016
Samarium	Sm	62	$[Xe]4f^6\ 6s^2$	0.958	1.079	150.36	1,072
Europium	Eu	63	$[Xe]4f^7\ 6s^2$	0.947	1.066	151.96	822
Gadolinium	Gd	64	$[Xe]4f^7\ 5d^16s^2$	0.938	1.053	157.25	1,330
Terbium	Tb	65	$[Xe]4f^9\ 6s^2$	0.923	1.040	158.93	1,356
Dysprosium	Dy	66	$[Xe]4f^{10}\ 6s^2$	0.912	1.027	162.50	1,412
Holmium	Ho	67	$[Xe]4f^{11}\ 6s^2$	0.901	1.015	164.93	1,472
Erbium	Er	68	$[Xe]4f^{12}\ 6s^2$	0.890	1.004	167.26	1,529
Thulium	Tm	69	$[Xe]4f^{13}\ 6s^2$	0.880	0.994	168.93	1,545
Ytterbium	Yb	70	$[Xe]4f^{14}\ 6s^2$	0.868	0.985	173.04	824
Lutetium	Lu	71	$[Xe]4f^{14}\ 5d^16s^2$	0.861	0.977	174.97	1,663
Yttrium	Y	39	$[Kr]4d^1\ 5s^2$	0.900	1.019	88.91	1,522
Scandium	Sc	21	$[Ar]3d^1\ 4s^2$	0.745	0.870	44.96	1,541

On the basis of the difference in atomic weight of the rare earth elements, the group is commonly divided into *light rare earth elements* (LREE) for elements with atomic number 57-62, and *heavy rare earth elements* (HREE) for elements with atomic number 63-71; yttrium (Y), which has an atomic number of 39, is grouped with HREE because of chemical similarities. In certain contexts, the REE is divided into three classes, introducing as well the *intermediate (medium) group of rare earth elements* (MREE). The division between these groups is arbitrary and applied differently by different professional groups. Geologists and metallurgical engineers normally divide them up so the elements from lanthanum (La) to europium (Eu) belong to LREE, whilst those from gadolinium (Gd) to lutetium (Lu), along with yttrium (Y) are included with the heavy rare earth elements (HREE). In this report, the Chinese method of division is predominantly used as Chinese quota system and production is based on this division, where lanthanum (La) to neodymium (Nd) belong to the group of light rare earth elements, and samarium (Sm) to lutetium (Lu) together with yttrium (Y) belong to the group of heavy rare earth elements. Figure 2-2 shows some of the ways the elements are divided up.

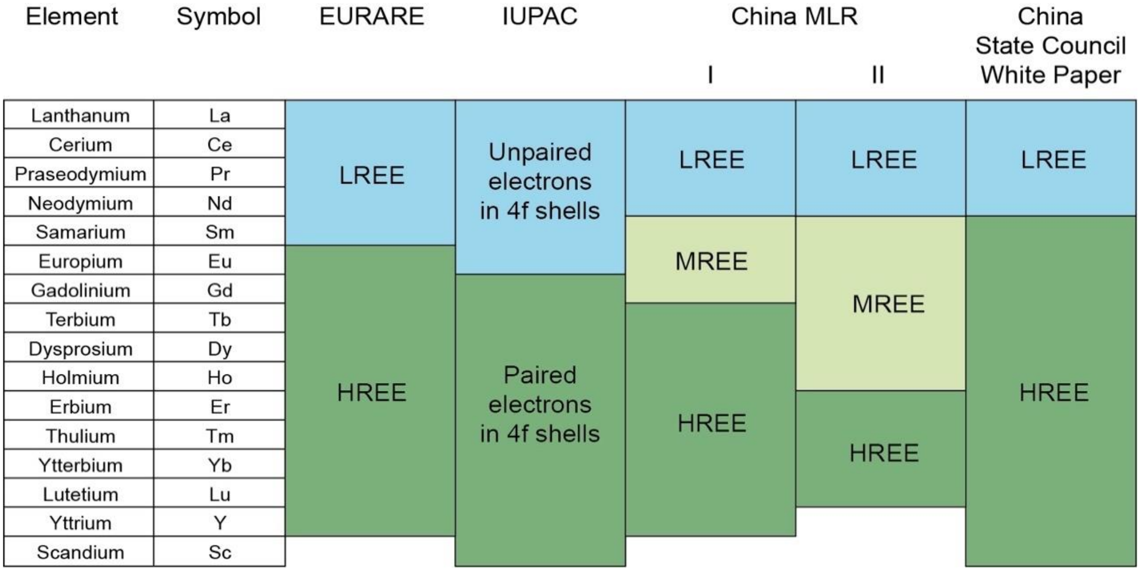


Figure 2-2 *Overview of the different divisions of subgroups of rare earth elements. Source: Machacek & Kalvig (2017).*

Rare earth elements are often mentioned using the chemical abbreviation of the element (e.g. La for lanthanum), and/or its oxide (e.g. La_2O_3). If the designations are used to indicate specific quantities, the weight is different. The conversion factors from elements to oxides are shown in Table 2-2.

Table 2-2 *Conversion factors from elements to oxides.*

Name	Chemical symbol	Oxide form	Conversion factor
Lanthanum	La	La_2O_3	1.1728
Cerium	Ce	Ce_2O_3	1.1713
Praseodymium	Pr	Pr_2O_3	1.1703
Neodymium	Nd	Nd_2O_3	1.1664
Samarium	Sm	Sm_2O_3	1.1596
Europium	Eu	Eu_2O_3	1.1579
Gadolinium	Gd	Gd_2O_3	1.1526
Terbium	Tb	Tb_2O_3	1.1510
Dysprosium	Dy	Dy_2O_3	1.1477
Holmium	Ho	Ho_2O_3	1.1455
Erbium	Er	Er_2O_3	1.1435
Thulium	Tm	Tm_2O_3	1.1421
Ytterbium	Yb	Yt_2O_3	1.1387
Lutetium	Lu	Lu_2O_3	1.1371
Yttrium	Y	Y_2O_3	1.2699

The rare earth elements are chemically quite similar, but minor discrepancies do occur, for example, in solubility or the capability for complex formations. Frequently, these properties are applied to the separation of the individual elements, and given that only minor differences in chemical specifications, separation of the individual rare earth elements from each other, is technically challenging. By contrast, there is a noticeable difference in the physical properties, which appear in Table 2-1.

Overall, the rare earth elements distinguish themselves by having the following characteristics, which have given them major industrial significance (Table 2-1):

- The electron configurations form distinct spectra for emissions and absorption of light and can form coloured solutions
- Fluorescence in the colours red, green and blue
- Rare earth elements such as Nd, Pr and Sm can be alloyed with iron and / or cobalt to produce alloys with significant magnetocrystalline anisotropy, suitable for high-performance permanent magnets; others such as Dy and Tb can be additionally utilized in these same alloys to induce significant resistance to demagnetization (coercivity) High electrical conductivity
- High melting point (the lowest is ytterbium at 824°C and the highest is lutetium at 1,663°C).

2.2 Rare earth elements – historical perspective

The story of the discoveries of rare earth elements began in 1751 near Bastnäs in Central Sweden, when Swedish mineralogist Axel Cronstedt found an unusually heavy, reddish mineral that was given the name cerite. At that time, the chemical analyses did not reveal the content of unknown soils, but only that of aluminium, beryllium, iron and silicates.

In 1787, 36 years after Cronstedt’s discovery, Carl Axel Arrhenius, a chemist and lieutenant, found a heavy, black, shiny mineral, that was given the name ytterbite, in a feldspar mine in Ytterby on Resarö, not far from Stockholm. In 1794, chemist Johan Gadolin, identified this new mineral as containing a new ’metal’, that was named ceria. This is why 1794 is seen as the starting point of the history of rare earth elements.

Cronstedt’s cerite mineral was then widely studied. In 1803, 52 years after the discovery of the heavy mineral (tungsten) in Bastnäs, two independent research teams identified the element cerium. It was Hisinger and Berzelius from Sweden and Klaproth from Germany who both made the discovery based on the cerite mineral. Subsequently, it turned out that the cerium was not completely separated, and in 1842, Mosander detected the existence of lanthanum in the cerite mineral, and as soon as 1843, he detected the elements erbium and terbium. At this time, it was clear to several chemists that previously detected elements could also contain other elements. Subsequent research in the 1880s resulted in the detection of the elements samarium, praseodymium, neodymium, gadolinium, terbium, scandium, dysprosium, holmium, thulium and erbium. Europium and lutetium were detected in the period 1900-1910.

Dmityr Medeleyev, who developed the modern periodic table of elements, discovered that some elements were ‘missing’, and in 1902, Bohuslav Brauner found that an element was lacking between neodymium and samarium. This hypothesis was confirmed in 1914 when Henry Moseley, with the help of X-ray crystallography data, could divide the elements up based on their atomic weight/atomic number and thus ascertained that number 61 had not been detected. The last of the rare earth elements, promethium, was first isolated in 1947 by Marinsky, Glendenin and Coryell as a fission product of uranium.

Figure 2-3 gives a historical overview of when the individual rare earth elements were detected. But as the figure shows, new *soils* were detected within *soils* that were not isolated from elements. For example, Hisinger and Berzelius'/Klaproth's discovery of cerite in 1803 resulted in the discovery of seven elements (cerium, lanthanum, promethium, neodymium, gadolinium, samarium and erbium). Similarly, Gadolin's discovery of yttrium in 1794 resulted in the discovery of the elements yttrium, gadolinium, terbium, scandium, erbium, thulium, dysprosium and holmium.

The industrial application of rare earth elements began in 1884, when the production of incandescent bulbs used, amongst other things, lanthanum and yttrium that were extracted from raw materials from Sweden. This was also the beginning of the mineral exploration of rare earth elements and mining of the mineral monazite that began in the United States and Brazil in 1887 and in India in 1911.

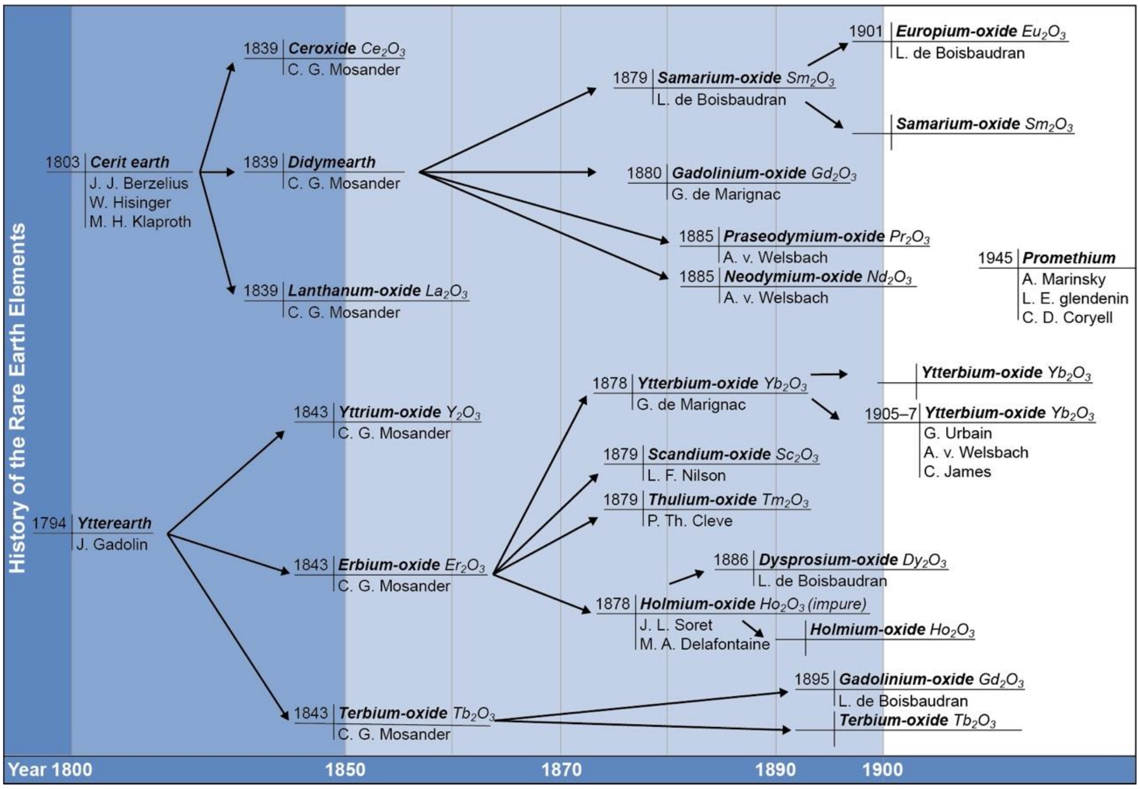


Figure 2-3 *Historical overview of the elements constituting the group of the rare earth elements. Source Zepf (2013).*

In the early 1900s, methods for manufacturing alloys of rare earth elements were developed, including lanthanum, cerium, praseodymium and neodymium (often referred to as mischmetal) (Figure 2-4). Around the same period, methods were also developed to use neodymium, praseodymium and cerium for colouring glass. Phosphorescent substances, based on gadolinium, europium and yttrium, were used industrially from the 1940s on. In 1950, methods for refining oil products (fluid carbon cracking (FCC)) were developed, where cerium and lanthanum were often utilised. Following on from that in the 1960s was the development of permanent magnets of samarium cobalt (Sm-Co) and, magnets using neodymium, praseodymium, terbium, and dysprosium were developed beginning in the 1980. ; as a consequence ofthe development ofa fast growing and diversified permanent magnet markets, the demand for neodymium, praseodymium, terbium and dysprosium accellerated.

2.3 Rare earth elements – geological perspective

The majority (99 %) of the Earth's crust consists of only 12 elements (O, Si, Al, Fe, Ca, Mg, Na, K, Ti, H, Mn, and P); the remaining 80 naturally occurring elements make up only 1 % of the Earth's crust. The majority of the raw materials that we humans use is included in this small group and can, therefore, be reasonably defined as 'rare'. For example, the uppermost rocks in the Earth's crust contain, on average, approx. 170 g of rare earth elements per tonne of rock, however, there is a very large disparity in the amounts of the individual rare earth elements. Cerium, which is the most common in the group of rare earth elements, makes up approx. 33 g/tonne, whereas the amount of thulium and lutetium is only approx. 0.3 g/tonne (Figure 2-5) (Balaram (2019)). But the changes in the average contents are not consistent, as the concentration of the rare earth elements having even atomic numbers is slightly higher compared to the two REE neighbours with odd atomic numbers; for example, the concentration of cerium is higher than that of lanthanum (which follows Oddo-Harkin's rule (https://www.oxfordreference.com/view/10.1093/oi/authority.20110803100245510)). By comparison, the average content of copper and lead in the crust is respectively 27 and 11 g/tonne, thus 'rarer' than lanthanum and cerium, and the precious metals gold, silver and platinum group metals are 'rarer' than lutetium, which is the most 'rare' of the rare earth elements (Figure 2-5)

As mentioned above, the term 'rare' should be seen from the historical perspective: The first rare earth elements were detected in 1794 and it took more than 150 years before all 17 rare earth elements were detected. Today, the rare earth elements are not assessed as rare from a geological perspective, see Chapters 6 and 9.

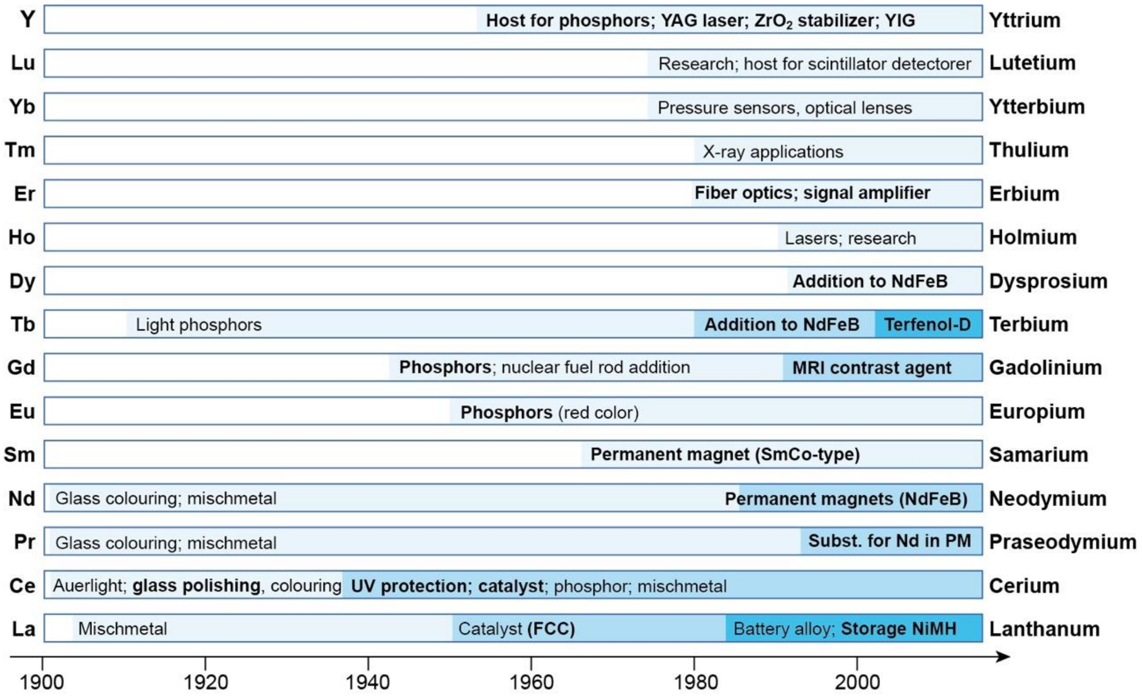


Figure 2-4 *Historical overview of the industrial applications of rare earth elements. The colour indicates that new types of applications have emerged. MRI – Magnetic Resonance Imaging, PM – Permanent Magnets, YAG – Yttrium aluminium garnet, YIA – Yttrium iron garnet. Source: Zepf (2012).*

A number of geological conditions have an impact on whether minerals with rare earth elements occur to the extent that it is profitable to construct a mine. Among other things, most rare earth elements have a large ion radius and valence 3+ (with the exception of Ce and Eu), and therefore, are less likely to be found in mineral rock formations but, under special geological conditions, form their own minerals with a high content of rare earth elements. The order of crystallization in the mineral is determined by their coefficient of distribution, which increases from lanthanum to lutetium, with the exception of europium, which tends to be incorporated more rapidly into the minerals.

More than 200 REE-bearing minerals have been identified in which the rare earth elements form a significant part of the crystal structure of the mineral. In addition, rare earth elements are found as trace elements in many other minerals. Changes in the content of rare earth elements in mineral rock-formations are used to study how these rock formations occur, such as pressure, temperature and geochemical composition. The content and composition of the rare earth elements is therefore an important tool for geologists when determining the geological development of an area.

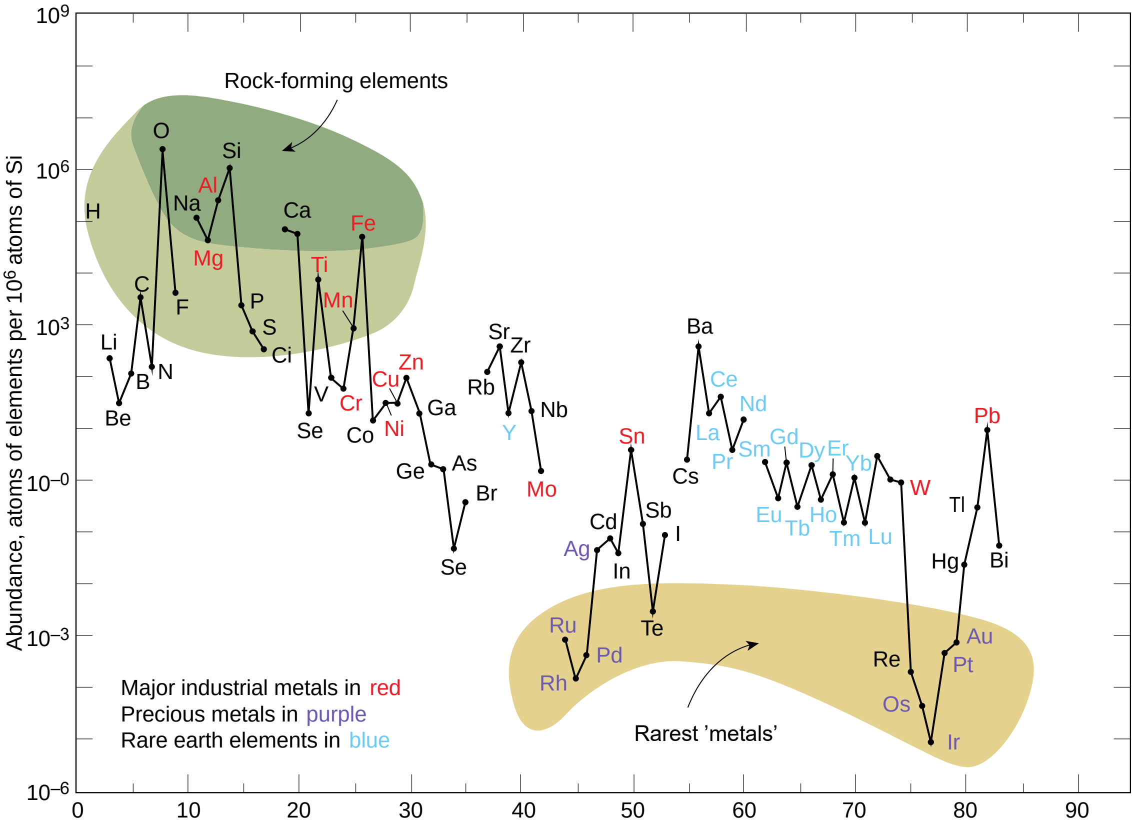


Figure 2-5 *The average concentration of rare earth elements in the rocks of the crust plotted as a function of the atomic number. As shown, the rare earth elements are found in significantly higher concentrations than, for example, the gold, silver, and platinum group metals. Source: Haxel et al. (2002).*

Minerals with a high content of rare earth elements are generally physically and chemically robust and do not dissolve when rocks and minerals decompose. This last property is the reason why some of the original REE minerals can be found as weathering products in heavy minerals sand and laterite deposits. The REE minerals and geological deposits are described further in Chapter 9.

3. Industrial Applications of Rare Earth Elements

3.1 Trade goods

In the upper and middle parts of the value chains of rare earth elements, a wide range of products are traded. REE trade goods can include anything from:

- Mineral concentrates consisting of minerals that contain rare earth elements
- Mixed products of rare earth elements (non-separated/partially separated), mostly in the form of carbonates, oxides and organic solutions
- Metals of the individual rare earth elements
- Alloys with rare earth elements (mischmetal).

In the lower parts of the value chains, which are not dealt with in this report, the rare earth elements are included in the manufacture of e.g. consumables, chemicals and industrial products.

The specifications of the rare earth elements used in the lower parts of the value chains are determined by the particular industry using the raw materials. The specifications can be, for example, chemical compounds such as oxides, carbonates, fluorides etc., and metals. In addition, there are a large number of product specifications where, for example, purity is included as one of the most important parameters. The current trend is towards higher demands on the purity of products, *i.e.* that they may only contain completely insignificant residues of other rare earth elements. Purities are typically specified via two purity requirements: (i) the purity relative to total REEs/ total REOs (TREO); and (ii) purity relative to all element/oxide-equivalents present, expressed as a percentage and is indicated for certain products up to six decimal places. For example, a purity of 99.99 % states that the product still contains 0.01 % ‘impurities’ in the form of other rare earth elements/oxides and/or other elements/oxides that have not been separated. Purity is often indicated by the number of ‘9s’ (in this case 4N (four nines)). For certain industrial applications, 5N (> 99.999 %) is required. The prices of REE products reflect the cost of refining and processing; for example, a 4N product is many times more expensive than a comparable 3N product.

3.2 Consumption - industrial sectors

The industrial consumption of rare earth elements occurs primarily in nine industrial sectors, where they are included as either consumables or auxiliaries in the manufacture of permanent magnets (1), glass (2), technical ceramics (3), batteries (4), phosphorescence and luminescence (5), catalysts (6), oil and gas refining (7), polishing (8) and metallurgical processes (9). REE are thus used primarily in consumer electronics and communications, chemicals, the oil industry, defence systems, wind power, solar cells and fuel cells, as well as for pharmaceuticals and medical devices (Figure 3-1 and Table 3-1). Figure 3-2 shows that seen worldwide, approx. 50 % of the annual production of rare earth oxides (REO) is used in the production of permanent magnets, for catalysts in vehicles and for refining oil products, whereas the distribution of consumption in Europe is different with approx. 43 % used for catalysis and approx. 19 % for the glass industry. These differences in the distribution of consumption are due to the variation of industrial structures from region to region and from country to country, reflecting differences in economic conditions, consumption patterns, and access to raw materials, logistics and markets. As the individual industrial sectors do not demand the exact same types of raw materials of rare earth elements, there are regional and national variations in the products that are most widely used, which affects the quantities that the industries demand. Similarly, there have been major changes in demand over time; in particular, raw materials for the manufacture of permanent magnets are on the rise.

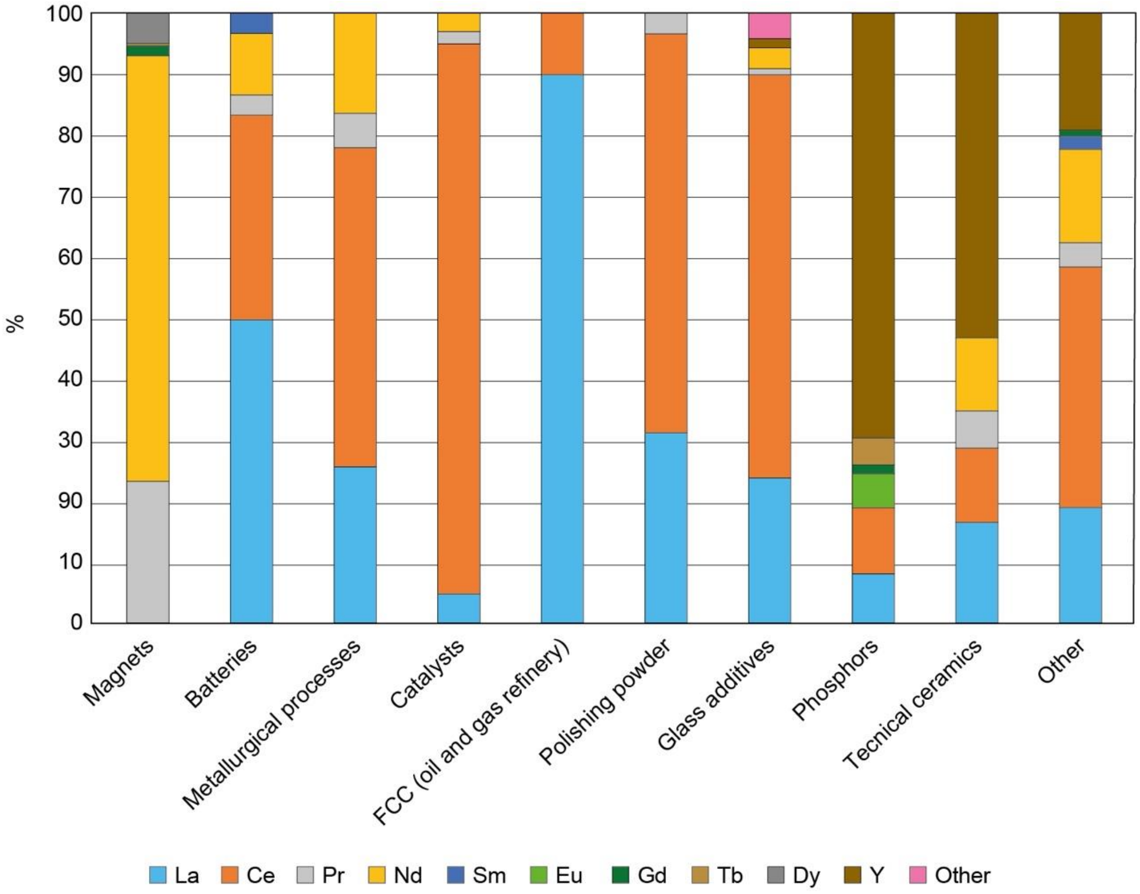
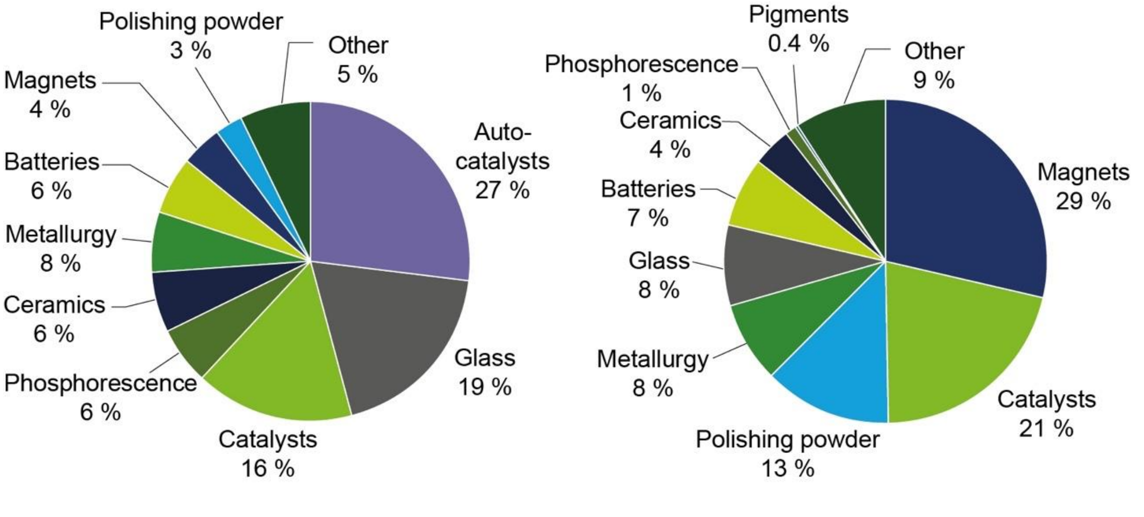


Figure 3-1 *Relative distribution of the rare earth elements across the nine most important industry sectors. Source: Binnemans (2014).*

The approximate distribution of the individual rare earth elements used in industrial applications is shown in Figure 3-1, which shows that among the ten most commonly used rare earth elements, lanthanum and cerium, are used in a wide range of industries, in contrast to e.g. europium and terbium. It should be noted, however, that due to the natural distribution of the rare earth elements in the minerals, there is an imbalance between the quantities of rare earth elements that the industries demand and the quantities available; this discrepancy is called the ‘balance problem’ and is discussed in section 9.4.1.

Table 3-1 *The most common industrial applications of rare earth elements.*

Element	Most important industrial application
Yttrium	Superconductors, lasers, phosphorescence, LEDs, LCD and plasma screens, camera lenses, medicines
Lanthanum	Vehicle catalysts and catalytic processes for oil refining, water treatment, special glass, alloy metal for steel, plasma screens, rechargeable batteries
Cerium	Vehicle catalysts and catalytic processes for oil refining, glass polishing, alloy metal in steel, magnesium and aluminium, LCD and plasma screens, rechargeable batteries
Praseodymium	Permanent magnets, orange colour pigment in ceramic materials, aluminium alloy metal for the aerospace industry, catalytic processes
Neodymium	Permanent magnets, catalytic converter systems for vehicles, infrared lasers for industrial and defence purposes
Promethium	Radioactive element with short decay time, no industrial applications
Samarium	Permanent magnets, cancer diagnosis and treatment, nuclear fuel rods
Europium	Phosphorescence in lighting, laser, plasma screens and banknotes, LCD, and plasma screens
Gadolinium	Shielding of nuclear reactors and neutron radiography; as a contrast medium in high magnetic scanners (MRI) to improve body scanning; X-ray analyses
Terbium	Permanent magnets, LCD and plasma screens, fuel cells, fluorescence, sonar systems
Dysprosium	High temperature permanent magnets, lasers, electronics, control rods in nuclear reactors, missile control
Holmium	Permanent magnets, colour pigments in glass and technical ceramics, microwave equipment
Erbium	Nuclear industry for neutron absorbing control rods, fibre optics, colour pigment (pink) in glass, lasers for medical use
Thulium	Hand-held X-ray instruments, lasers for defence, medical and meteorological purposes
Ytterbium	Pharmaceutical industry, cancer treatment, alloy steel
Lutetium	Oil refining, age dating, cancer diagnosis (positron emission tomography)



EEC consumption of REO: 4,734 t (2019)
EEC consumption of REE metals and alloys: 683 t (2019)

Global consumption of REO: 139,551 t (2019)

Figure 3-2 *The industry sectors' consumption of rare earth elements in the EU and worldwide respectively. Source: Machacek & Kalvig (2017); European Commission (2020).*

3.2.1 Permanent magnets

Permanent magnets are used in many different contexts, the most important of which are motors for electric transport, power steering, windscreen wipers, sensors, etc. in electric and conventional vehicles, for wind turbine generators, consumer electronics, air conditioning systems, robot technologies, medical equipment (*e.g.* MRI scanners), as well as in defence systems (Figure 3-3).

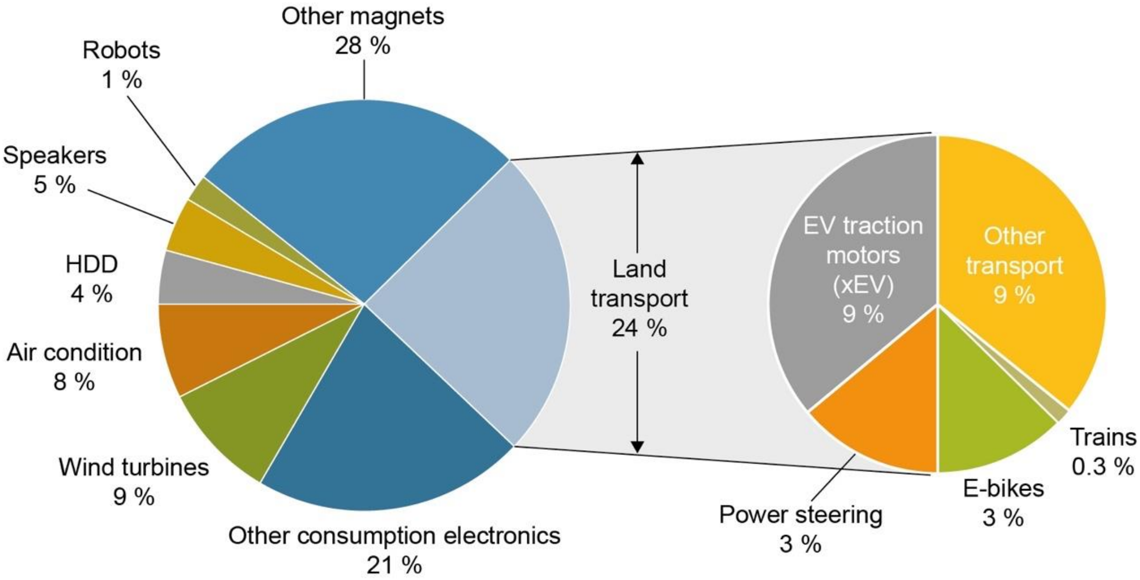


Figure 3-3 *Global distribution of uses of permanent neodymium iron drill (NdFeB) magnets in 2019 (consumption for military defence systems is included under 'other consumer electronics'). Source: Roskill (2021b).*

The separate production steps through the value chains for the manufacture of permanent magnets are carried out in some cases by the same companies, and in others by a series of specialised companies. Firstly, the rare earth elements are produced in metal form (REM), for which oxides of rare earth elements (REO) are used as raw materials and are reduced by using electrolysis. Typical REM products are Nd metal, Dy metal, Pr metal and Tb metal and the alloys of these; all with high purity. The subsequent part of the value chain produces 'super-alloys', such as neodymium-iron-boron (NdFeB) or samarium-cobalt (SmCo). An overview of the consumption of rare earth elements for the magnet sector is shown in Table 3-2.

Table 3-2 *Consumption of permanent magnets divided by sector. It is clear to see that there is a marked increase. Source: The Rare Earth Observer (2021).*

Sector	Share 2019 (%)	Growth rate 2019-20 (%)
Conventional vehicles	38	-1.4
Electric and hybrid vehicles	12	17.5
Wind turbines	10	20
Air conditioning plants	8	55
Others	32	No information

Ferrite magnets (metal Fe_2O_3) are the most common and cheapest permanent magnets, but they are not strong, and, in addition, their magnetic properties are affected by both high and low temperatures. Many of the applications mentioned in Table 3-3 require that the magnetic properties do not change under extreme temperature conditions, that they do not demagnetise and that the magnets be small, robust and have a high magnetic field strength. Permanent magnets based on rare earth alloys meet these requirements; Neodymium-iron-boron magnets ($Nd_2Fe_{14}B$, commonly referred to as neodymium magnets or NdFeB magnets) and samarium-cobalt magnets ($SmCo_5$ or Sm_2Co_{17}, commonly referred to as samarium-cobalt magnets) dominate the market.

The two types of REE magnets have different advantages and disadvantages and, therefore, have different markets. SmCo magnets can be used at higher temperatures and in more corrosive environments than NdFeB magnets. However, the magnetic field for NdFeB magnets is stronger and NdFeB magnets are cheaper than SmCo magnets, so are therefore used to a large extent in the electrification of the transport sector and for certain types of wind turbines (Kalvig & Machachek 2018). The magnetic crystals are often coated with 1.5 % cobalt (Co-coating), or surface treated with epoxy or other corrosion resistant materials, after which they can be used in highly corrosive environments. Due to the cobalt content, the SmCo magnets are more resistant without coating, but they are often coated anyway to make them more resistant to physical influences such as impact and pressure. Examples of the consumption of magnets in wind turbines and electric vehicles are shown in Table 3-3.

Table 3-3 *Consumption of rare earth elements in permanent magnets in different applications. Source: Binnemans (2014).*

Product	**Most important REE-raw materials**	**Application**
NdFeB magnets	Nd, Pr, Dy, Ce, Gd, Tb, Ho	*Wind turbine generators (with gearbox)*: approx. 80-100 kg NdFeB/MW *Wind turbine generators (direct drive):* approx. 700-1,200 kg NdFeB/MW *Electric vehicles*: approx. 1.2 kg NdFeB/100 kW Due to process losses during production, the actual consumption is approx. 30 % higher. Typical composition of sintered NdFeB magnets: Nd (31 %), Dy (1-4 %), Tb (1 %) Ce (2 %), Fe (61.5 %), B (1 %) $NdPr_2O_3$ for electric vehicles use the following amounts: BEV: 2.21 kg, PHEV: 0.89 kg, hybrid: 0.60 kg (King 2021)
SmCo magnets	Sm	Typical composition: SmCo (Sm max. 35 %); Co 60 %; Fe (5 %)

Permanent magnets are manufactured in two different ways: (i) by a sintering process of a magnetic alloy and (ii) by a process in which the alloy powder is heated and cooled very rapidly (‘bonded’ magnet); the sintering process is the cheapest method. The market distribution between the two types is approx. 90 % for sintered magnets and 10 % for bonded magnets.

When magnets are made through a sintering process, the outer surfaces of the powder melt, filling in the voids between particles, and are subsequently formed into magnetic blocks that are reheated and cut to the desired shape, then finally surface treated and magnetised to the desired specifications. During the manufacture of magnets for specific purposes, the material waste is 15-30 %, which can, however, be partially recycled during the process. Sintered NdFeB magnets tend to corrode along the grain boundaries, and it is therefore common for the magnets to be surface-treated with nickel or nickel-copper alloys (Co-coating), though this, however, presents challenges for recycling. China and Japan have built up significant production capacities for sintered magnets.

Sintered NdFeB magnets retain their magnetic properties at temperatures up to around 350 °C if dysprosium and terbium are added to the alloys, and are used in high temperature environments, such as in wind turbines and electric vehicle engines. NdFeB magnets are based on alloys of iron (about 66 %), while neodymium and praseodymium make up approx. 28 % and 6 % respectively. This is close to the common ratio between neodymium and praseodymium in nature, which reduces the need for the costly separation of these two rare earth elements.

SmCo magnets contain approx. 35 % samarium, which in nature occurs in significantly lower concentrations than neodymium, whilst ‘Co’ consists of mixtures of cobalt, iron, copper and zircon, where cobalt usually makes up 50-65 % (weight). Unlike NdFeB magnets, SmCo magnets do not corrode, but they are not physically sturdy.

Magnet manufacturers face great challenges in procuring sufficient supplies at low prices, which has led to significant research and development activity with a view to substituting for less critical raw materials and developing alternative magnets. For example, cerium can replace up to approx. 40 % of neodymium in magnets to be used at low temperatures. A potential example of alternative technologies are iron nitride ($Fe_{16}N_2$) magnets, which do not contain critical raw materials, and which are also recognised as being more sustainable (Wang 2020); although the magnetic-materials community is generally skeptical of claims that production of useful block magnets has been achieved (G. Hatch, personal info, August, 2022)

Properties of the magnets are determined in large part by the microstructures of the material and the alloy compositions. Patents of alloy compositions, grain boundary diffusions and manufacturing methods are central to the value chains of permanent magnets and have meant, for example, that Magnequench and Hitachi Metals have been able to control the production of NdFeB magnets. Hitachi Metals owns more than 600 patents for NdFeB magnets, most of which expire in 2021; however, it is unclear to what extent they have been extended (Less Common Metals 2021). Up until 2014, only ten factories in China, Japan and Germany were licensed to produce permanent magnets; since then, the number has increased significantly, and China has developed an industrial culture where patents are essential for maintaining control of the supply chains. Magnet factories typically specialise in producing either sintered or bonded magnets. Both types of production are largely controlled by IP-rights, with Hitachi Metal's many hundreds of licenses controlling the majority of sintering processes, while Magnequench's IP rights focus primarily on the production of bonded magnets. The European magnet manufacturers Neorem Magnets Oy, Vacuumschmelze Gmbh & Co. and ThyssenKrupp Material Trading specialise in the manufacture of sintered magnets, whilst factories such as Grundfos, Magnetfabrik Bonn, JL Mag, IMA and MS Scramberg specialise in the manufacture of bonded magnets.

In recent years, the consumption of NdFeB magnets for traction motors in electric vehicles has risen sharply, making permanent magnets the most economically important area of consumption for rare earth elements (see Chapter 14). The increase in the consumption of NdFeB magnets for motors in electric vehicles in 2020 is shown in Figure 3-4. Magnet factories have research departments that will develop new types of magnets to replace NdFeB and SmCo magnets and reduce the risk of supply shortages of rare earth elements. For example, Toyota Motor Groups and DENSO are working on developing a heat-resistant super magnet, consisting of iron and nickel.

3.2.2 Phosphorescence and fluorescence

Phosphorescent materials emit light for some time after they have been illuminated, whereas fluorescent materials only emit light when they are illuminated. These properties are used in lights, lasers, and computer and television screens, and are therefore vital to a range of medical and military equipment. In phosphorescent and fluorescent materials, rare earth elements are used both as activators and for the surface treatment of crystals. There are generally very few replacement options, and the development has therefore primarily focused on options for reducing consumption.

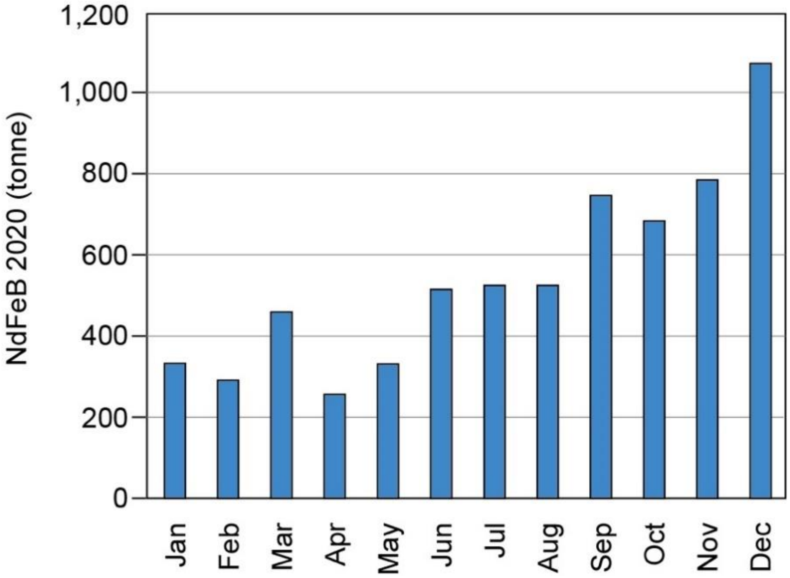


Figure 3-4 *Overview of the consumption of NdFeB magnets for motors for electric vehicles in 2020. Source: Adamas Intelligence (2021).*

Lamps and lights: For fluorescent lights, the oxide products of Eu, La, Ce, Tb and Y are primarily used. For LED lights and LCD screens, Eu, Ce, Y, Gd, Lu, Pr and Tb are mainly used. In all cases they must be products of high purity (4-6N). Figure 3-5 shows examples of which colours emerge from terbium, europium, dysprosium, and samarium phosphorescence in different wavelength ranges. The phasing out of neon lamps (Compact Phosphorescent Lamp (CFL)) during the 2010s in favour of LED lights has resulted in a significant reduction in the market for Y-products, with grave economic consequences for the mining companies that extract yttrium.

Screens: For computer screens, smartphones, etc. with CRT technology, oxides of Y, Ce, Eu, Gd, and Tb are primarily used. For plasma screens, phosphorescence of Eu, La, Ce, Y, Tb, and Gd are mainly used. Both groups use products with a high purity (4-6N).

Medical equipment: X-ray equipment primarily uses phosphorescence of Eu, Y, Gd, La, Tb, and Tm. Additionally, rare earth phosphorescents are used for diagnostic technologies. In all cases, high-purity oxides (4-6N) are used.

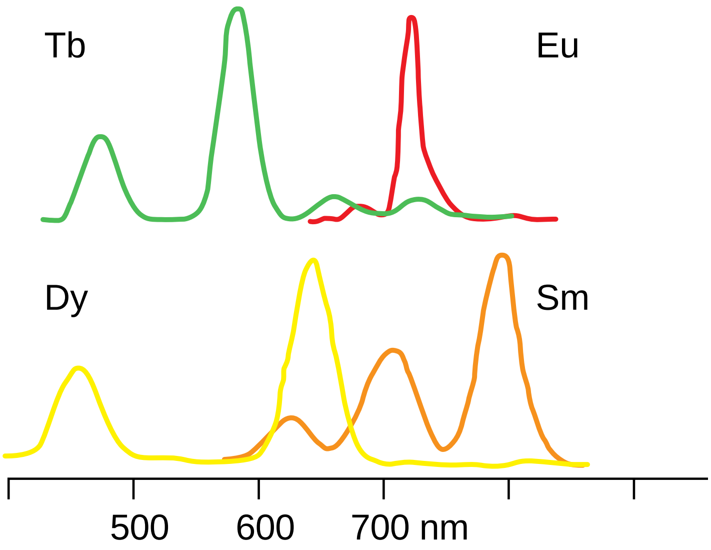


Figure 3-5 *Visible luminescence for Eu^{3+}, Tb^{3+} and Dy^{3+}. Note: y-axis is intensity (relative scale without unit). Source: Binnemans (2014).*

3.2.3 Batteries

Batteries are used to store energy for later use, which with the right specifications makes them useful for everything from hearing aids, handheld tools, electronics, to starting vehicle engines and to propelling ships and vehicles, and they are therefore a central part of the green energy solutions. Each application has special requirements for the functionality of the batteries, *e.g.* requirements for energy density, size, shape, weight, rechargeability, charging speed and much more. To meet these requirements, various battery technologies are used, and the widespread use of portable equipment has led to a diversified and dynamic development of battery technologies. An example of this is the widespread nickel-metal hydride (NiMH) battery, which replaced the nickel-cadmium (NiCd) battery in the 1990s. NiMH batteries are rechargeable, charge quickly, have a high energy density and can be recharged many times, which means that the batteries are widely used for handheld tools and electronics.

In the NiMH battery, the metal part (M) consists of rare earth elements and e.g. nickel, cobalt or manganese. Among the rare earth elements, lanthanum is most prominent, typically either as La metal or alloys (mischmetal) consisting of La (65 %), Ce (25 %), Nd (1-8 %), and Pr (3-8 %). In total, the rare earth elements in NiMH batteries make up about 17 % of the weight of the metals.

Both in Japan (Toyota and Honda) and the EU (Umicore and Solvay), technologies have been developed to recycle the rare earth elements from NiMH batteries, but the contributions from these plants are very small, partly because the batteries are not sent for recycling until 7-10 years after installation.

In the 2010s, lithium-ion (Li-ion) batteries replaced many of the functions that were met by NiMH batteries as, amongst other things, they are easier to manufacture in custom shapes, which is why this battery type dominates the markets today.

3.2.4 Metallurgical applications

Metallurgical applications are understood here to mean all types of rolling, casting and alloy production (except magnets, which are treated separately, see section 3.2.1). The majority of the rare earth elements are used as mischmetals for desulphurisation in steel production and to improve the formation of graphite nodules. Moreover, they bind to unwanted trace metals in cast iron, thereby improving the product and processing properties of steel and metal products. The mischmetals used typically consist of Ce (48-56 %), La (25-34 %), Nd (11-17 %), and Pr (4-7 %), where the addition of cerium reduces the harmful effects of any residual sulphur. China, the world's largest steel producer, is the largest consumer of mischmetals. In the west, the consumption of rare earth elements has been declining, as European and North American smelters have increasingly replaced rare earth elements with magnesium ferrosilicon, which is cheaper. An overview of the most common uses of rare earth elements in the metallurgical industries is shown in Table 3-4.

Lanthanum is used to make lanthanum-nickel ($LaNi_5$) alloys to store hydrogen. The material has potential uses for many different applications and may eventually become a new growth area.

Table 3-4 *Overview of the most common uses of rare earth elements in the iron and steel industry. RE compounds indicate unspecified alloys. Source: Jha (2014); Machacek & Kalvig (2017).*

Application	Most prominent REE	Objective
Cast iron and steel	Mischmetal (Ce, La, Nd, Pr), Ce Typically added are 0.1 % mischmetal REM and RE compounds; purity 4-6N	Addition reduces the negative properties of residues of oxygen, sulphur, magnesium, silicon, lead and antimony, while improving the material properties.
HSLA steel	Mischmetal (Ce, La, Nd, Pr) (added < 1 % mischmetal) REM and RE compounds; purity 4-6N	For the production of High-Strength-Low-Alloy (HSLA), the melting point decreases Cerium or mischmetal is used in small amounts (< 1 %) to improve the microstructure.
Stainless steel	Y, Ce REM and RE compounds; purity 4-6N	Addition provides better strength at high temperatures and better ductility
Special alloys	La, Gd, Y, Ce, Nd, Pr REM and RE compounds; purity 4-6N	Improves casting properties and increases strength at high temperatures (e.g. jet engines)
Mg alloys	Y, Nd, Gd, Pr Typically added up to 3.5 % REE REM and RE compounds; purity 4-6N	Reduces ‘creep’ at high temperatures, used particularly for engine blocks and the like. Pr increases strength and resistance to corrosion Nd increases heat resistance
Al alloys	Y, La and Ce: < 3 wt% REM and RE compounds; purity 4-6N	Modifies the mechanical properties and increases corrosion resistance Ce compounds are also used in electrowinning of aluminium

3.2.5 Catalysts and catalytic processes

Rare earth elements are used both as catalysts in the oil industry (Fluid Catalytic Cracking (FCC)) and as catalysts in vehicles, where they reduce emissions of NOx and other gases from petrol and diesel engines.

In the operation of FCC plants, the oil is heated to approx. 550 °C to break it down into a variety of commercial hydrocarbons, and zeolites are added as catalysts to advance the process. The zeolites contain 2-4 % REO, predominantly in the form of oxides of La, Ce and Nd (the conditions depend on the specific purposes). La can make up to 80 %, Ce up to 46 %, while Nd typically makes up around 15 %. The requirement for the purity of the products is very variable (2-5N) (Machacek & Kalvig 2017).

Ce, La, and Nd are mainly used for the production of catalytic converters for vehicles, but here Ce is the predominant one. The use of rare earth elements improves the transition from liquid to gas. The composition of the rare earth elements varies between different vehicle makes and models. There are no obvious substitution options for the rare earth elements. Catalysts are collected from most vehicles before scrapping, but for the purpose of recycling the content of the platinum group metals (PGM), there does not appear to be systematic industrial recycling of rare earth elements from catalysts.

Globally, catalytic processes and catalysts consume about 21 % of the total production of REO (Figure 3-2). It is expected that the transition to green energy technologies, with declining oil production and an increasing percentage of electric vehicles, will reduce this consumption in the long term.

3.2.6 Technical ceramics and intermetallic materials

Rare earth elements are used for a variety of technical ceramics and intermetallic materials that are involved in the production of *e.g.* fuel cells, oxygen sensors, fibre optics, electrode materials, heat shields in jet engines, dental products and for surface coatings in special metallurgical crucibles. Certain types of technical ceramics, which are stabilised with rare earth elements, replace metals in *e.g.* cutting tools and wearing parts. For this, yttrium is the most widely used of the rare earth elements and often in high purity oxide form (3-6N), and it is included in all of the above uses. In addition, cerium is in demand for certain purposes (in particular for fuel cells and metallurgical crucibles), as well as small amounts of gadolinium, lanthanum and samarium, where there are varying requirements for the purity of the material (2-6N).

Intermetallic materials include materials for permanent magnets (section 3.2.1), and for transducers and materials capable of storing gases; examples of the latter are lanthanum-nickel ($LaNi_5$) compounds.

3.2.7 The glass industry

Rare earth elements have a variety of uses within the glass industry. It can be used for both staining and decolourising glass and can prevent certain types of rays from passing unhindered through the glass (*e.g.* infrared, X-ray and UV light). Ce oxides and fluorides are the main products, but some La and Er are also used, as well as small amounts of oxides of Gd, Nd, Y, Pr, Sm, Eu, Ho, and Tm.

Below are the most common uses of rare earth elements in the glass industry.

Staining: The addition of rare earth elements can stain the glass in light tones of violet, pink, green and yellow. In particular, oxides of varying purity (2-5N) of Nd, Pr, Er, Ce, Eu, Ho, Sm, and Tu are used. For example, Nd_2O_3 produces red colours and in combination with MnO_2, the glass obtains purple colours. Pr_6O_{11} produces green colours, while combinations of CeO_2 and TiO_2 produce yellow colours.

Colour filters: Oxides of rare earth elements are added to the glass mass when it is to be used for the purpose of blocking out specific light spectra. It can, for example, be used in special goggles and glass containers. Nd filters are applied for yellow light, Sm is used as a filter against infrared light, while Eu is used as a filter for UV light. The products vary in purity (2-5N).

Discolouration/bleaching: Natural glass can have unwanted discolouration that the glass manufacturers want removed to obtain clear glass. The addition of oxides of Ce, Pr, Nd, and Er to the glass mass can remove discolouration. Ce oxides are primarily used to remove green colours and replace the toxic arsenic oxide (As_2O_3). Products with varying purity (2-5N) are used.

Refractive index regulator: The addition of oxides of rare earth elements can increase the refractive index of the glass and is used particularly in the manufacture of fibre optic cables (primarily Er, Nd, and Yb), optical lenses in smartphones and cameras (primarily La), and in solar cells (primarily La, but also occasionally Gd and Y).

Radiation resistance: Glass materials that are affected by UV and X-rays darken over time. By adding Ce oxides of various grades (2-5N) reduces this type of discolouration.

As the market for smartphones and tablets is expected to grow significantly, work is underway to find methods to substitute Ce; La can to some extent replace CE.

3.2.8 Polishes

Polishing powder based on rare earth elements is used for polishing glass and electrical components and is typically divided into these four main areas: (i) display panels (LCD and flat screens for TVs, computers, tablets and smartphones); (ii) flat glass (decorative glass, mirrors and windows); (iii) optical glass (camera lenses, spectacle lenses, etc.) and (iv) consumer electronics (glass hard drives and silicone semiconductors for integrated circuits). Additionally, it is used to a lesser extent for polishing gemstones. Various products of Ce oxides are most common, but oxides of La, Pr and Nd are also used.

Worldwide, the consumption of REO in relation to polishes is approx. 13 % of total consumption in 2021 (Figure 3-2). In general, this market is expected to remain fairly constant.

3.2.9 Other industrial applications

About 9 % of rare earth elements are used for a variety of industrial purposes, some of which are listed below.

Microwave ovens: Crystals for microwave ovens contain, amongst other things, Y, Ga, Nd, Ho, Tm, Er and Yb.

Lasers for industrial, medical and defence technology contain Y and Ni as fluorescent material. The purity should be a minimum of 5N.

Nuclear facilities: rare earth elements are used in materials for neutron absorption and for instruments that can measure radioactive emissions. These areas consume primarily Ga, Sm, Eu, Er and Ga.

Pharmaceutical industry: rare earth elements are added to various types of pharmaceutical and antiseptic products. These industries demand primarily Ce, Nd, La and Eu.

Fertilisers: rare earth elements are added to some fertilisers, *e.g.* superphosphate for use in the production of cotton and palm oil. This area consumes primarily La and Ce.

Magnetic cooling: the technology is based on certain materials changing temperature when they enter a magnetic field. For example, Ga alloy acts as a refrigerant when sent into a strong magnetic field; in addition to Ga, alloys are also used in which one or more of the following rare earth elements are included: Nd, Tb, Er, La and Pr. The technology is under development for use in ordinary refrigerators.

4. Trade and Prices

4.1 Trade

Rare earth elements are traded many times and in many forms along their way from top to bottom of the value chains, therefore traders include different types of products: (i) mineral concentrates consisting of minerals containing rare earth elements, (ii) mixed products of rare earth elements (non-separated/partially separated), (iii) metals of the individual rare earth elements and (iv) rare earth element alloys (mischmetal).

China is the focal point of trade in all types of rare earth products but especially in the import of mineral concentrates and the export of finished products. Some of the most significant trade partners are shown in Figure 4-1. International trade in REE products is dominated by China's purchases of raw materials via long-term contracts from the upper parts of the value chains, and there is only a small volume available for spot markets, where it is primarily cheap lanthanum and cerium products that are available.

In terms of value, the majority of international trade in rare earth elements takes place in the form of goods from the lower parts of the value chains, where the rare earth elements are included in the products, either as an independent product or as a component(s) in another product; this applies, for example, to vehicles and electronics and communication equipment (Hou *et al*. 2018).

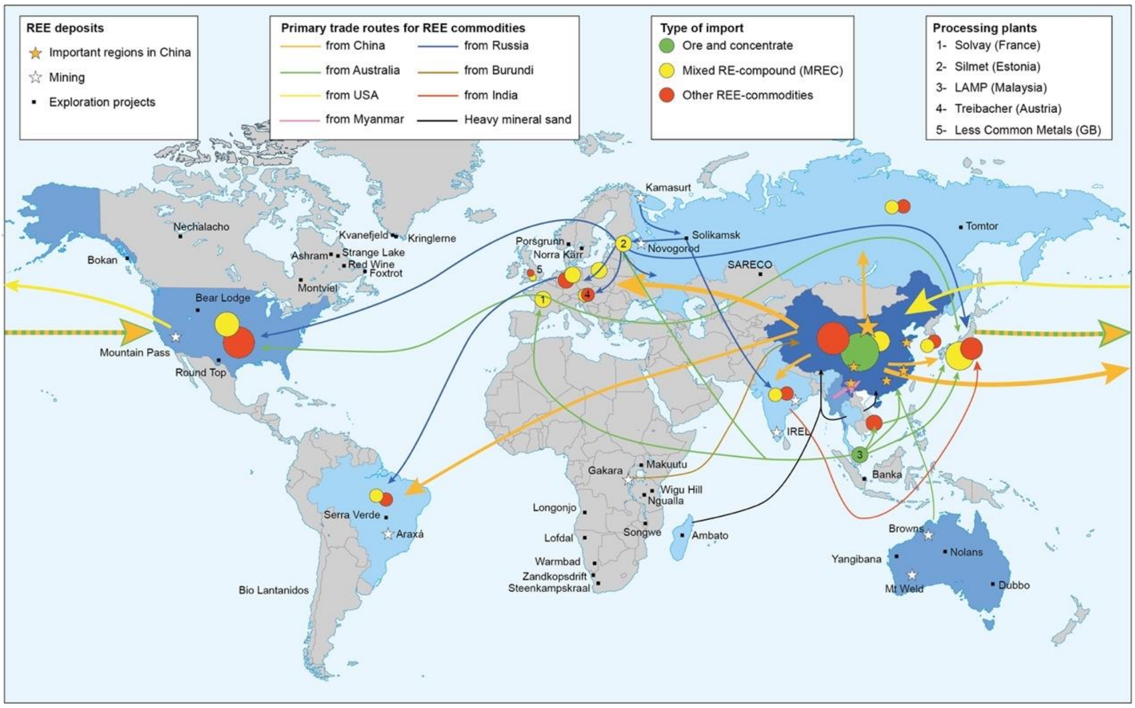


Figure 4-1 *China dominates the trading patterns of rare earth elements. Based on Roskill (2021a).*

Global demand for rare earth elements increases annually when measured in volume and in value; the largest growth rates are seen in products for permanent magnets (Figure 4-2 and Figure 4-3). In response to rising demand, China significantly increased its production in 2000 (Figure 4-4); a significant portion of the production was exported to Japan.

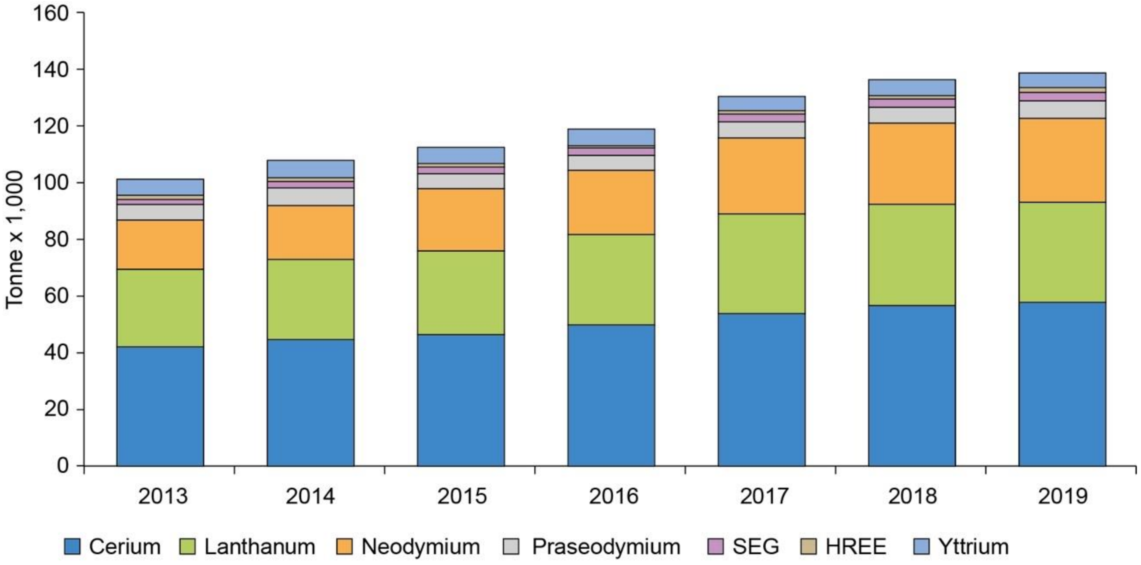


Figure 4-2 *Global consumption of rare earth elements in the period 2013-2019. SEG: Samarium, europium, gadolinium. Source: European Commission (2020).*

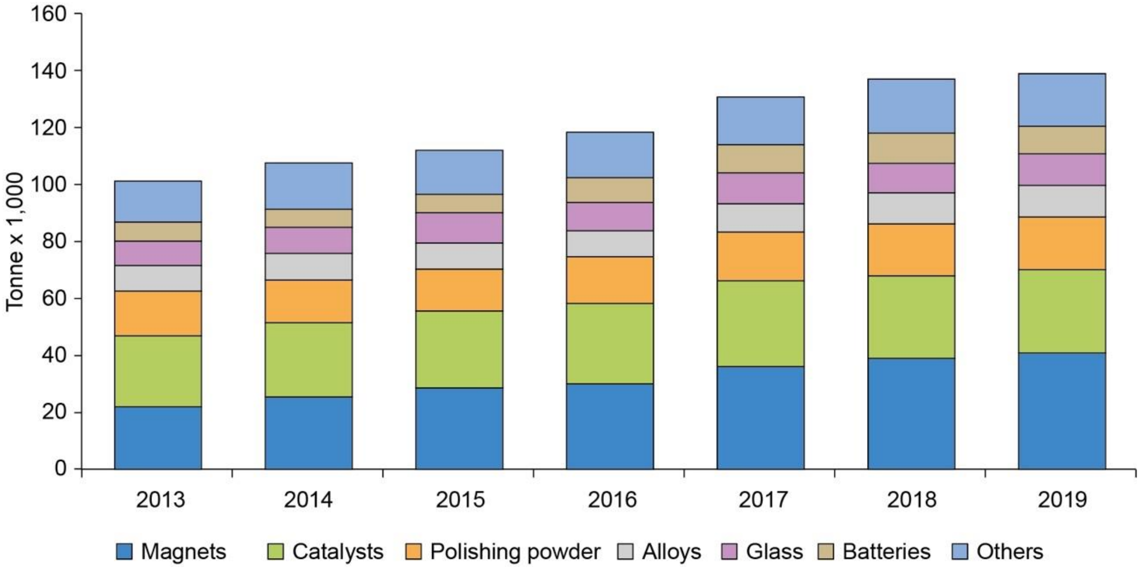


Figure 4-3 *Global demand for rare earth elements in the period 2013-2019, broken down by industrial sectors. Source: European Commission (2020).*

Imports of rare earth elements to the four major markets, the EU, USA, Japan, and Korea, amounted to around 51,000 tonnes in 2019 and around 54,000 TREO/year in 2018 (Table 4-1). The import statistics cover a wide range of products, some of which are re-exports; as the production year for the imported tonnages is unknown, the import figures cannot be assessed in relation to China's production quotas.

As discussed in Chapter 14, there is a strong increase in demand for permanent magnets (NdFeB magnets), which are key components in the electrification of the transport sector, for wind turbines, air conditioning systems, etc., and thus, there is a particularly high demand for neodymium, praseodymium, terbium and dysprosium, all of which are high priced products.

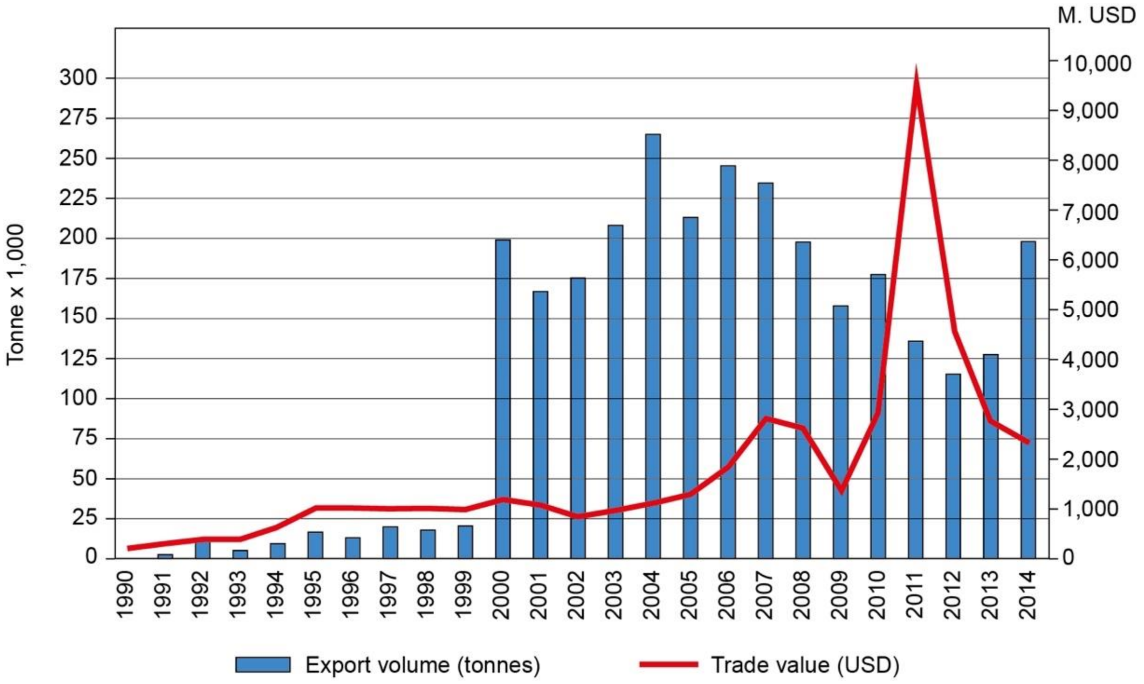


Figure 4-4 *China's exports of rare earth elements and associated export value. Both exports and associated value changed radically in 2000, with increases over the following four years, after which the trend has been declining overall. Source: Mancheri & Marukawa (2018).*

Table 4-1 *Imports of REE consumables to the EU, USA, Japan, and Korea from the countries in the first column in 2019. Source: Ginger International Trade & Investment Pte., Ltd. (2021).*

	EU		USA		Japan		Korea		Total
	%	tonne	%	tonne	%	tonne	%	tonne	
Estonia			5	61	5	944			**1,005**
France					17	3,209	16	587	**3,796**
India	2	213			2	378	3	110	**701**
Italy					1	189			**189**
Japan	4	425	3	7			14	513	**945**
China	38	4,038	78	15,780	66	12,460	58	2.127	**34,405**
Korea	1	106							**106**
Malaysia	5	531	9	1,821	7	1,322	4	147	**3,821**
Russia	47	4,995							**4,995**
South Africa			1	2					**2**
Taiwan					1	189	2	73	**262**
Germany			2	4			1	32	**36**
USA	2	213					2	73	**286**
Vietnam					1	189			**189**
Austria			1	2					**2**
2019		**10,521**		**17,677**		**18,880**		**3,662**	**50,740**
2018		**12,467**		**17,033**		**21,054**		**3,153**	**53,707**

In general, REE magnets are industrially important and economically significant product groups (Figure 4-5), but the importance of these product groups varies between countries due to the countries' industrial structure with Germany, Italy, Poland, and France as some of the largest importers of magnets from China. In the first half of 2021 alone, the EU imported approx. 8.000 tonnes of NdFeB magnets with a total value of approx. 500 million USD (Rare Earth Industry Association 2021) (Figure 4-6).

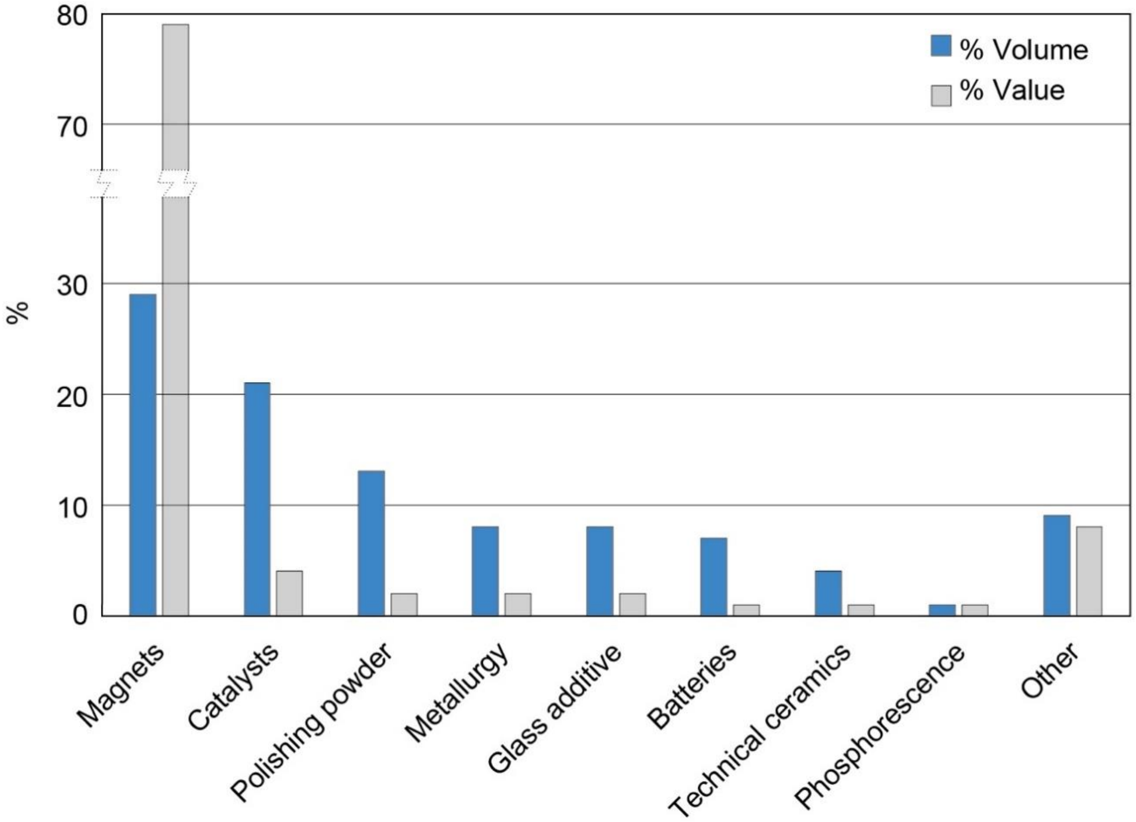


Figure 4-5 *Market shares for the consumption of rare earth elements in various industrial sectors measured in % of volume and % of value. Source: European Commission (2020).*

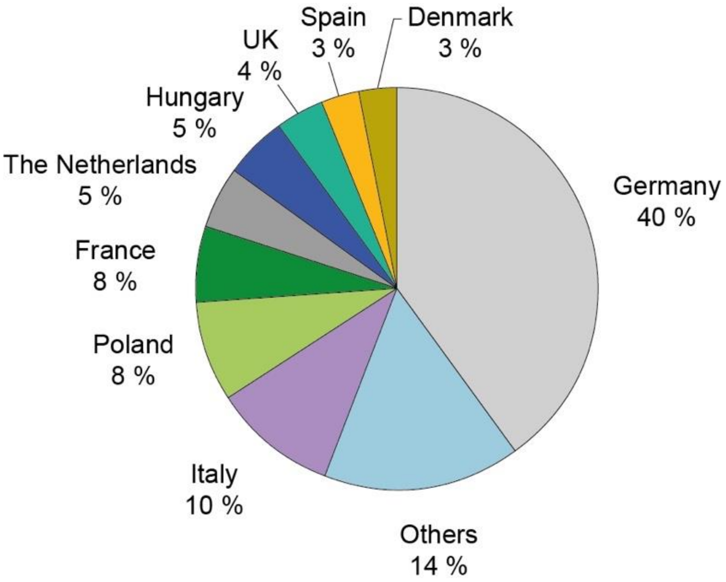


Figure 4-6 *The percentage distribution between the EU countries' (including the United Kingdom) imports of NdFeB magnets in the first half of 2021. A total of 8,000 tonnes of NdFeB magnets were imported for a total value of approx. 500 million USD. Source: Rare Earth Industry Association (2021).*

4.2 Prices for what?

Substantial price differentials occur for different products of rare earth elements, which is partly a result of value added through the individual steps of the supply chains. The large differences in the price level for the individual rare earth elements are also due to the imbalance between the individual rare earth elements' natural state and the market demand, which means that there is a surplus of certain rare earth elements (e.g. lanthanum and cerium), while there are periodic shortages of others (e.g. neodymium, terbium and dysprosium). This is called the balance problem and is discussed in section 9.4.1.

China publishes official export prices for processed raw materials of individual rare earth elements on a weekly basis. Several smaller exchanges (e.g. Baotou Rare Earth Exchange) publish prices for some of the products on a daily basis.

The published prices for rare earth elements are for guidance only, as conditions on specifications and terms are not disclosed. China buys increasing amounts of mineral concentrates from mines in other countries (see Chapter 8). The prices for these products are not published, but are evaluated significantly lower than the price that can be calculated based on the concentrate of rare earth elements, as the price reflects the costs related to the many processing steps prior to the ore content of rare earths is incorporated into the goods that China exports. In addition, there will be deductions for China's import restrictive duties and taxes, cf. Chapter 12.2.

4.3 Historical prices

Over the course of the last 60 years, the fluctuation in prices of rare earth elements can be divided into three historical periods, each with their own influence on price; from 1960 to approx. 2000, from approx. 2000 to 2015 and from 2015 onwards.

4.3.1 The Long look back (1960-2000)

In the period from about 1960 to the early 1990s, the United States was the world's largest producer of rare earth elements with a production based on the by-products of monazite from heavy sand deposits, and from the production of bastnäsite from the Mountain Pass mine in California. Subsequently, China took over the role as the world's largest producer and has been so ever since. When the United States stopped uranium production from heavy sand monazite in 1994 (Bray 2011), the 'Monazite period' was replaced by the 'Mountain Pass period', but in 2002 the Mountain Pass mine closed as a result of low prices and the US authorities' concerns about radioactive residues in connection with the production of rare earth elements. The Mountain Pass period was replaced in around 2005 by the current ‘Chinese period’ in which China, in a rapidly growing and diversified market, has built industries that dominate all the value chains for rare earth elements.

The earliest price data for rare earth elements stems from the United States in the late 1950s. Direct comparisons between the different data sets are not possible, as methods of calculation and discounting are not fully disclosed; therefore, data is used here solely to illustrate some general trends. In the period 1950-1975, the trend was falling prices, which was mainly due to a vast growth in supply from the Mountain Pass mine in California, which was the world's largest producer (Figure 4-7). Global production in the period 1965-1974 grew from approx. 7,000 tonnes to approx. 16,000 tonnes, of which the United States accounted for approx. 3,000 tonnes and 12,000 tonnes respectively, which in 1974 corresponded to approx. 78 % of global production.

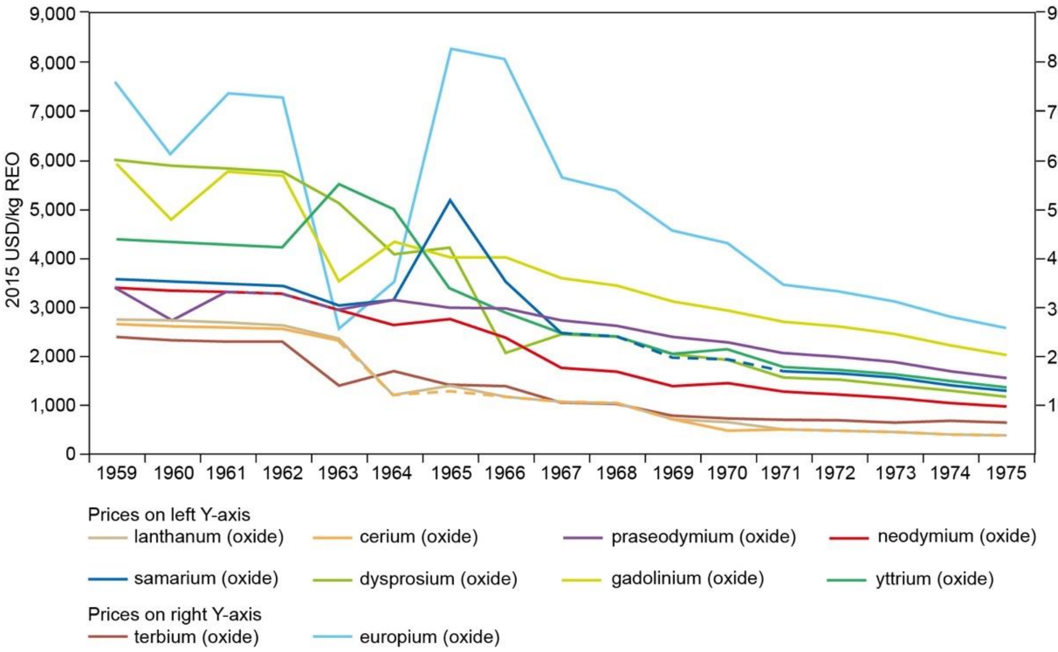


Figure 4-7 *Price developments for rare earth oxides in the United States in the period 1959-1975. Prices are given in 2015 prices. Source: Fernandez (2017).*

Based on REE-containing by-products from the production of uranium products from monazite, the United States had already in the 1960s developed infrastructure and value chains for the production of metals and alloys of rare earth elements. However, the International Atomic Energy Agency (IAEA) considered that the control and storage of uranium and thorium monazite production was inadequate and posed an environmental challenge, and was contributing to declining interest in monazite that led to falling prices, which occurred concurrently with the increase in prices for bastnäsite (Figure 4-8). So, in 2002, the US government decided that monazite production should cease, which meant that know-how about rare earth elements and associated patent rights was transferred to Chinese companies. This was the beginning of China's dominance within rare earth value chains, both related to the processing of REE raw materials and to the REE-consuming industries (see Chapter 11 and 12).

Despite a sharp increase in the demand for REE products during the 1990s and up to 2010, market prices trended downwards e.g. as a result of the global economic crisis (Figure 4-9).

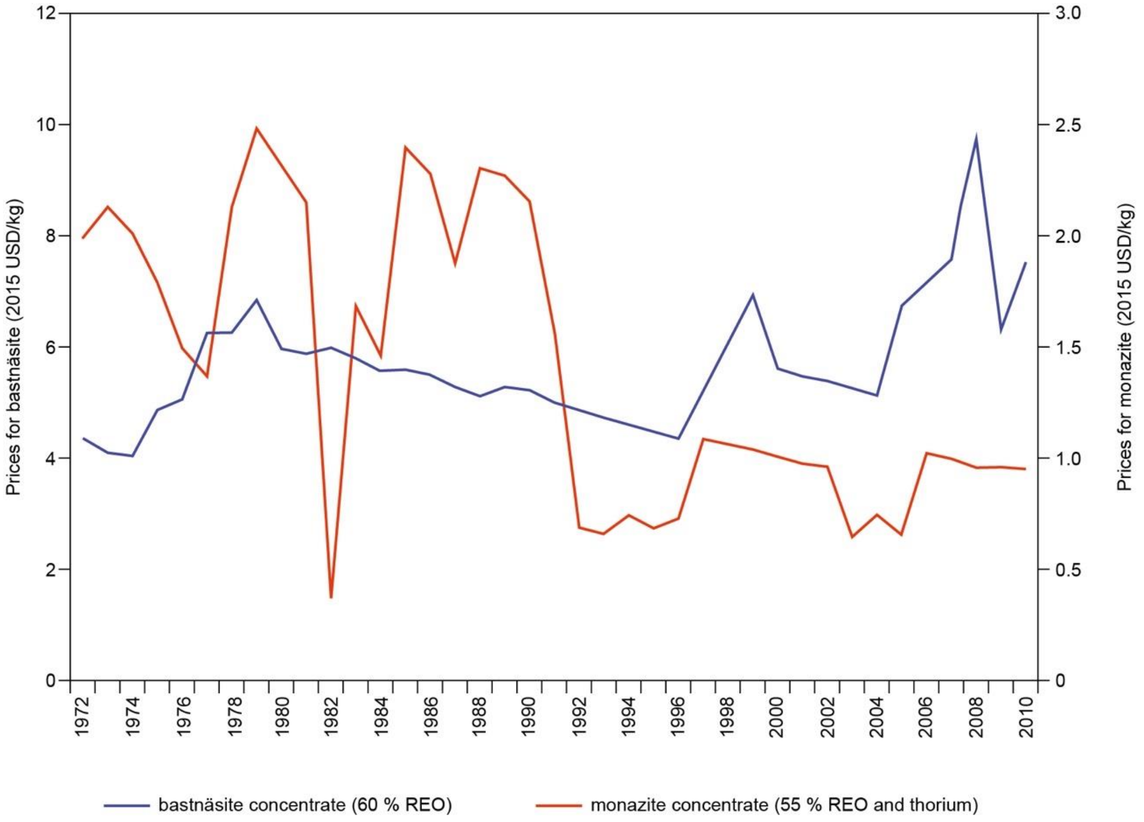


Figure 4-8 *Prices for bastnäsite and monazite concentrates in the period 1972-2010. Figures given in 2015 prices. Source: Fernandez (2017).*

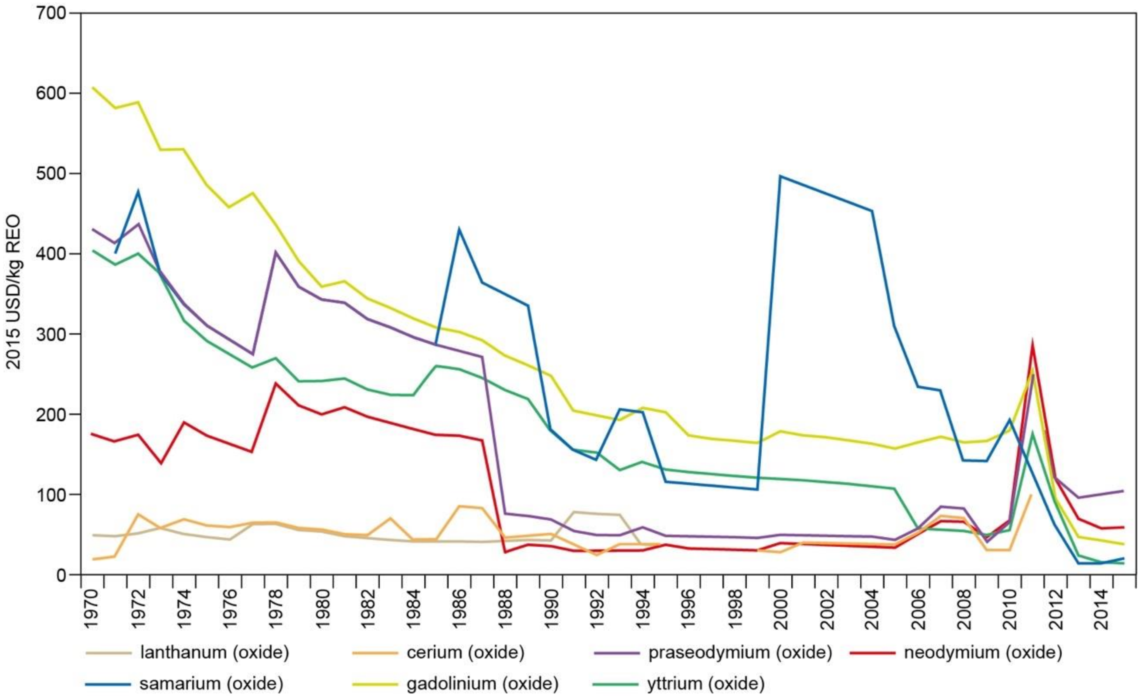


Figure 4-9 *Price development for selected rare earth metal oxides for the period 1970-2015. Prices are given in 2015 prices. Source: Fernandez (2017).*

4.3.2 The Period 2000-2015 and the 2011-2012 price spike

In the period 2000-2010, prices of rare earth elements were generally in decline, with samarium being the only exception. The large price increases of samarium, especially from the early 2000s, were primarily due to increased demand for SmCo magnets. In July 2010, the second half of that year's export quotas were announced, indicating a significant drop compared to the previous year. However, it was still above the total actual exports in 2009, and above estimated ROW demand for 2010. Nevertheless, this move was misunderstood and started to influence prices (G. Hatch, personal info., Aug. 2022). A sharp and sudden price increases on virtually all rare earth elements occurred in 2011 as a result of China's export ban on rare earth elements to Japan, at that time China's largest export market. Officially, sanctions against Japan were triggered by border disputes in the East China Sea, where a Chinese fishing trawler was seized by the Japanese coastguard in September 2010. This foreign policy crisis and rising prices were used to demonstrate China's control of value chains for rare earth elements and for the consolidation of China's own supply chains. The export ban, which lasted for two months, was replaced by a 40 % drop in China's export quota and total exports in 2010 fell by 77 % as prices multiplied (Figure 4-9 and Figure 4-10). China explained the declining exports by saying that environmental conditions in Chinese mines (especially ion adsorption deposits) had forced Chinese producers to reduce their production.

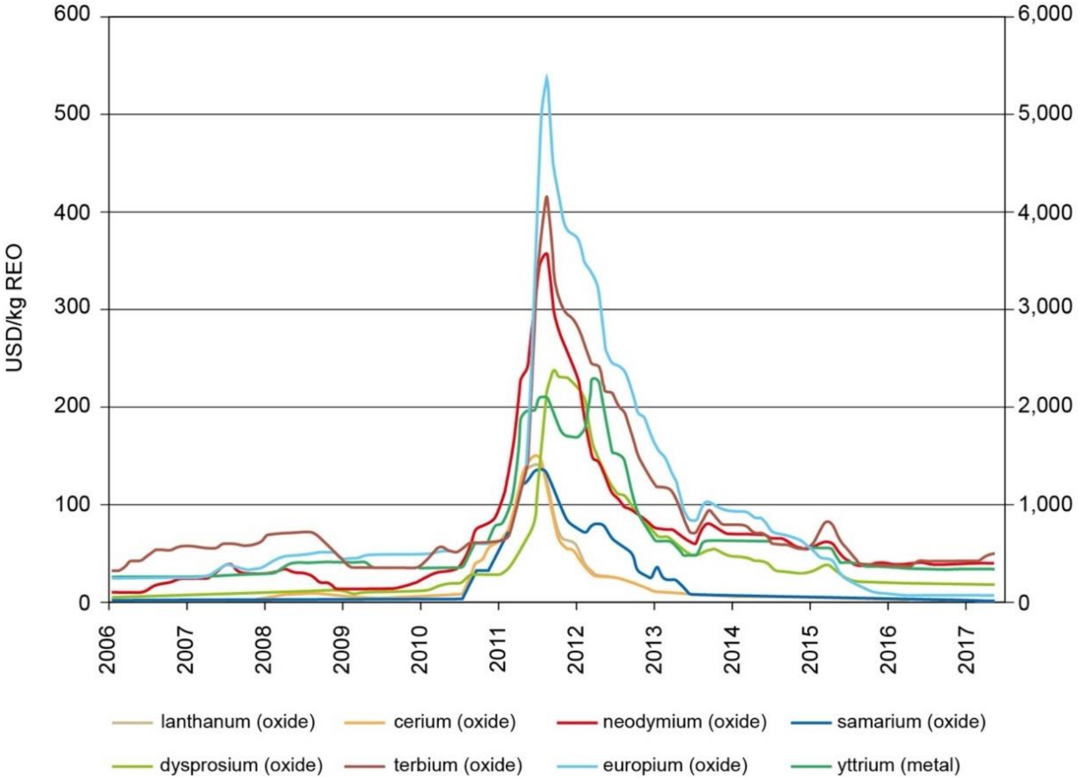


Figure 4-10 *Price development for selected rare earth metal oxides in the period 2006-2017, showing as well the price spike in 2011-13. Prices are given in 2015 prices. Source: Fernandez (2017).*

Seen over the period 2009-2020, the price decrease for rare earth elements was 50-100 % for lanthanum, cerium, samarium, europium, and yttrium, whereas the prices for the 'magnetic metals' praseodymium, neodymium and dysprosium increased by 100-200 %, mainly due to an increase in demand due to the electrification of the transport sector and growing needs for communication and data technology. Increasing consumption of magnetic metals inevitably triggers overproduction of lanthanum and cerium (see section 9.4.1), which is already under pressure from declining markets (in particular, the reduced consumption for oil refining), and therefore the decrease in prices is particularly large for products that use these elements. Falling prices for europium and yttrium can be attributed to a lower consumption of phosphorescence due to e.g. the introduction of LED lighting and the phasing out of halogen, FTL and CFL lamps.

4.3.3 The period after 2015

Falling prices around 2015 also started to be a problem for the Chinese REE-producing companies, which meant that more companies in China closed down and the whole sector was reorganised. Further reorganisation was initiated in 2021 to strengthen China's global leadership in the rare earth value chains (see section 12.1).

Export prices from China on selected products are shown in Figure 4-11 and Table 4-2. As Table 4-2 shows there are large price differentials between the individual rare earth elements, with the magnetic metals being the most expensive and lanthanum and cerium as some of the cheapest. Prices are generally not available for the five heavy rare earth elements holmium, erbium, thulium, ytterbium, and lutetium, as these are only used in niche markets, so the prices quoted are uncertain in their validity.

The development in export prices for different types of REE raw materials in the period 2017 to 2019 is shown in Figure 4-11 and commented on below.

Cerium: Falling prices are due to the demand for magnetic metals creating over-production of e.g. cerium at the same time as there is declining demand for cerium for oil refining.
Dysprosium: Production is low and delivers primarily to manufacturers of NdFeB magnets. Price fluctuations are mainly due to dysprosium being a by-product of the light rare earth elements, such as neodymium, and that the amount of dysprosium on the market varies depending on which mines currently dominate supplying the market.
Erbium: Prices have been fairly constant.
Europium: Prices have been falling sharply during this period due to the declining market for phosphorescence as a result of the introduction of LED lighting.
Lanthanum: The cheapest of the rare earth elements. Markets have been declining and prices are almost constantly falling, due to vast oversupply and declining demand from the traditional markets.
Neodymium: Prices have declined slightly during this period, but overall, more than half of the turnover of rare earth elements in 2019 was due to sales of neodymium.
Praseodymium: The price of praseodymium oxides has declined, whereas the prices of praseodymium metal have fallen only marginally.

Prices for rare earth elements, which are available in free trade, fluctuate significantly from month to month (Table 4-2 and Figure 4-12). However, it is unclear to what extent these fluctuating prices affect trade, as the largest volumes of trading are tied up in long-term contracts.

With the exception of lanthanum and cerium, there have been substantial price increases in the period from 2019 to autumn 2021. In 2021, prices increased primarily for semi-products such as rare earth carbonates (MREC) (154 %) and for refined products such as yttrium oxide (141 %) and erbium oxide (103 %) (Table 4-2); only the prices of lanthanum and cerium oxide have fallen slightly. Market analysts expect large price increases, for Nd-Pr products in particular, which are primarily due to the increase in demand for electric vehicles (SMM News 2021). It should be noted that the price level is still much lower than the level during the supply crisis in 2011 (Table 4-2).

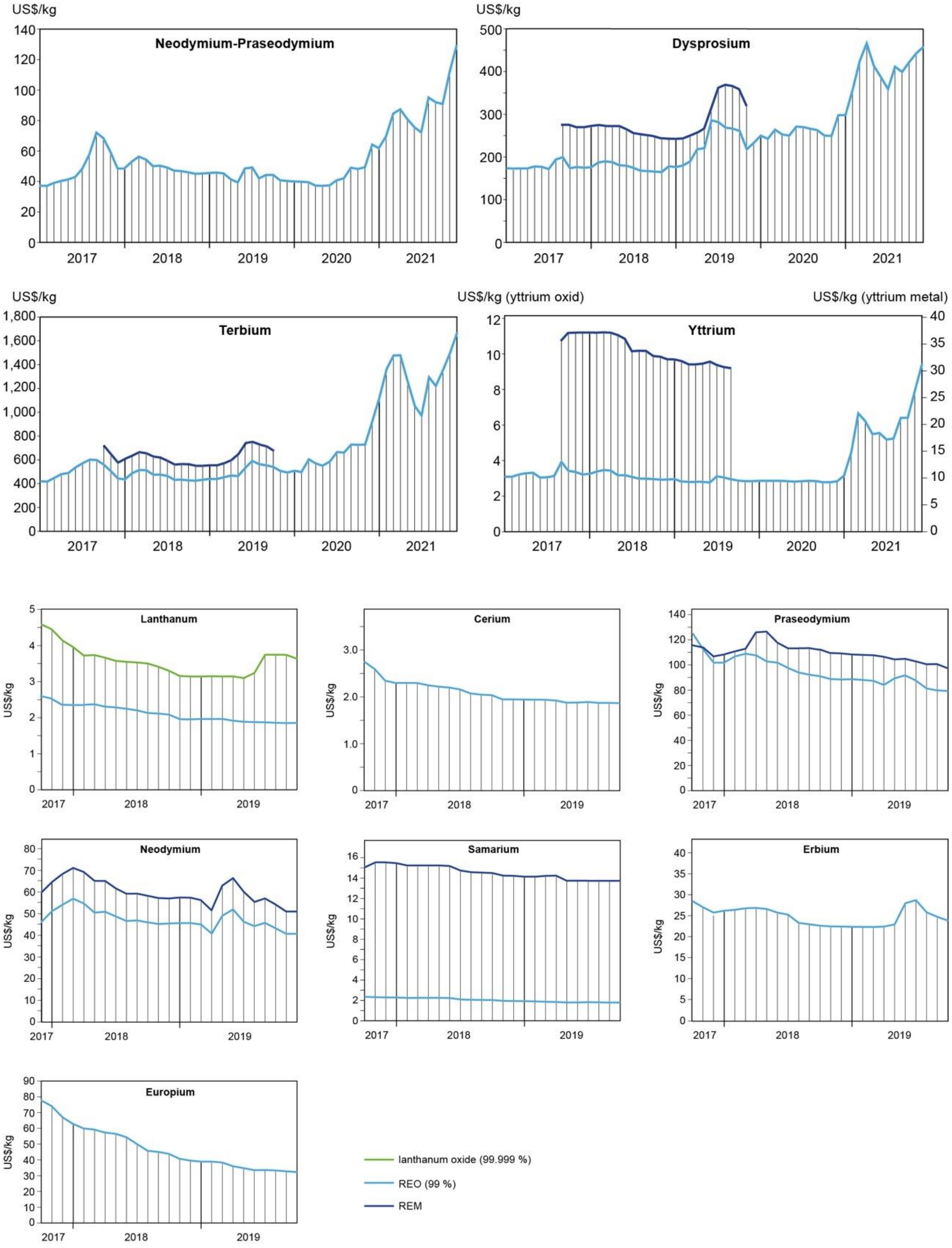


Figure 4-11 *The development in export prices for different types of REE raw materials in the period 2017-2019. Source: European Commission (2020).*

Table 4-2 *The development in the prices of export products from China in the period between December 2nd, 2019 to December 15th, 2021. The price level for 2011 is included as a reference. Graphic representation of data is shown in Figure 4-12. Sources: The Rare Earth Observer (2021) and Ginger International Trade & Investment Pte., Ltd. (2021).*

	2011	02-12	06-11	08-12	15-12	20-01	04-02	19-03	30-04	08-05	28-05	21-06	07-06	06-08	27-08	03-09	18-09	30-09	13-10	29-10	15-11	26-11	15-12
		2019	2020	2020	2020	2021	2021	2021	2021	2021	2021	2021	2021	2021	2021	2021	2021	2021	2021	2021	2021	2021	2021
MREC		3.0	3.1	3.5	3.5	3.5	3.5	4.8	4.8	4.8	4.9	4.6	4.6	7.8	7.6	7.6	7.5	7.5	7.5	8.9	9.9	10.6	10.4
Lanthanum oxide	172	1.7	1.4	1.5	1.5	1.5	1.5	1.3	1.5	1.5	1.5	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.5	1.5	1.5	1.4	1.4
Cerium oxide	158	1.6	1.4	1.5	1.5	1.5	1.5	1.4	1.5	1.5	1.5	1.4	1.3	1.4	1.3	1.3	1.3	1.3	1.5	1.5	1.5	1.5	1.5
Neodymium oxide	338	40.8	55.6	78.8	75.2	86.4	88.7	103.7	84.3	83.7	81.4	73.3	78.4	96.2	96.0	95.6	96.9	95.6	97.7	115.8	128.4	132.6	141.3
Praseodymium oxide	249	47.7	48.9	57.3	55.7	60.9	63.5	79.9	83.1	83.5	81.0	81.1	83.2	99.8	99.4	99.9	100.0	99.5	102.2	110.3	132.3	134.5	137.3
Terbium oxide	4,510	488.6	755.2	1,032	1,031	1,340	1,358	1,525	1,264	1,233	1,055	973.7	1,011	1,323	1,249	1,208	1,325	1,342	1,382	1,508	1,854	1,705	1,750
Dysprosium oxide	2,840	233.3	258.5	299.7	296.2	332.0	357.6	463.9	414.4	404.3	384.5	359.4	375.2	419.3	400.8	398.8	416.9	421.0	422.5	442.1	476.1	459.1	460.3
Europium oxide	5,870	30.6	31.4	32.1	32.1	32.4	32.5	30.0	43.3	29.8	30.2	29.8	29.7	29.8	29.7	29.8	29.8	29.7	30.7	31.1	31.0	30.5	31.4
Yttrium oxide	183	2.8	2.8	2.8	2.8	3.3	4.5	6.5	5.5	5.5	5.6	5.5	4.8	5.3	6.4	6.4	6.4	6.4	8.9	8.0	8.7	9.5	10.2
Gadolinium oxide	203	22.6	26.1	28.8	27.5	29.1	30.6	36.6	44.8	30.0	29.2	28.9	33.0	40.8	39.2	38.6	39.9	39.7	41.8	51.6	59.3	62.6	71.8
Erbium oxide		23.1	23.7	26.8	26.6	26.2	26.7	31.5	33.4	33.4	29.4	28.7	29.8	31.3	31.2	31.4	31.4	31.2	34.4	53.2	56.6	56.3	56.5
Samarium oxide	129	1.8	1.7	1.8	1.8	1.8	1,8	2.1	2.3	2.3	2.4	2.3	2.3	2.3	2.3	2.3	2.3	2.3	2.2	2.2	3.7	4.2	4.2
Nd-Pr oxide		40.5	51.4	66.9	61.0	70.0	71.1	88.7	82.1	80.9	77.1	72.5	80.7	95.9	94.1	92.6	92.8	91.7	94.0	114.2	123.3	133.3	134.2
Lanthanum metal		4.8	4.3	4.4	4.4	4.4	4.4	4.5	4.4	4.4	4.5	4.3	4.3	4.3	4.3	4.3	4.3	4.3	4.3	4.4	4.4	4.4	4.4
Praseodymium metal		92.5	91.9	90.2	87.8	97.1	97.5	105.2	100.4	99.7	100.1	98.5	108.3	130.0	129.5	130.1	133.7	133.0	134.3	149.4	173.3	182.2	182.8
Neodymium metal		51.2	69.6	95.6	92.4	105.5	109.9	131.3	108.6	104.4	98.6	90.6	93.9	120.4	118.6	118.5	118.6	118.0	120.7	140.1	156.5	165.0	175.0
Nd-Pr alloy		51.2	64.5	83.3	76.7	85.7	88.2	111.4	108.6	104.0	95.8	88.5	98.4	119.5	117.9	115.0	115.5	114.9	116.2	137.7	152.2	164.6	165.6
Battery grade mischmetal		21.1	21.7	22.2	22.1	22.3	22.4	22.3	22.4	22.4	22.7												
Mischmetal (La-Ce)		4.9	4.2	4.3	4.3	4.3	4.3	4.4	4.7	4.4	4.8	4.6	4.6	4.6	4.6	4.6	4.6	4.6	4.6	4.6	4.6	4.6	4.6
Dy-Fe alloy		236.6	254.7	296.6	294.7	325.9	352.9	461.6	411.3	393.5	376.6	354.8	371.4	414.7	398.5	394.9	413.8	413.2	418.7	442.1	465.9	459.1	459.1
Holmium oxide			64.5	92.5	90.1	100.9	108.0	157.5	134.5	126.8	105.7	100.7	107.7	150.9	139.9	139.0	148.8	151.1	158.6	169.0	188.9	183.8	198.5
Lutetium oxide																			804.8	813.7	827.3	829.0	831.8
Thulium oxide																			110.7	126.0	125.7	125.9	126.3
Ytterbium oxide																			16.6	16.8	16.8	16.8	20.0
Exchange rate US$ 1= RMB		7.0	6.5	6.5	6.6	6.5	6.5	6.5	6.5	6.5	6.4	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.4	6.4	6.4	6.4

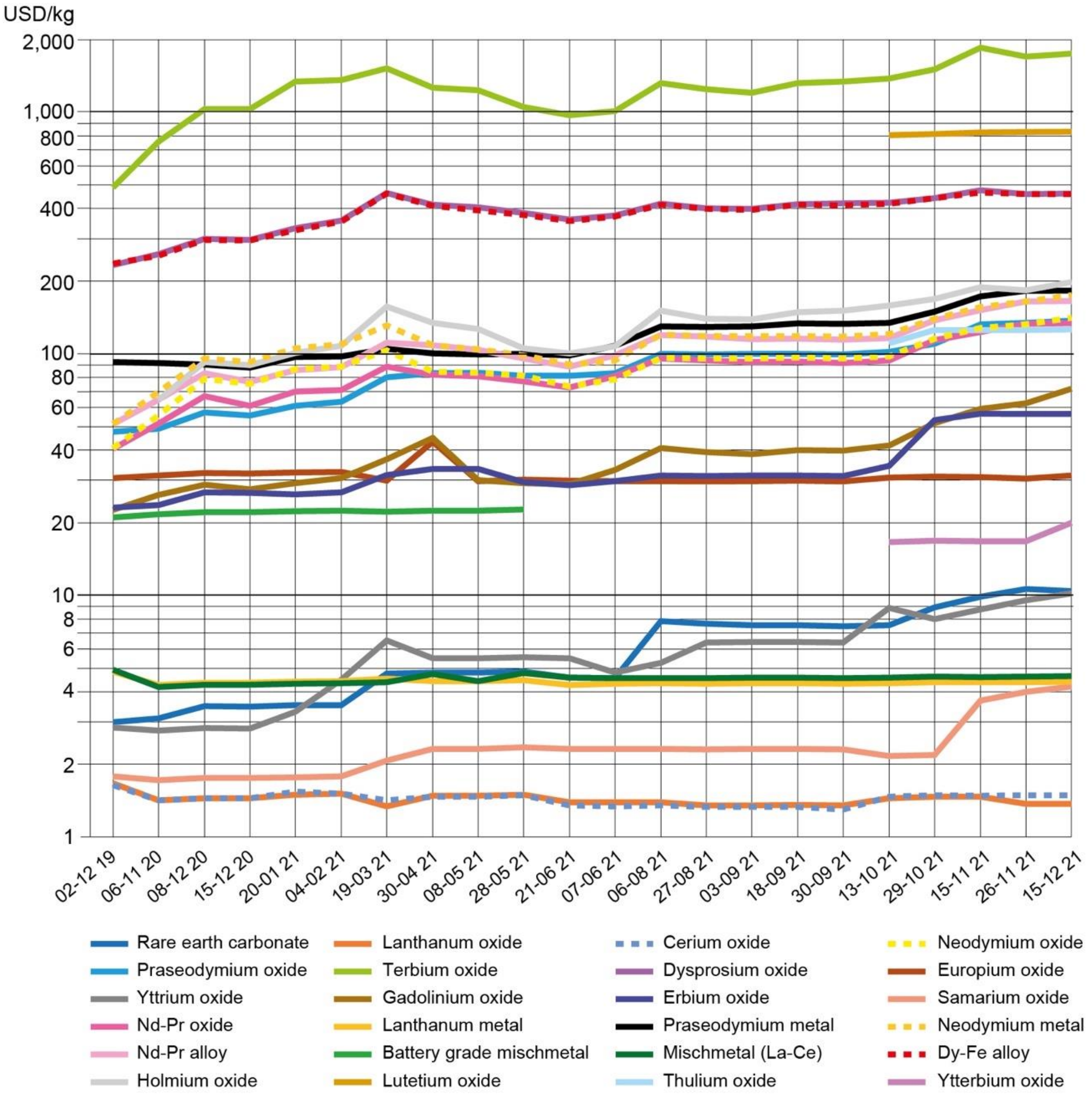


Figure 4-12 *The development in the prices of export products from China in the period 2 December 2019 to 15 December 2021. Graphic presentation of data shown in Table 4-2. Source: The Rare Earth Observer (2021) and Ginger International Trade & Investment Pte. Ltd. (2021)*

Table 4-3 shows examples of prices for different product types that are based on the same rare earth element. As can be seen, prices generally increase with the degree of processing.

During the supply crisis of 2010-2011, China introduced a pricing policy based on a principle of significant differences between export prices and domestic prices for rare earth elements (Figure 4-13). Following negotiations with the World Trade Organization (WTO), China changed this pricing policy and instead established a tax system that favours the processing and manufacture of rare earth element products in China. The tax system makes it economically advantageous to finish processing goods in China and makes it more difficult and expensive to import processed raw materials, which in turn is designed to give Chinese companies advantages in the marketplace similar to those they had during the period when there was a difference between export prices and domestic prices. The tax system thus makes it possible to maintain control over the global value chains.

Table 4-3 *Prices for different raw material types based on the same individual rare earth element. This shows that the price rises with the purity of the product amongst other things. Source: Institut für seltene Erden und Strategische Metalle (2020).*

Product	Quality	USD/kg
Ce-carbonate	TREO 45 % MIN CeO_2 REO 100 % EXW China	1.36
Ce-carbonate	TREO 45 % MIN CeO_2 REO 100 % FOB China	1.60
Ce-oxide	99 % FOB China	1.58
Ce-oxide	99.9 % EXW China	7.83
Ce-oxide	99.99 % min EXW China	1.43
Ce-metal	99 % min EXW China	4.07
Ce-metal	99 % min FOB China	4.30
Dy-oxide	99.5 % min EXW China	247.59
Dy-oxide	99.5 % min FOB China	245.00
Dy-metal	99.5 % min EXW China	323.65
Dy-metal	99.5 % min FOB China	325.00
Eu-oxide	99.999 % min EXW China	30.28
Eu-oxide	99.999 % min FOB China	30.00
Eu-metal	99.5 % min FOB China	285.00
La-chloride	99.9 % min EXW China	1.36
La-oxide	99.9 % min EXW China	1.39
La-oxide	99.999 % min EXW	3.35
La-metal	99 % min EXW China	4.30
Nd-oxide	99.5 % min EXW China	52.64
Nd-metal	99 % min FOB China	67.00
Pr-oxide	99.5 % min EXW China	47.70
Pr-metal	99.5 % min FOB China	91.00
Sm-oxide	99.9 % min EXW China	1.75
Sm-metal	99.5 % EXW China	13.30
Tb-oxide	99.99 % min EXW China	721.88
Tb-metal	99.9 % min EXW China	929.25
Y-oxide	99.999 % min FOB China	3.00
Y-metal	99.9 % min EXW China	30.28

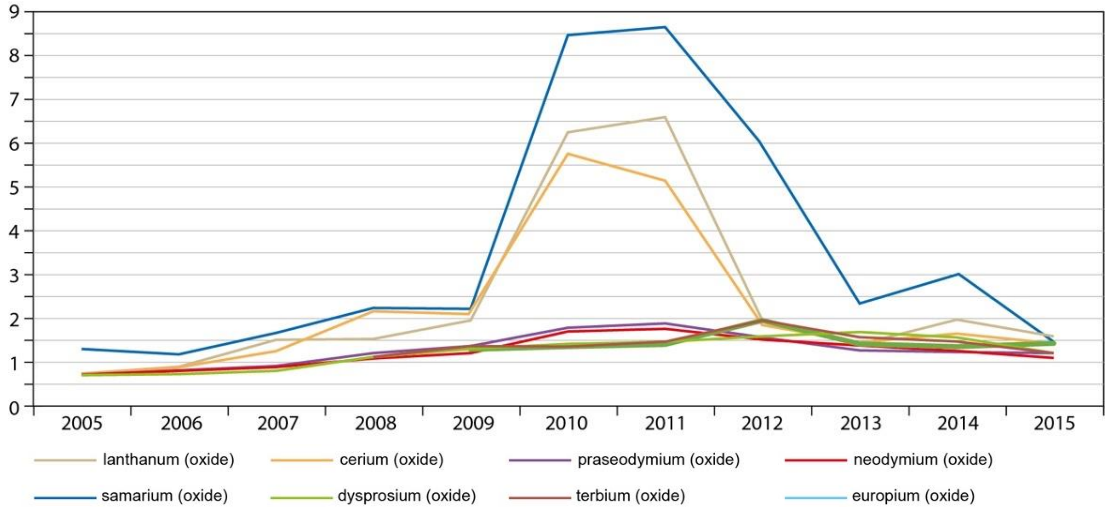


Figure 4-13 *The relationship between export prices and domestic prices in China in the period 2005-2015. A value of, for example, 8.5 for samarium in 2010 means that the export price was 8.5 times higher than the domestic price. Source: Friedrichs (2017).*

4.4 Ore value and basket price

Mineral exploration, which is the uppermost part in the mineral industry's value chains, requires that investors, analysts and decision-makers are able to compare and evaluate REE-exploration projects. Since rare earth elements are, by definition, polymetallic deposits, i.e. that all 16 rare earth elements occur (promethium is excluded, see section 2.1), alongside a number of other metals, the assessments cannot be made as a unit price for the Total Rare Earth Oxide (TREO), as two deposits with the same TREO percent may have different compositions of the rare earth elements and thus have different ore value; deposits with higher TREO percent than others do not necessarily perform better commercially. The project assessments therefore typically include both the ore value and the basket price (see section 4.4.2).

4.4.1 Ore value

The ore value indicates the in-situ value per tonne of ore (USD/tonne) calculated based on the grade of each individual rare earth elements. The ore value only includes the ore's value and the prices for the individual rare earth elements, so neither the deposit tonnage, process loss nor the project's overall economic factors are included in the ore value estimates; moreover, some high content of e.g. lanthanum and cerium, which may be the main reason to a high TREO, may not necessarily attract only very low prices.

4.4.2 Basket price

When pricing mineral concentrates and assessing mining projects the basket price is frequently used. The basket price indicates the potential price of 1 kg of rare earth elements (TREO), produced from a given rock, disregarding the amount of rock which should go into this quantum. The use of basket price has the built-in inconvenience that the ore's quality – the grade – is not included; therefore, a low value ore can achieve a higher basket price than a high value ore. For example, certain granitic rocks with only a few g/ton REE (i.e. low ore value) will be able to achieve high basket price if the HREE/LREE ratio is high. Therefore, basket price cannot solely be used as a parameter for the economy of an exploration project.

Based on the prices in Table 4-2 and public data on the minerals' relative content of rare earth elements, the basket price for selected mines and projects has been calculated (Figure 4-14). Basket price is calculated both as a total value, in which all elements are included, and specifically for the magnetic metals neodymium, praseodymium, terbium, and dysprosium. The basket price varies between 7 and 30 USD/kg with the highest prices for projects with xenotime as the main mineral (Ptinga in Brazil and Lehat in Malaysia) and IA deposits (Longnan and Guangdong in China). Deposits with eudialyte (Norra Kärr in Sweden and Kringlerne in Greenland) both have relatively high basket prices, while Kvanefjeld/Kuannersuit (Greenland), which is dominated by the mineral steenstrupine, has a slightly lower basket price. The lowest basket prices are seen for deposits dominated by monazite (Mt. Weld in Australia) and bastnäsite (Mountain Pass in the USA and Bayan Obo in China), which is due to their relatively high content of lanthanum and cerium.

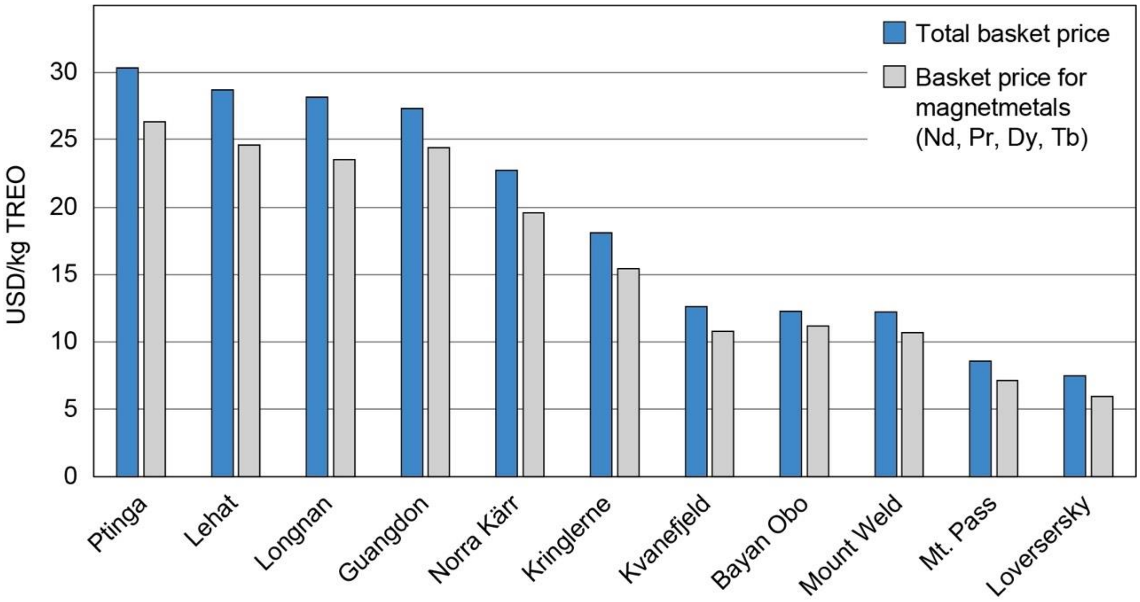


Figure 4-14 *Basket price for selected mines and projects is calculated on the basis of the prices in Table 4-2 and public data on the minerals' relative content of rare earth elements. Blue bars indicate total basket price, while gray bars indicate basket price calculated for the four magnetic metals Nd, Pr, Dy and Tb.*

4.5 Prices affect mineral exploration activities

The western world's response to the substantial price increases in 2010-2011 was to launch many new mineral exploration projects, exploring for new rare earth elements deposits in countries outside China. In the period 2010-2015, several hundred REE exploration projects were initiated, as many investors without background in the industry took the concept of rare earth elements demands very literally and the price increases as an expression of a lack of primary raw material supplies. Many of the investors were not aware that prices not only reflected global conditions in supply and demand, but in particular that China, through its de facto monopoly in processing and consumption, could influence both supply and prices, thus making it difficult to establish non-Chinese competition (Barakos et al. 2018). As the recognition of these factors increased, a large number of projects shut down over the subsequent years. However, low prices have also challenged Chinese producers of rare earth elements economically.

The remaining exploration projects are primarily those projects that lean towards the markets for NdFeB magnets (Nd, Pr, Dy, Tb). Therefore, there is less interest in projects based on carbonatite deposits, characterized by a less attractive distribution of the rare earth elements, and thus less attractive project economics.

In all phases of exploration, price expectations are the most important decision-making parameters to the exploration companies. Projects focusing on rare earth elements are polymetallic deposits (see section 4.4), and the economic assessments and decisions are thus influenced by the price development for the individual rare earth elements of which the specific ore consists of.

The susceptibility of exploration projects to the price variations of recent years is shown in Table 4-4. The table compares price expectations for 2018 with the actual prices in December 2019 and August 2021 respectively, calculated as the value of 100 kg of rare earth elements (TREO). It shows that prices in 2019 were significantly lower than the expected 2018 prices, and that the basket price only accounted for 57 % of the expected basket price. On the other hand, compared with the prices for August 2021, the total value is approx. 19 % higher than the expected 2018 prices. The three most important rare earth elements at that time were praseodymium, neodymium, and dysprosium. Lanthanum and cerium amounted to approx. 60 % (in this example) of the volume, while the value was barely 1 %. In relation to the price, the exploration companies can only obtain long-term price guarantees if long-term agreements can be entered into for the sale of their products. Recognising the very limited western capacity for processing, such agreements can only be reached with Chinese companies affiliated with 'The Big Four' (see section 12.1), and due to Chinese legislation, customs and tax policy, this will be done almost exclusively as the sale of mineral concentrates, which would be processed in China.

The price that a mining company can obtain for its products of rare earth elements is lower than the market prices of the finished products. The difference between the two prices will depend on the extend of processing that the raw material undergoes. For example, mineral concentrates will have a lower price than alloys, where the rare earth elements are extracted from the mineral, and subsequently processed in many downstream steps in order to produce REE-alloys, and correspondingly the price will increase with the degree of processing of the product (the degree of purity expressed in the number of N’s, see section 3.1). Further, as there is a large surplus production of lanthanum and cerium, these will not necessarily be paid for.

There is great uncertainty about prices in the future, and companies generally do not publish their expectations. A single company, Leading Edge Materials Ltd., owner of the Norra Kärr project in Sweden, stated in September 2021 that they expect a basket price of 53 USD/kg over the mine’s 26 year lifespan and estimated a production cost of 33 USD/kg, including costs for separation undertaken by subcontractors (Leading Edge Materials Ltd. 2021). Comparing the basket price from the Norra Kärr project with the example in Table 4-4, the figures from Norra Kärr indicate that many projects will have difficulties to achieve economically attractive business models; particularly as mineral concentrates and MREC (Mixed Rare Earth Compound) products are sold significantly below the list prices. However, it is important to realise that in many new rare earth element projects, including Norra Kärr, there will be supplementation via by-products, such as niobium, tantalum, and zircon, which are not included in the basket price, but can be included in the ore value.

The large price variations, large quantities of low-cost products such as MREC and uncertainty about technological changes in the markets mean that many of the existing exploration projects have difficulty finding funding for their projects, which delays the decision-making processes for launching new rare earth mining projects. However, the generally low prices for MREC products, the product most new mines will produce, are probably the main challenge. In November 2021, the Chinese market price for MREC products with a content of at least 44 % TREO is around 10 USD/kg, incl. 13 % VAT and 5 % import duty, corresponding to approx. 8 USD/kg CIF China (The Rare Earth Observer 2021e).

Table 4-4 *Basket price for 100 kg TREO at 2018, 2019 and 2021 prices. The significance of the price variations for the profitability of new projects is calculated in relation to a total production of 100 kg TREO. It is based on a typical composition for several of the ongoing exploration projects. Prices marked in blue indicate the magnetic metals.*

	Volume	**Price 2018***	**Value 2018-prices***	**Price Dec. 2019**	**Price difference 2014-2018**	**Value 2019-prices**	**Price difference 2014-2021**	**Price Aug. 2021**	**Value 2021-prices**
	REO kg	**USD/kg**	**USD**	**USD/kg**	**%**	**USD**	**%**	**USD/kg**	**USD**
La	26	4	1006	2	-58	44	-65	1	37
Ce	44	4	176	2	-59	7	-66	1	60
Pr	4	95	409	48	-50	205	5	100	429
Nd	13	58	766	41	-30	538	66	96	1.269
Sm	1	4	6	2	-56	2	-42	2	3
Eu	0	741	74	31	-96	3	-96	30	3
Gd	1	29	29	23	-22	23	41	41	41
Tb	0	652	65	489	-25	49	103	1.323	132
Dy	1	318	318	233	-27	233	32	419	419
Ho	0	40	8				277	151	30
Er	1	58	29				-46	31	16
Tm		10							
Yb	0	10	3						
Lu		500							
Y	7	13	95	3	-78	21	60	5	38
Total	**100**		**2,083**			**1,190**			**2,477**
Pr+Nd+Tb+Dy			1,55			1,025			2,250

* average prices as of September 2021

5. The Value Chains (Upper to Middle)

Unlike some mineral raw materials, such as gold, the value chains of rare earth elements are long and complicated. The value chains for rare earth elements typically include the following process steps: (1) mining and production of mineral concentrates, (2) extraction of the 16 rare earth elements from the minerals, (3) separation of the individual rare earth elements, (4) refining, (5) alloying, (6) product/component manufacturing and after a number of years also step (7) recycling. Step 1 is usually performed by the mining company; the following steps are performed by companies specialising in each particular process step and most often take place far away from the mine. China is dominant in all parts of the supply chains but has a declining share of stage 1.

5.1 Mining and processing of REE minerals

As discussed in Chapter 9, the rare earth elements exist as minerals in solid rocks, as minerals in loose deposits, and as ions in clay. There are three fundamentally different ways in which they can be mined or recovered: (i) mining and processing of REE ores from solid rocks, (ii) excavation or suction of heavy sand deposits and (iii) production from ion adsorption deposits that contain clay; these methods are reviewed below.

5.1.1 Mining and processing of REE ore from solid rocks

A generic process diagram for the work steps involved in the mining and processing of ore with rare earth elements from solid rocks is shown in Figure 5-1. Deposits with rare earth elements in solid rocks can, as for all other types of metals, lie deep below, or close to the earth's surface. Deposits that are close to the surface (~ 100 m below the surface) can in some cases be mined as ‘open pit’, while it is usually necessary to establish an underground mine if the deposits are deeper. As open pit mines are generally the cheapest to establish and operate and at the same time are technically less challenging, this method is explored first. Some of the largest rare earth element mines, such as Bayan Obo in China, Mt. Weld in Australia and Mountain Pass in the United States are open pit mines. In the case of a deep-lying, large deposit, an underground mine is established, such as the Lovozero mine in Russia.

The principles of mining and treatment of the ore are the same for underground and open pit mines and typically include the following work steps: (i) drilling of blast holes in which the explosives are mounted; (ii) blasting the ore into pieces usually measuring 0.1-0.5 m; (iii) unloading the ore and transporting it to the first crushing plant; (iv) crushing and grinding of the ore, where the minerals of the rock are ground to a size where the ore minerals are released as independent grains and without residues of other minerals (typically 0.1-0.5 mm, but vary from deposit to deposit); and (v) sorting and separating the ore minerals from the other minerals in the rocks. The product is a mineral concentrate consisting of the mineral or minerals containing the rare earth elements, which is then transported from the mines for further processing. These products generally account for less than 10 % of the tonnage of ore mined and contain approx. 20-60 % TREO; the residual material is called tailings and is deposited in or near the mine.

The Bayan Obo mine in China is a combined Fe-REE-Nb mine, where the rare earth elements were originally only a by-product of the iron ore, but with prices for the rare earth elements on the rise, they have become the main product in the mine, and the Bayan Obo mine is now the world's largest mine for REE. The predominant iron minerals are magnetite and hematite, and the predominant rare earth minerals are bastnäsite and monazite in a ratio of approx. 3:2 (Li & Yang 2014); in addition, there are a number of niobium minerals with columbite as the most important. The process diagram of the Bayan Obo mine is shown in Figure 5-2. Once the ore is crushed and ground, the REE minerals are separated from the other minerals using magnetic techniques. Subsequently, the REE mineral concentrates are treated in a flotation plant, where the different properties of the minerals for floating on liquid surfaces (due to the surface tension) can be used to separate the mineral groups from each other, which is how the final residues of other minerals are sorted out. The mineral concentrates, which may contain up to 60 % TREO, are then sent for chemical treatment, where the minerals are dissolved, and the rare earth elements are extracted.

In some mines, the sorting of these minerals can be done based on the density of the minerals. The most commonly used methods for this are 'shaking table', 'cyclones' and 'jigs'.

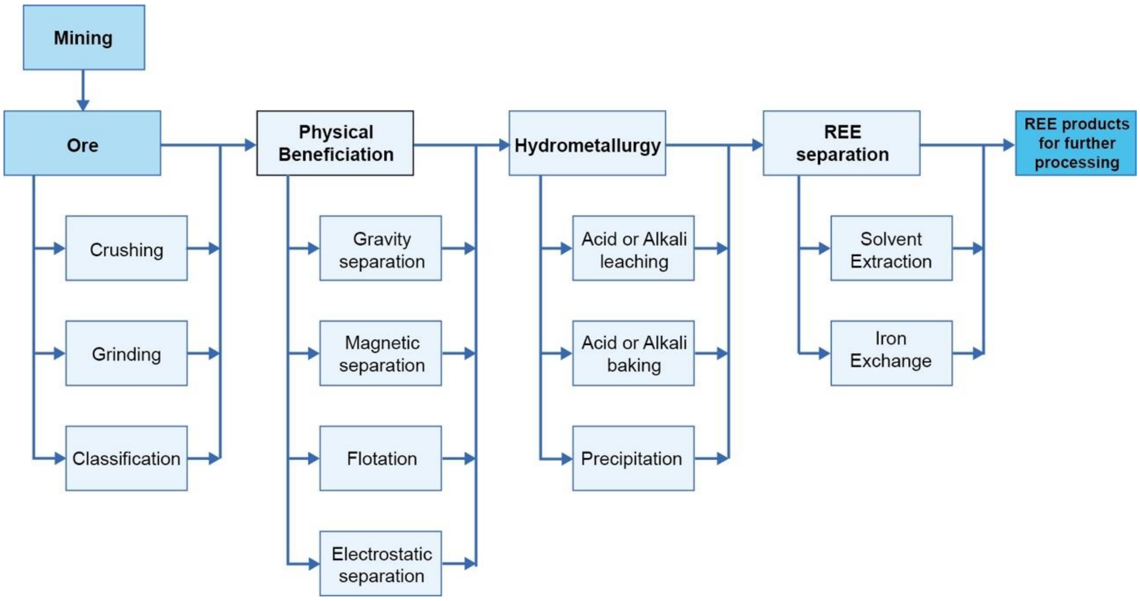


Figure 5-1 *Generic process diagram for the treatment of solid rocks containing rare earth elements.*

5.1.2 Excavation or suction/pumping (dredging) of heavy sand deposits

Heavy sand deposits, which consist of loose sediments with valuable minerals, are recovered by excavation or suction/pumping (dredging). Heavy sand deposits can be divided into two groups: (i) the active deposits that are underwater by beaches, rivers or lakes and are still being developed; and (ii) the fossil deposits (paleo deposits) now lying on land. For the first group, sand extraction techniques are primarily used, where the deposit is pumped up through a pipe mounted on ships or rafts that usually operate at water depths of less than 100 m. For the second group, the deposits are mostly dug up using different types of excavators, depending on the size of the area. The REE minerals most often found in heavy sand deposits are monazite and xenotime, both of which are relatively heavy and resistant to physical and chemical degradation, and therefore have survived both weathering processes and subsequent sediment transport. They are deposited together with other heavy minerals such as the titanium minerals ilmenite, rutile and leucoxen as well as the mineral zircon. In heavy sand deposits, the content of minerals with rare earth elements will generally be significantly less than the other commercial heavy sand minerals and will only be by-products in these instances. After excavation/pumping, the heavy minerals are separated from the commercially less viable, lighter minerals; the non-viable elements are deposited nearby as tailings. The remaining minerals are separated using techniques based on the varying density of the minerals, and their magnetic and electrostatic properties. If the material is very fine-grained (< 100 µm), flotation may be considered. The resulting mineral concentrates are commercial products that can be sold to companies that specialise in dissolving the minerals and extracting the rare earth elements from the minerals.

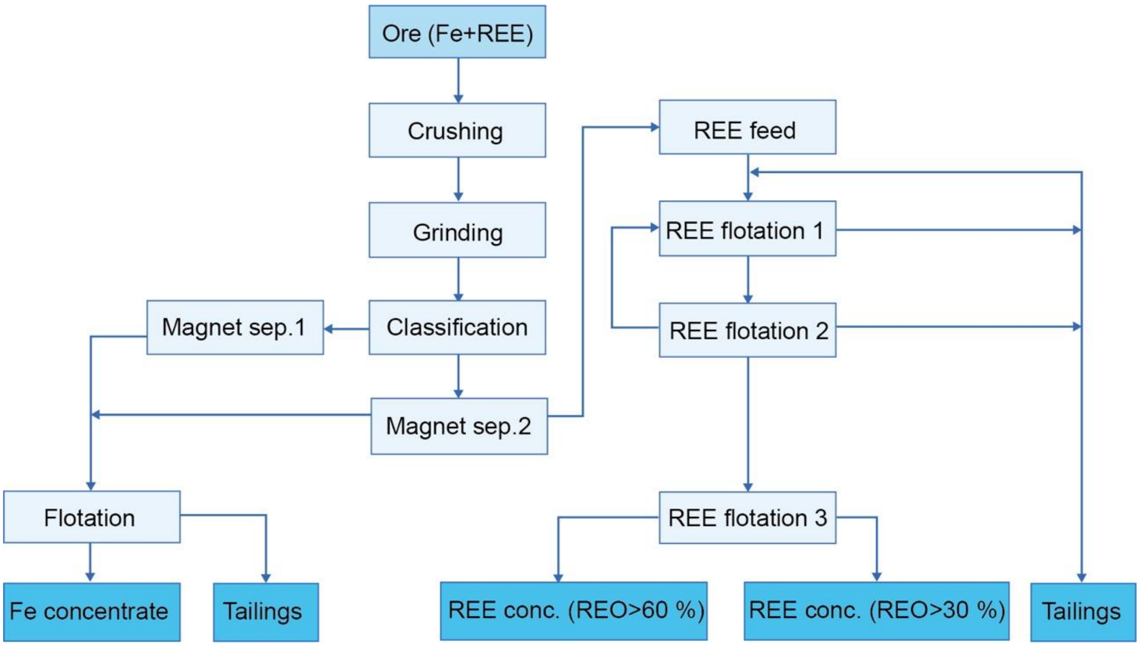


Figure 5-2 *Process diagram for the production of mineral concentrate from ore from the Bayan Obo mine. Source: Li & Yang (2014).*

5.1.3 Production of REE from clay IA deposits

Rare earth elements can, under certain conditions, bind to the surface of clay minerals. These types of deposits are called ion adsorption clay deposits (IA deposits) and are formed where the rare earth elements, connected to minerals in granitic rocks, dissolve during weathering processes caused by percolating groundwater. The dissolved REE ions can be precipitated and adsorbed to the surface of the clay minerals (e.g. kaolin, halloysite and illite) under special pH and Eh conditions. IA deposits are therefore typically near-surface, not consolidated, fine-grained, have low REE grades and are small in tonnage. The low grade means that 2-3,000 tonnes of material often have to be processed to produce 1 tonne of REO. However, IA deposits are often characterised by having a very high HREE/LREE ratio and are therefore commercially attractive and have until now been the most important deposit type in Eastern and Southern China.

In IA deposits, the rare earth elements are chemically bonded to the surfaces of clay particles. Therefore, they are not mined, but are recovered by a chemical process. In the chemical process, the bond of the clay minerals to the clay particles is broken using oxalic acid or ammonium bicarbonate ($(NH_4)HCO_3$), and the REE ions exchange ions with the cations in the liquids, after which the ion-exchanged liquid with the rare earth elements is collected and then treated so that the rare earth elements can be recovered (Li & Yang 2014). Two different methods are used for IA deposits: (i) in the in-situ method, the ion exchange liquid is passed down into the clay deposit through boreholes (Figure 5-3), i.e. here the deposit remains in the ground; (ii) in other instances, the clay material containing REE is excavated and the ion exchange liquid is fed into large basins. Both methods can give high content of rare earth elements in the finished concentrates (> REO = 92 %) (Li & Yang 2014).

The *in-situ* methods often cause great damage to the environment because it is difficult to ensure that all the ion exchange liquid is collected. The Chinese authorities are therefore officially discontinuing this type of operation (see Chapter 7).

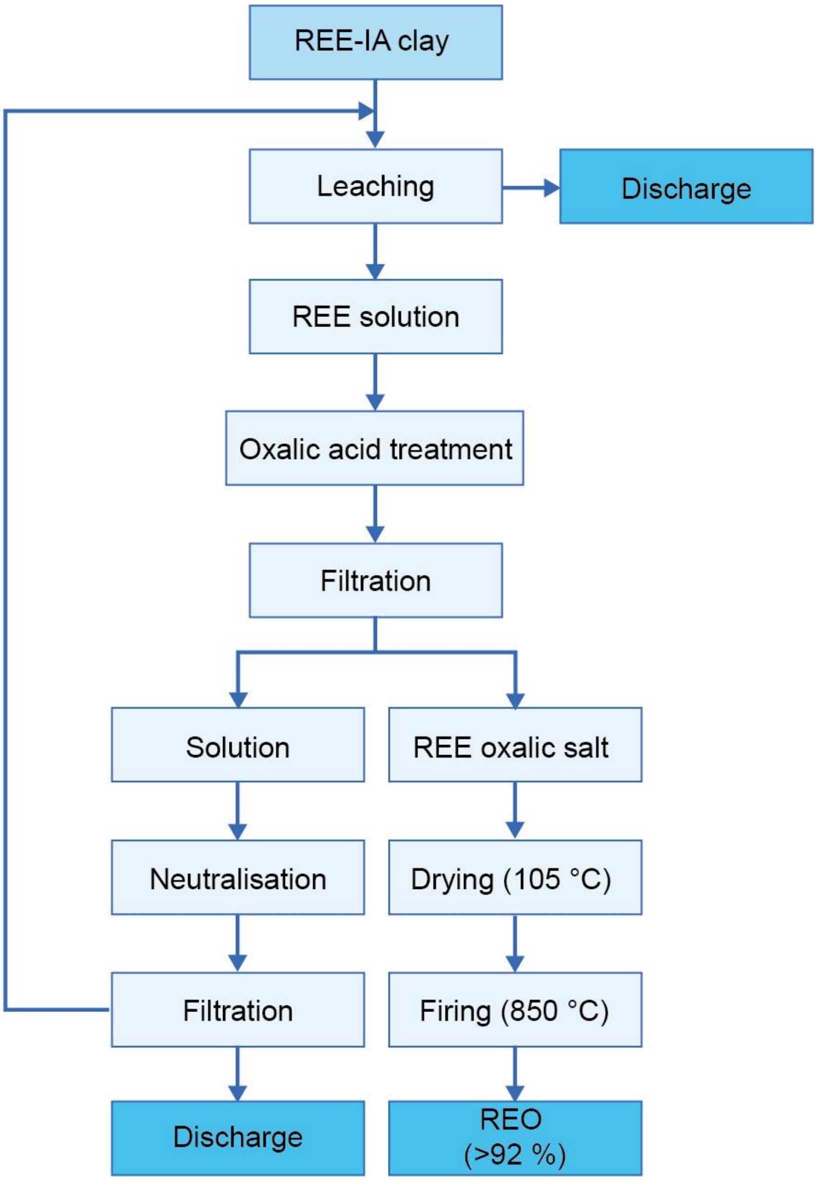


Figure 5-3 *Process diagram for extraction of rare earth elements from ion adsorption deposits. Source: Li & Yang (2014).*

5.2 Processing of the REE minerals – the chemical processes

The mineral concentrates with the rare earth elements must undergo a series of physical and chemical treatments for the content of rare earth elements to be released and separated from the other elements of the minerals. Since different REE minerals have specific properties that are linked to the crystal structure and chemical composition of the mineral, it is necessary to develop and optimise methods that are specifically designed for each deposit's mineral composition, grade, production capacity, environmental conditions, and economy. Often the following major steps are involved: (i) dissolving the minerals by treatment with acid or base (optionally supplemented with roasting (400-500 °C)), (ii) rinsing, (iii) filtration, (iv) drying and (v) any subsequent chemical purification to produce a mixture of rare earth elements. The product is often referred to as Mixed-Rare-Earth-Oxide (MREO) or Mixed-Rare-Earth-Compound (MREC) and must subsequently undergo further chemical processing for the individual rare earth elements to be separated. In the resulting concentrate, the ratio of the rare earth elements is largely the same as that of the original minerals that were treated.

At the Bayan Obo mine in China, the mineral concentrate consists of bastnäsite and monazite. Here, bastnäsite is treated with concentrated sulfuric acid (H_2SO_4) at 300-600 °C, whereby the rare earth elements in the bastnäsite minerals change into a partially dissolved form and the rare earth elements precipitate as sulphates. After some purification steps with hydrochloric acid, which removes unwanted elements, the rare earth elements precipitate as a carbonate product containing the 16 rare earth elements found in the mineral (British Geological Survey 2011). At Mountain Pass in the USA, which is also dominated by bastnäsite, a process was used in which the mineral was first dissolved with hydrochloric acid (HCl) to remove strontium and calcium, after which a calcination process removed CO_2 from the MREC concentrate. Minor chemical differences between the bastnäsite minerals and the two deposits are probably the reason why different processes are used for the materials taken from the two mines. The processes for bastnäsite and monazite are shown in Figure 5-4.

Dissolution of monazite and xenotime, which often occur in heavy sand deposits, is typically achieved through an alkaline process, often referred to as the caustic method. Here, the minerals are dissolved in a concentrated solution of sodium hydroxide (NaOH) at approx. 150 °C, whereby the rare earth elements, thorium and uranium are converted into hydroxides and the phosphates are removed as sodium phosphate (Na_3PO_4). Finally, the rare earth elements are separated from thorium and uranium using a partial solution, whereby the rare earth elements are brought into dissolved form by the addition of concentrated hydrochloric acid (HCl). Regular treatment procedures for uranium and thorium are described in Chapter 7.

5.2.1 Separation of the individual rare earth elements

The group of minerals that contain rare earth minerals always contain all 16 rare earth elements; but the correlation between them is mineral specific. Therefore, when rare earth minerals are dissolved, the solution contains a mixture of all 16 rare earth elements, which then must be separated before they can be used industrially. Due to the chemical and physical similarities between the rare earth elements, the separation process is difficult and becomes even more so with increasing rare earth element atomic number. For some applications, it is of great functional importance that the individual rare earth elements are separated into very pure products without residues of other rare earth elements (see section 3.1).

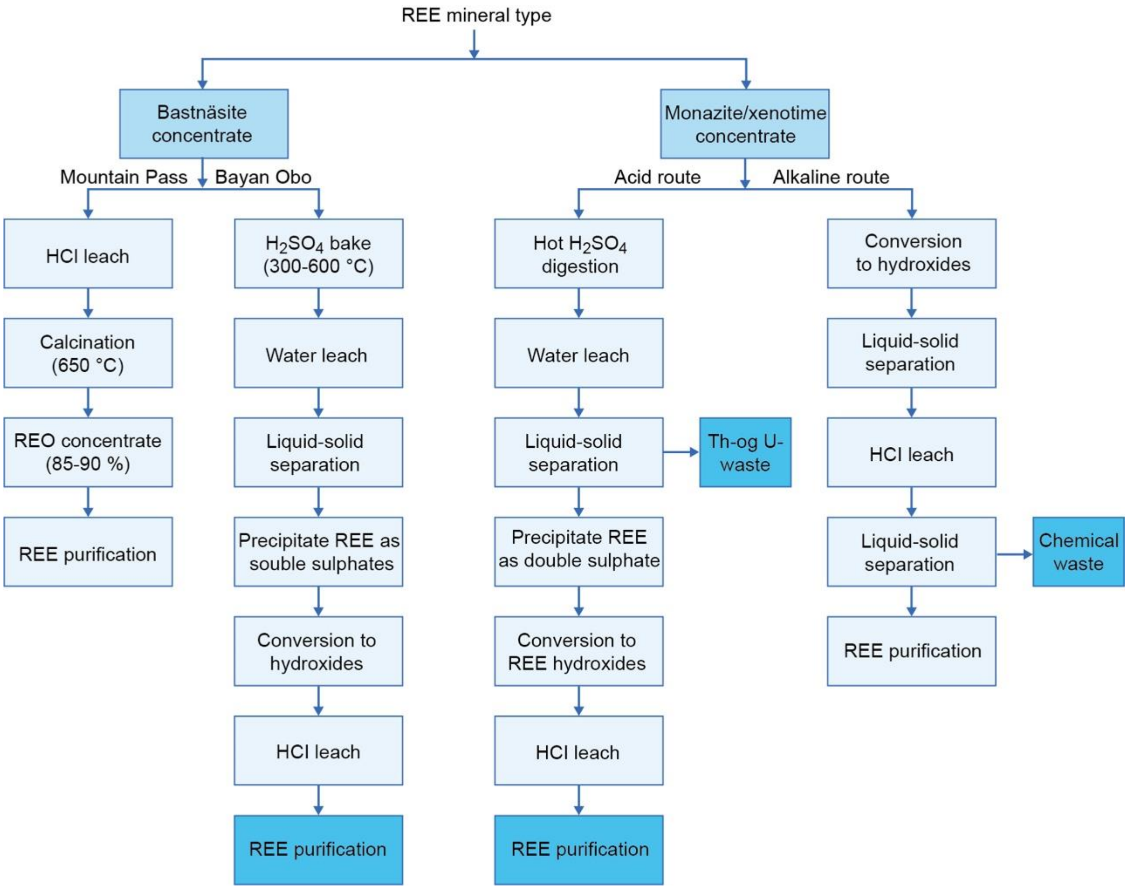


Figure 5-4 *Examples of typical processes in the production of rare earth element concentrates from the Mountain Pass mine and the Bayan Obo mine. Source: British Geological Survey (2011).*

Separation of rare earth elements is a specialised industry dominated by Chinese companies. In addition, there are also companies in, amongst others, France, Japan, Indonesia, England, and Estonia, which specialise in the separation of rare earth elements on an industrial scale (see section 13.1).

Over time, a variety of methods have been developed to enable the separation of rare earth elements, and they take advantage of the fact that the individual rare earth elements can be manipulated to have different oxidation stages and thus different solubilities (Jordens et al. 2013). The methods are usually based on either one or a combination of the following principles: crystallisation, precipitation, solvent extraction (SX) and ion exchange (IX). Commercially, it is primarily the SX and IX methods that are used most prominently in the separation of rare earth elements. However, both methods suffer from several technical, economic and, not least, environmental challenges, which is why intense development work is undertaken to find useful alternative methods. Some of the methods are described below as well as in Figure 5-5.

The conventional methods - SX and IX - are performed as sequential process steps and require 30-100 sequences to separate the individual rare earth elements into concentrates with a purity of 2N and up (Leveque 2014).

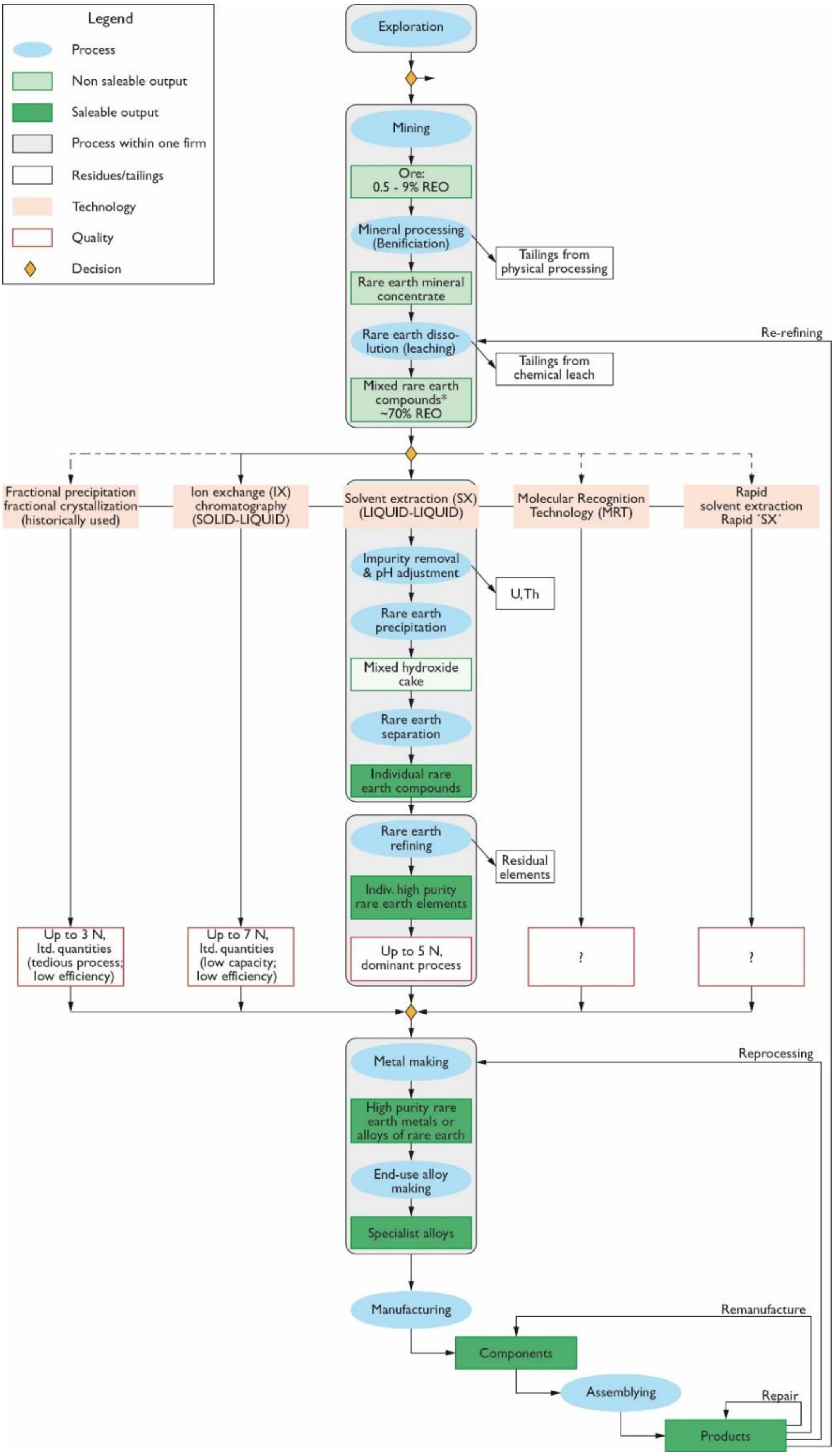


Figure 5-5 *Generic value chain for rare earth elements. Source: Machacek & Kalvig (2017) based on Gupta and Krishnamurty (2005).*

Solvent Extraction (SX) (Liquid-Liquid Extraction (LLE))

Solvent Extraction (SX), also called Liquid-Liquid Extraction (LLE), functions due to there being small differences in the solubility of the individual rare earth elements in two immiscible liquids. The liquid with the dissolved rare earth element ions (Pregnant Liquid Solution (PLS)) is added to an immiscible liquid, often an organic solution, which is a complexing agent for the rare earth element ions. Subsequently, the REE ions are extracted from the organic phase by adding a liquid in which the REE ions are more soluble (e.g.HCl solution), whereby the content of rare earth elements in the organic phase (PLS) has been reduced. This process step – 'stripping' – is repeated until the desired purity is achieved. Thereafter, the rare earth elements are commonly precipitated as carbonates, oxalates or oxides. As a general rule, the process works better for the light rare earth elements than for the heavy ones. The principle of the method is illustrated in Figure 5-6.

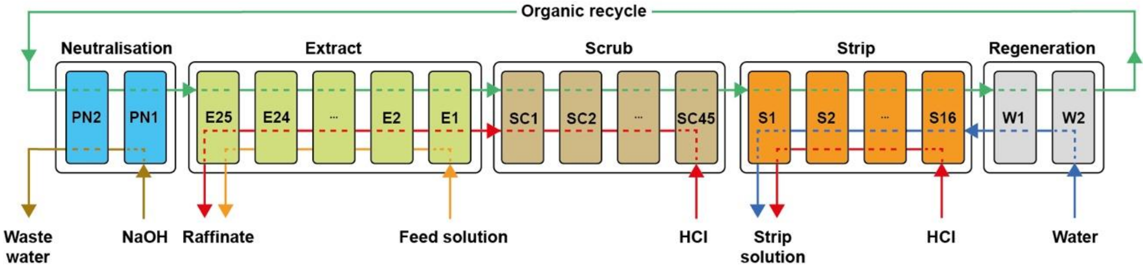


Figure 5-6 *Principle sketch of conventional SX separation process for separating La-Ce-Pr-Nd from La-Ce/Pr-Nd. The method requires more than 90 sequences. Based on Innovation Metals (2017).*

The SX separation method is slow (some steps can take weeks), inefficient and requires the process to be repeated many times. Figure 5-7 illustrates some of the typical sequences used in the SX separation process. Eventually, rare earth element concentrates, when sufficiently pure, are precipitated as REE salts or oxides, and as such are commercial products. The SX method is the most commonly used in the REE industry, where hundreds of mixer-settler devices[1] are connected in one countercurrent system. Construction of SX facilities requires very large investment, and only a few mines with rare earth elements will establish such facilities connected to the mine.

Ion Exchange Method (Ion Exchange (IX))

The Ion Exchange Method is used to produce very pure REE products (> 4N). The method uses the small varying systematic, quantitative chemical differences from lanthanum to lutetium. For example, there is an inverse correlation between ion radius for dissolved REE ions and how strongly the ion binds to anions in resins[2]. This causes the heaviest rare earth elements to bind weakly and pass through an ion exchange column and remain as REE cations in the solution, whereas the lightest rare earth elements continue into the ion exchange medium. By repeating this process many times, the individual rare earth elements can be separated. The small differences in the ion exchange properties between the individual rare earth elements can be exploited by the use of complexing agents with a specific affinity to the individual rare earth elements. The method tends to produce very clean products, but the capacity is small and the method time-consuming. The ion exchange method is therefore only normally used to produce very pure products and not for the separation of large quantities.

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[1] Mixer settler: a type of mineral processing equipment used in the solvent extraction industry.

[2] Resins are typically synthetic, organic polymers used in the chemical industry; and here to precipitate the anions on. Epoxy is an example of a resin.

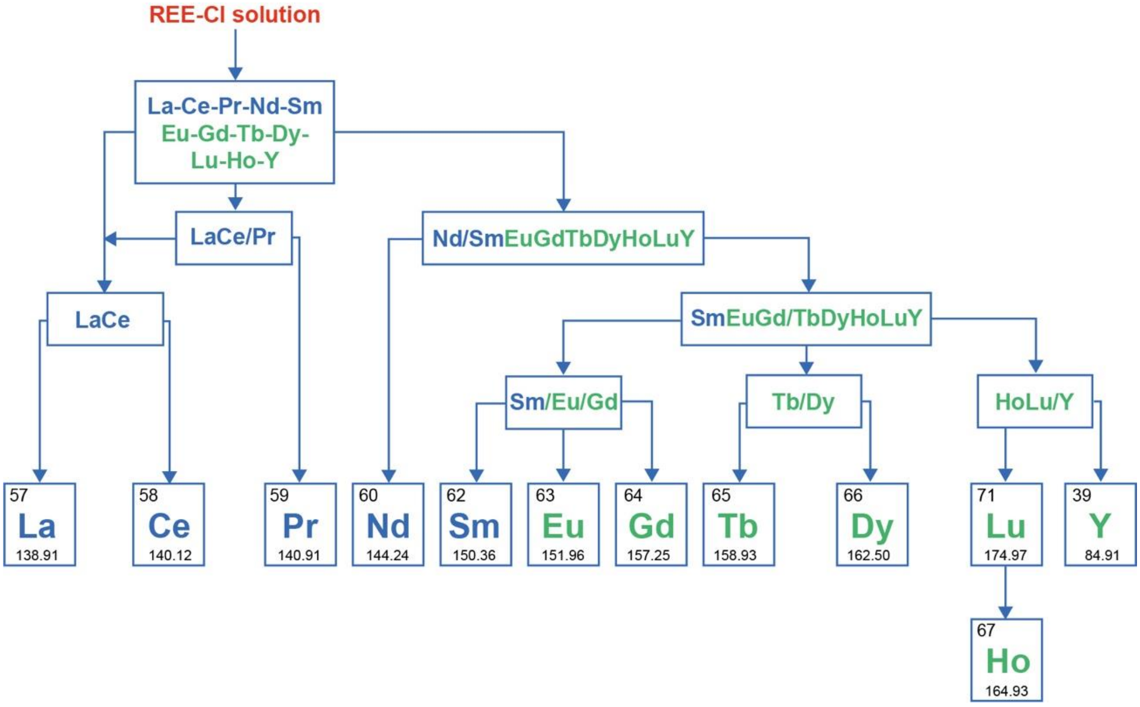


Figure 5-7 *Principles of sequential separation of rare earth elements using the SX separation process. Source: Machacek & Kalvig (2017).*

Molecular Recognition Technology (MRT)

The Molecular Recognition Technology method was developed around the year 2000 by commercial companies in the United States, and there is very little detailed information about the method's principles and operation. Allegedly, the method is based on selective transport of meta-ions as a function of being bound to metal-selective ligands in a silica gel called SuperLig®. Ligands, cation and system parameters can be adapted to all rare earth elements (Izatt et al. 2016). The method has been tested by Ucore Rare Metals and IBC Advanced Technologies Inc. on REE solutions from the ore from the Bokan-Dotson Ridge deposit in Alaska, USA. It is reported that the separation of the individual rare earth elements was > 99 % (Ucore 2015). The method is also promoted as being environmentally friendly and cheaper than the other methods (Izatt et al. 2016).

Ligand-Assisted Displacement (LAD) chromatography

Medallion Resources Ltd. informed the public in February 2021 about a licensing agreement with Purdue University, Indiana, USA, on the use of a new method for separating rare earth elements from the mineral monazite (referred to as Ligand Assisted Displacement (LAD) ion exchange technology). The method is stated to be environmentally friendly and scalable in relation to needs. According to Ding et al. (2020), the method allows the separation of neodymium, praseodymium, and dysprosium to a high purity (> 99 %) and almost without process loss (< 1 %), both when the method is applied to minerals and to recycled magnets. The method has a production capacity of over 100 kg REE/m^3/day, which is approx. 100 times faster than conventional methods. Medallion Resources Ltd. plans to separate extracts of monazite using the company's monazite process' (Medallion Resources 2021).

Based on an annual treatment of 7,000 tonnes of monazite, Medallion Resources has calculated that 870 tonnes/year of Nd-Pr oxide can be produced using their unspecified monazite process.

The model calculations include a cost level equivalent to that of the South-Eastern United States and to the purchase of monazite concentrate in the United States. The production price for 1 kg of mixed REO product with reduced cerium content is estimated at 12 USD/kg, while the production price for NdPr oxide (Ce-‘depleted ’) is estimated at 28 USD/kg; the prices are pure production costs, where the purchase of the monazite is not included.

Penn State method

Penn State University, Pennsylvania, USA, and Lawrence Livermore National Laboratory, California, USA, have developed a separation method based on isolating a particular protein from bacteria. The method is stated to be extremely effective at binding the rare earth elements without affecting other metals. During subsequent acid treatment, keeping pH > 3, the rare earth elements can be released *en bloc*. In the long term, the method can also be used for separation, so that the rare earth elements can be separated individually with a step-by-step adjustment of the pH. The method is thought to have potential for the treatment of tailings (*e.g.* phosphorus-containing tailings from gypsum from fertiliser production) and for the treatment of certain types of scrap for the purpose of recycling the rare earth elements (McCormick 2021).

EURARE separation method

The EU-funded project on rare earth elements, EURARE, developed a separation method that could eventually become an alternative to the MRT method. This separation method is based on the bonding of selected ligands to magnetic silica nanoparticles. When these nanoparticles are added to the liquid with rare earth elements, the selected REE ions are selectively adsorbed by the particles. Subsequently, the magnetic nanoparticles, ‘charged’ with the selected rare earth elements, can be separated magnetically. The principle of this method is shown in Figure 5-8. The method is expected to be able to reduce both investment and operating costs by establishing new separation plants (Larsson & Binnemans 2015).

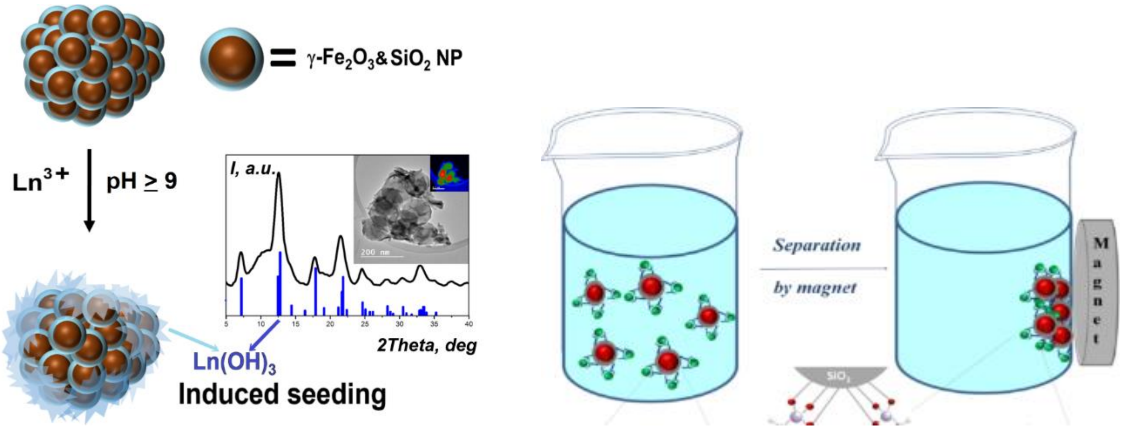


Figure 5-8 *The principles of the EURARE separation method. Source: Machacek & Kalvig (2017).*

Bioleaching

In bioleaching, metals are released from their ore using living microorganisms. The method is becoming increasingly common as it is cheap, meaning that production from low-grade ores can be profitable. Attempts are being made to develop the method for the extraction of rare earth elements from sediments (IA deposits) and from ore and scrap (Jalali & Lebeau 2021). The bioleaching method, which has a lower energy and CO_2 footprint than any of the alternative methods, also has the long-term potential that specific methods can be developed for direct extraction of the rare earth elements that are in demand and leaving the rest behind.

5.3 Refining and alloys

The rare earth element products that have emerged after the separation – often REE salts – must be processed further for a metal to be produced. Two different technologies are applied: the metallothermic reduction method, and the molten-salt electrolytic reduction method; for some REEs only one method is used, because of issues such as vapor pressure values etc. Both technologies are assessed as technically complicated and energy-intensive and is carried out only by companies with expertise in these specific process steps (Royen & Fortkamp 2016).

6. Recycling and Substitution

6.1 Recycling

For all products, the most effective method for reusing elements is recycling, as it reduces energy and raw material consumption and reduces the environmental footprint. This also applies to products that contain rare earth elements. If, for example, magnets can be reused with the existing specifications and size, it will reduce both the primary raw material consumption and the energy consumption. However, recycling is rarely an option as technology and design are constantly evolving. The next best thing, from an energy and resource point of view, is recycling, where the raw material from end-of-life products is used for new products of the same kind or for the production of completely different products.

However, there are also a number of challenges with recycling, which cause very low rates of recycling (< 1 % of the rare earth elements are recycled (Lixandru et al. 2017)). As a part of increasing resource awareness in society, and the desire to reduce the industry's environmental, resource and energy footprint, many projects with the goal of finding methods to increase the recycling of rare earth elements have been initiated over the past decade. In addition, a number of projects also aim to improve security of the supply of rare earth elements to the European industry, which is being challenged by China's de facto monopoly on the value chains.

Some products, such as the large NdFeB magnets in wind turbines, are obvious candidates for recycling as they contain large amounts of rare earth elements (especially neodymium, praseodymium, terbium and dysprosium), and because the collection of the turbines' magnets at the end of their service life can be systematised. From a global resource point of view, it is an advantage that products have long lifespan before they are phased out and have to be replaced by products made with new raw materials. However, this means that the raw materials that make up the product cannot be recycled during that lifespan. For wind turbines, the service life is 20-30 years, and the turbines' content of rare earth elements can only be recycled afterwards. The lifespan of permanent magnets in electric vehicles is about half that. Long service life is therefore a challenge when it comes to recycling magnets, as this is one way to reduce the supply difficulties for rare earth elements. Another challenge is that technology changes during the lifetime of the products and thus also the material composition of the products. It is uncertain whether phased-out products will contain the metals that we need in 10-20-30 years. Recycling discarded magnets from wind turbines, vehicles, electronics, etc. will not necessarily match the material consumption of future products. An additional challenge for recycling is that the consumption of raw materials is constantly growing, and the part that is available for recycling constitutes only a small proportion of the need; and in fact the proportion is even smaller due to losses associated with the recycling process.

Permanent magnets are not only used for the engine in an electric vehicle, but also for many other functions in both electric and conventional vehicles. Quantity, shape, size, strength, and chemical composition vary from model to model, which is a challenge for recycling. No infrastructure and value chains have been developed for secondary REE products, and therefore collection and treatment is unsystematic and unstructured. Generally, magnets in vehicles are not dismantled before scrapping; the vehicles are mechanically split (using a shredder) into cm-sized metal pieces, which are then sorted. In these sorted scrap piles, the content of rare earth elements can’t be calculated with large recycling losses as a result. Automated methods for dismantling magnets from larger units such as vehicles, air conditioners etc., are currently under development (Mitsubishi Electric 2017).

Establishing efficient recycling of rare earth elements from consumer electronics is a challenge due to the large quantity of devices and low content (often < 1g/unit) found in various parts of the products. For smartphones, rare earth elements are embedded in the batteries (where it is NiMH), as phosphorescence in the screens and as alloys in certain components. The recycling aspects are not not considered in the industrial design, which makes it difficult to recycle the REE-embedded components from the others. This problem is further complicated by the fact that components from different manufacturers do not have the same composition.

During recycling, the methods used must be able to produce a product that is competitive in both price and quality with primary REE products, and preferably where material losses during the process are small, which unfortunately is rarely the case. The recycling processes are generally very energy intensive. The energy usage depends on the method and in some cases, it may be less energy intensive to extract rare earth elements from minerals than by recycling.

Recycling can potentially reduce the supply risk of, for example, the rare earth elements used in permanent magnets (praseodymium, neodymium, terbium, dysprosium) and phosphorescence (europium, yttrium, erbium, terbium). Therefore, focus has been on recycling the wasteflow that occur during production, and on discarded products such as batteries, lamps, electronic waste (WEEE), catalysts and permanent magnets (Figure 6-1). Examples of industrial processes for recycling rare earth elements from magnets and consumer electronics are shown in Figure 6-2 and Figure 6-3.

Mitsubishi Electric (2017) has developed an automatic method, Resonance Damping Demagnetisation, for separating REE magnets from products quickly. The method detaches the magnet directly from the product, at the same time creating a better opportunity to group magnets with the same alloy.

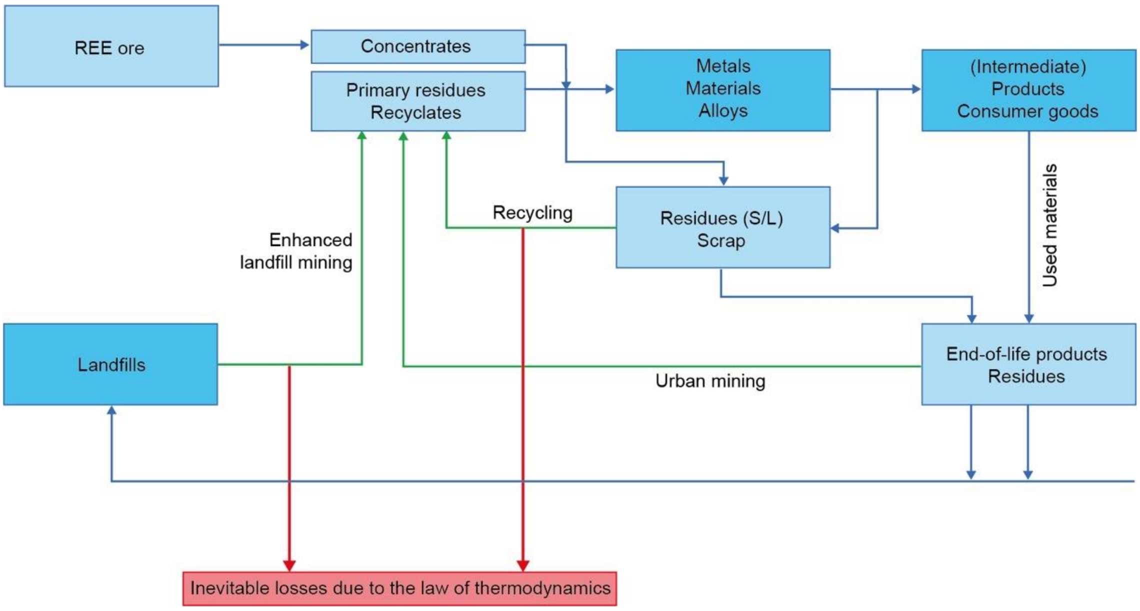


Figure 6-1 *Generic diagram for recycling of products containing rare earth elements, indicating waste streams that are lost. Source: Binnemans* et al. *(2013).*

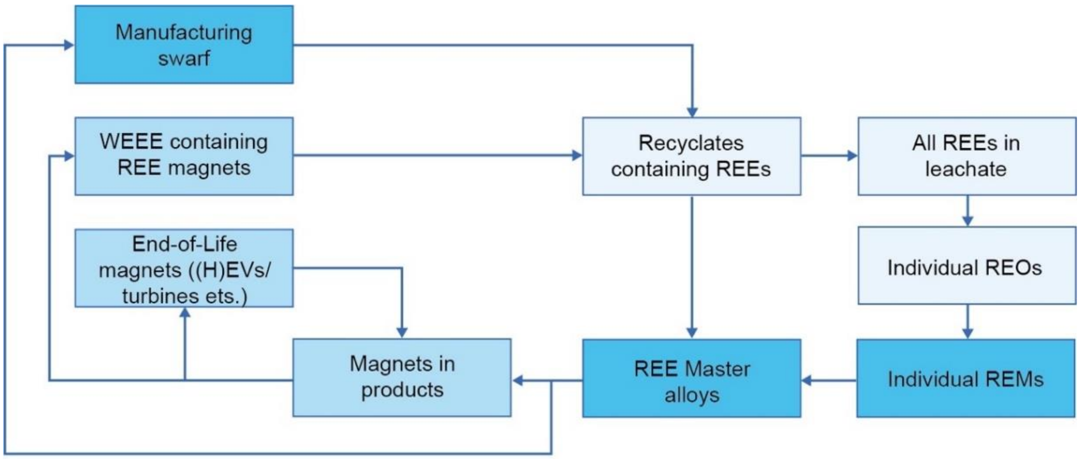


Figure 6-2 *Generic diagram for recycling permanent magnets with rare earth elements. Source: Binnemans* et al. *(2013).*

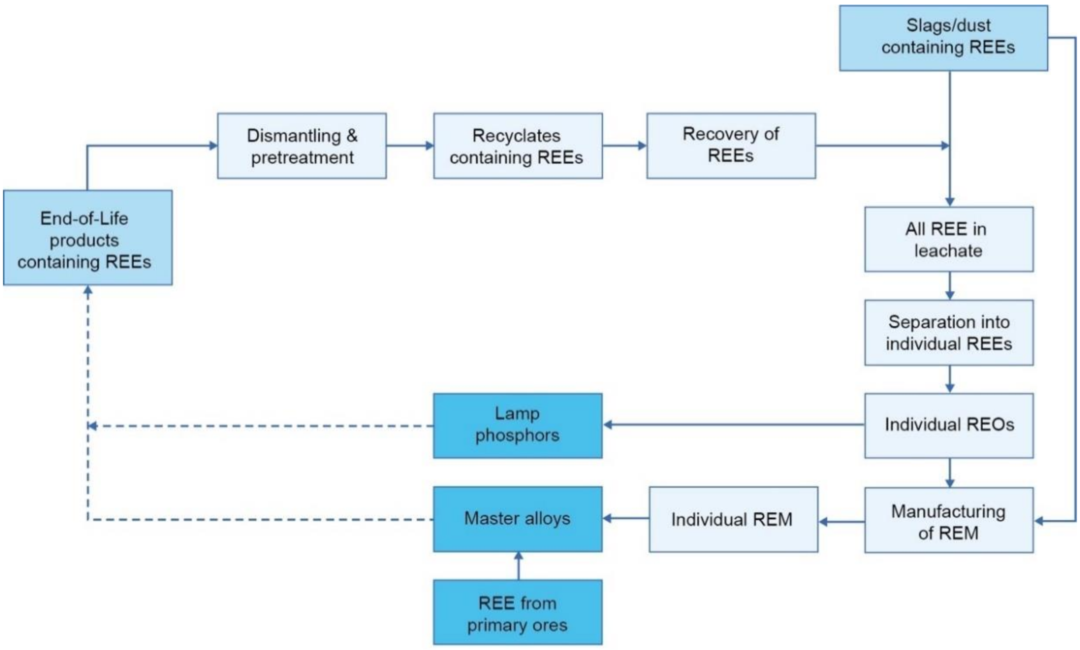


Figure 6-3 *Generic diagram for recycling of rare earth elements from WEEE products. Source: Based on Binnemans* et al. *(2013).*

Efforts are being made to develop methods for recycling the relatively large amounts of La- and Ce-polishes used in the glass industry. For example, Borra et al. (2021) developed a method based on electrolysis in which mixed La and Ce oxide can be used for Al-La-Ce alloys without prior separation of lanthanum and cerium. The principles of the method are shown in Figure 6-4.

For phosphorescence (typically europium, terbium, yttrium, gadolinium, lanthanum, and cerium) used in lighting and computer and smartphone screens, some manufacturers have established a recycling facility, where the company recycles phosphorescence from its own products so they can be recycled into their future products. There are also recycling companies that extract rare earth elements from phosphorescence and manufacture new products based on recycling. Take, for example, Solvay, which operates in 64 countries around the world and has developed, patented, and built a factory for recycling rare earth elements from fluorescent lamps, where recycling rates can reach as high as approx. 95 %.

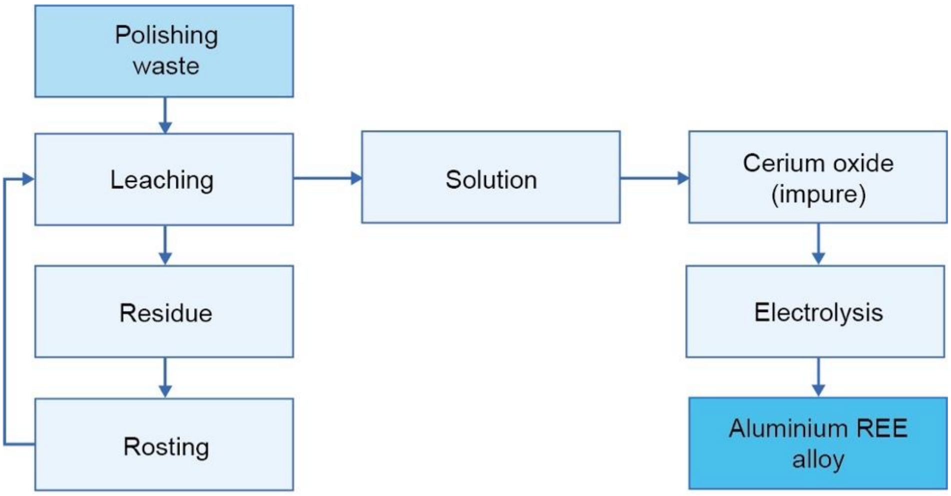


Figure 6-4 *Generic diagram for recycling rare earth elements from polishing powder used in the glass industry. Source: Borra* et al. *(2021).*

Figure 6-5 shows that the contribution of rare earth elements, which are included in recycling, was already increasing sharply in the period 2000-2012, and the largest amounts in the entire period came from electric motors; however, it also appears that changes occur over time with increasing contributions from electric bicycles and wind turbines in particular, but that there are also more challenges (Binnemans et al. 2021). These trends have intensified in the period since 2012; similarly, the quantities available have also grown. There is a growing industrial interest in the development of methods for recycling rare earth element products; some of these measures are shown in Table 6-1 and Table 6-2.

Table 6-1 *Estimated volumes of rare earth elements divided into the most important rare earth elements from the recycling of magnets, phosphorescence and NiMH batteries. The table should only be construed as an example of principle. Source: Binnemans* et al. *(2013).*

Application of REE	Recycled REE in 2020 (tonne) Different scenarios		Sector distribution	Pessimistic/ Optimistic
	Pessimistic	Optimistic	%	tonne (rounded to the nearest 100)
Magnets	3,300	6,600	Nd: 69 Pr: 23 Dy: 5 Gd: 2	2,300-4,500 800-1,500 200-300 100
Phosphorescent for lamps and computer and smartphone screens	1,333	2,333	Y: 69 Ce: 11 La: 9 Eu: 5 Td: 5 Gd: 2	900-1,600 100-300 100-200 100 100 -
NiMH batteries	1,000	1,750	La: 50 Ce: 33 Nd: 10	500-900 300-600 100-200
Total	**5,633**	**10,683**		

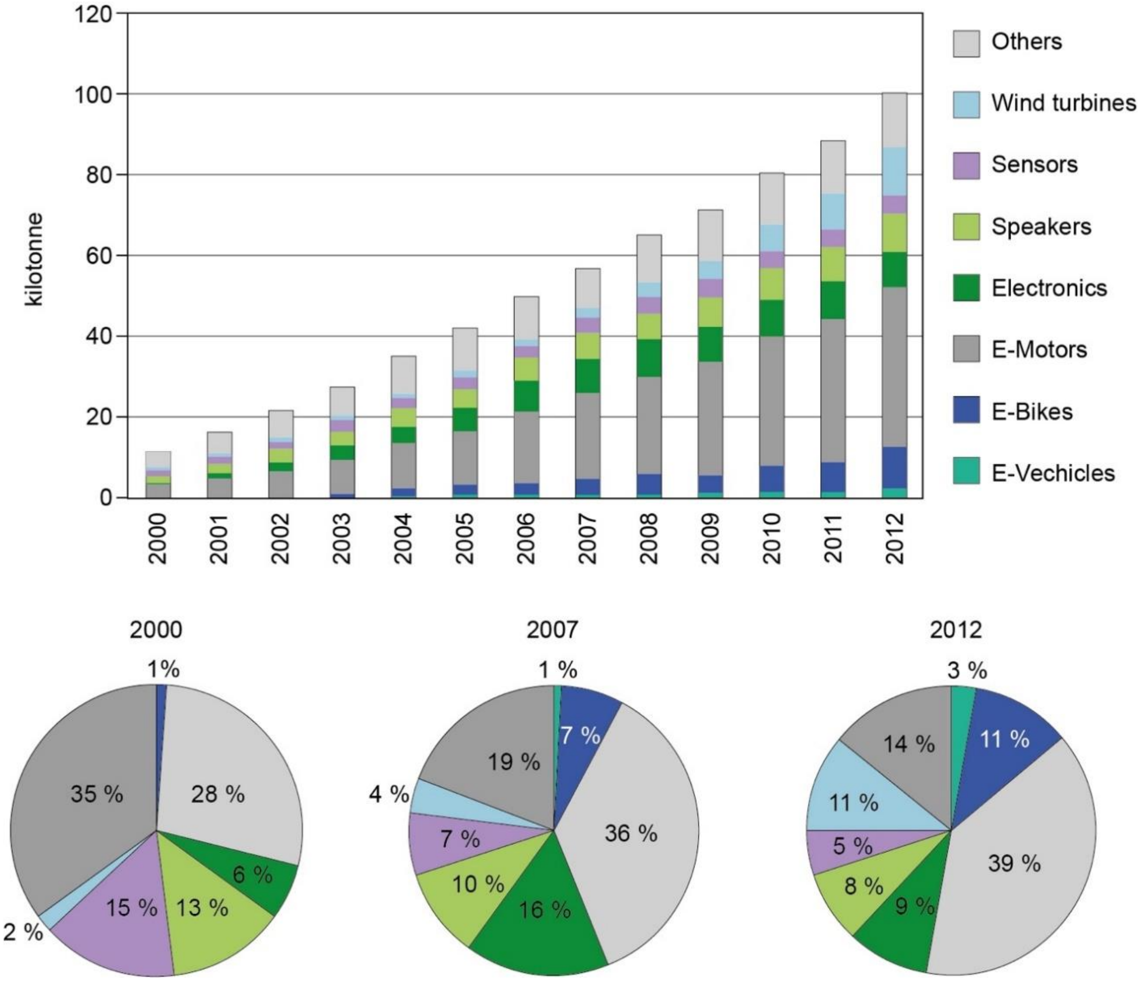


Figure 6-5 *Historical development of the sectors involved in recycling. Source: Gauss (2016).*

To increase the recycling of rare earth elements, several recycling companies have developed, or are in the process of developing, sorting methods that can produce material flows with a high content of rare earth elements, including WEEE. Figure 6-6 shows an example from Stena Technoworld's Swedish plant.

Binnemans et al. (2013) have estimated the recycling potential of permanent NdFeB magnets, phosphorescence, and NiMH batteries. Each of these sectors is dominated by 3-5 different rare earth elements. Using the average consumption in the three sectors, the potential for the individual rare earth elements is estimated (Table 6-1). No data has been found for the actual amounts of recycled rare earth elements from 2020. It should be noted that in addition to the material loss in the recycling processes, the losses due to products containing REE not being collected or not economically viable to recycle must also be included.

Mitsubishi Electrics (2017) estimated in 2017 that the recycling rate up to 2025 will increase to approx. 7 % and 11 % for neodymium and dysprosium in magnets respectively, half of which will be from electric vehicles (Figure 6-7). With the expected increase in magnet production, this ratio is likely to decline. Other analysts are more optimistic, such as The Rare Earth Observer (2021e), which expects that up to 30 % of PrNd oxide consumption in 2025 will be based on recycling.

Table 6-2 *Status of existing technologies/methods for recycling rare earth elements from End-of-Life products. Sources: Tsamis & Coyne (2015) and Binnemans* et al. *(2013).*

Secondary REE raw material source	Technology/method	Technology – development step	Expected relative contribution
Phosphorescent Y (69 %), Ce (11 %), La (9 %), Eu (5 %), Tb (5 %), Gd (2 %)			
Compact Fluorescent Lamp (CFL) Eb, Tb, Y	Chemical resolution, solvent extraction	Developed for industrial use (Rhodia)	Growing
Light Emitting Diode (LED) Ce, Y			Growing
Plasma screens Eu, Tb, Y, (Ce, Gd, La)			Stable
Cathode Ray Tube (CRT) Eu, Y	Chemical resolution and solvent extraction	Limited research and declining interest	Low
Permanent NdFeB-magnets Nd (69 %), Pr (23 %), Dy (5 %), Gd (2 %), Tb (0.2 %)	Hydrometallurgy	Still in lab-scale phase	Stable for small magnets in vehicles, mobile phones, laptops. Growing for electric bicycles, electric vehicles, and wind turbines
	’Rapid solidification’	Developed by Fraunhofer 2015. Powder can be used to manufacture new magnets.	
	Pyrometallurgy	Developed – but not for REE	
	Gas-phase extraction	Lab-scale	
	Reprocessing of alloys for magnets after **reduction of hydrogen**	Lab-scale	
	Biometallurgical methods	Lab-scale	
Permanent SmCo-magnets Sm			Stable
NiMH batteries La (50 %), Ce (33 %), Nd (10 %), Pr (3 %), Sm (3 %)	Combination of extremely high melting point and hydrometallurgy/pyrometallurgy	Very effective method for separating Nd, Pr, Dy. Full-scale (Umicore and Rhodia)	Growing
Optical glass (La)	Hydrometallurgical process	Lab-scale	
Glass polish (Ce)	Chemical process	Lab-scale	

With the increasing global consumption of rare earth elements, recycling will be insufficient to meet demand. However, increased recycling carries the potential to reduce the balance problem (see section 9.4.1), where the high demand for Nd and Dy means that there is actually an overproduction of Ce and La.

Reduction of material losses presupposes that industries develop common standards for products containing REE materials, and that the development of the industrial designs takes place with a focus on improved recycling opportunities.

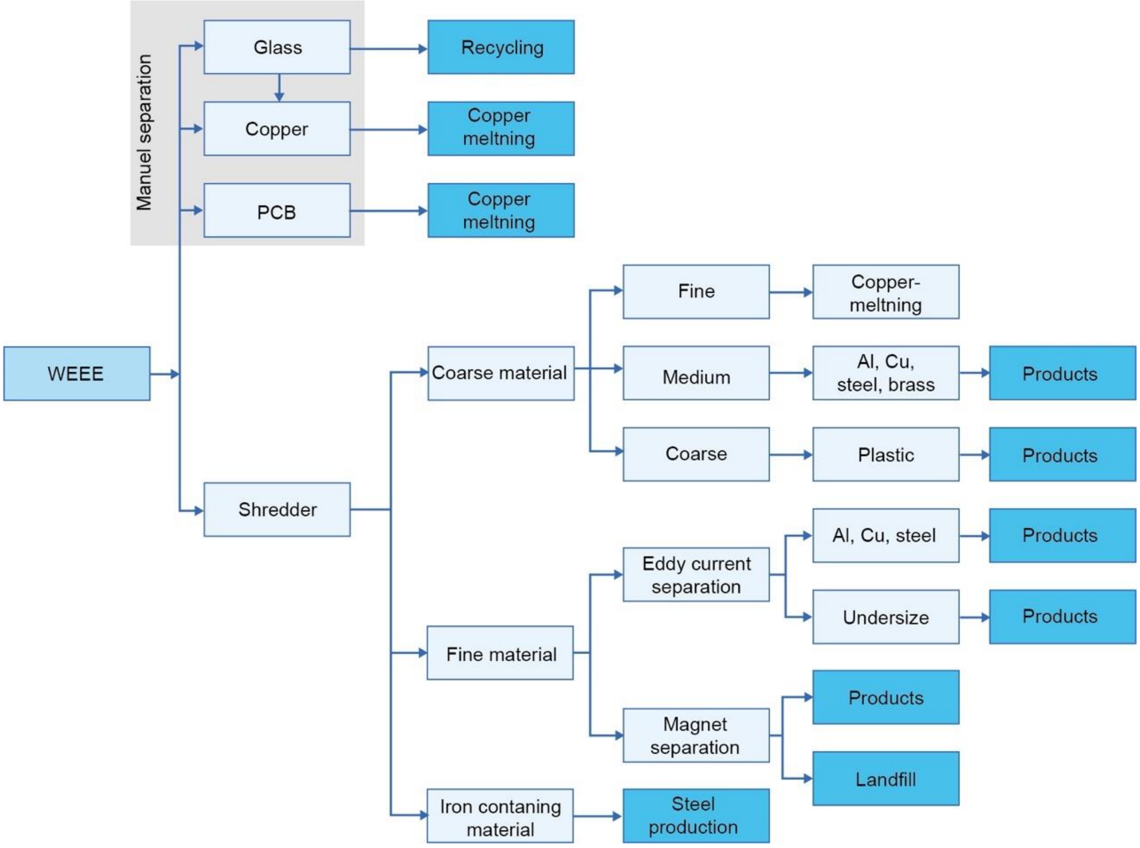


Figure 6-6 *Diagram of sorting fractions for WEEE products on Stena Technoworld's recycling plant for WEEE products. Source: Lixandru* et al. *(2017).*

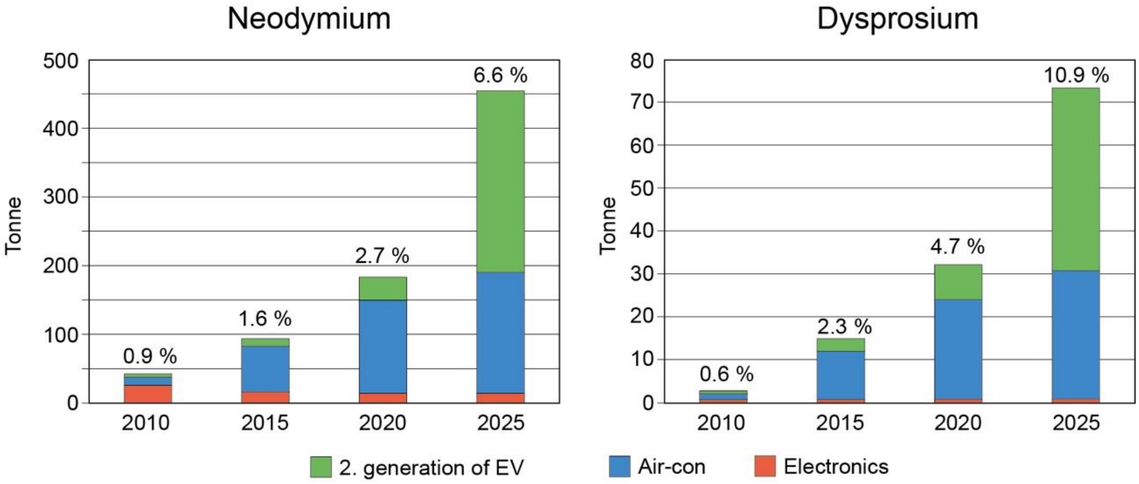


Figure 6-7 *Mitsubishi Electrics (2017) assessments of the main material flows that may be involved in the recycling of neodymium and dysprosium.*

6.2 Substitution

Substitution indicates here that a manufacturer replaces a given raw material with another; most often to reduce costs or to replace a raw material with another that has greater supply security. In most cases, this cannot simply be done by replacing one ingredient with another, but requires more radical design or production changes.

In some cases, technological changes lead to new products being preferred and making other products obsolete, which can affect the demand for new raw materials. This was the case, for example, with the rapid spread of Li ion batteries, which are mainly used for electric vehicles, electric bicycles, and hand-held tools, and they began to replace NiMH batteries, which has created a large and urgent demand for lithium, cobalt, manganese and graphite, and a reduced demand for lanthanum, cerium and neodymium. Correspondingly significant changes in the market for rare earth elements have occurred with the introduction of LED technology, which results in a significantly lower consumption of phosphorescence with declining demand for yttrium and europium. The implementation of the green transition in the transport sector and wind energy creates a large market for NdFeB magnets and a very high demand for praseodymium, neodymium, terbium, and dysprosium in particular. For the sake of both security of supply and price, work is being done to substitute neodymium with cerium; such a substitution could have far-reaching consequences for the markets for many of the rare earth elements (see Chapter 14). Changes in magnet technology, which has affected the consumption of rare earth elements, also occurred with the phasing out of disk drives (HHD) in favour of solid-state drives (SSD) that do not use rare earth elements, which led to a marked reduction in the consumption of the four magnetic metals neodymium, praseodymium, terbium, and dysprosium, however, there was an increased consumption of these metals in manufacturing magnets. These changes in consumption not only affect demand but can also affect recycling rates. The phasing out of HHD, where recycling of the four magnetic metals could previously take place after 5-10 years of service life, and the 'transfer' of the consumption of the raw materials to the transport and wind energy sectors with service lives of 10-15 years and 20-30 years respectively, means that there is a longer waiting period before the raw materials can be recycled.

7. Environment, Health, and Climate Impact in the Upper Parts of the Value Chains

The multitude of steps involved in the production of raw materials from rare earth elements consume significant energy and water and entails a sizeable CO_2 footprint. As a significant proportion of the rare earth elements are used for green technologies. It is therefore important to consider the total extent of these environmental footprints, which is in part determined by the ore's quality and mineralogy, how the mining is undertaken and how the ore is treated, as well as by the steps involved in the production of the final raw materials. As shown by Pell et al. (2019a, b), life cycle analyses (LCA), carried out in connection with feasibility studies for mining projects, can help to identify areas where it will be both appropriate and technically possible to make changes in mining and processing of the ore to reduce the production's environmental impact.

This chapter reviews some of the challenges associated with the environment and health conditions as well as climate impact.

7.1 Environmental and health conditions

Many of the environmental and health conditions associated with the production of raw materials with rare earth elements are similar those of the mining industry in general. Additionally, when it comes to the production of rare earth elements, there may be special challenges as some minerals contain thorium and uranium, making them radioactive. When mines are constructed, environmental risk assessments (ERA) are prepared, which include workflows, processes, emissions, potential pollution and impacts on people and the environment, as well as radiation risks. A general concept model for environmental risk assessments is shown in Figure 7-1. Detailed information on environmental conditions can be found in EPA (2012).

As with the mining of solid rock ore, the majority of the environmental challenges concerning ore containing rare earth elements are mainly related to ensuring that landfill, inferior ore and tailings are deposited in an environmentally sound manner, that dust and noise pollution are below set limits, and that effluent water from the mining area is treated before being discharged and that the discharge complies with set limit values.

For example, significant amounts of water and chemicals are used to separate the minerals that contain REE from the ones that do not. The environmental challenges due to mineral separation are predominantly related to the treatment of process water and the disposal of the large amounts (often > 90 % of the total volume) of finely crushed material (tailings) that do not contain rare earth elements. Tailings are a mixture of fine-grained, non-commercial minerals suspended in process water, which are typically deposited in basins near the separation plant. Since tailings usually have to remain deposited for many years, and in large quantities if the plant is large, such material must be safely deposited in the basin, ensuring that process water and inflowing rainwater do not pollute the environment. These conditions have given rise to major environmental problems for mines in general. For example, there have been several significant environmental problems associated with the production of rare earth elements in Brazil, China, India, Malaysia, and the USA (Kemakta Konsult 2014).

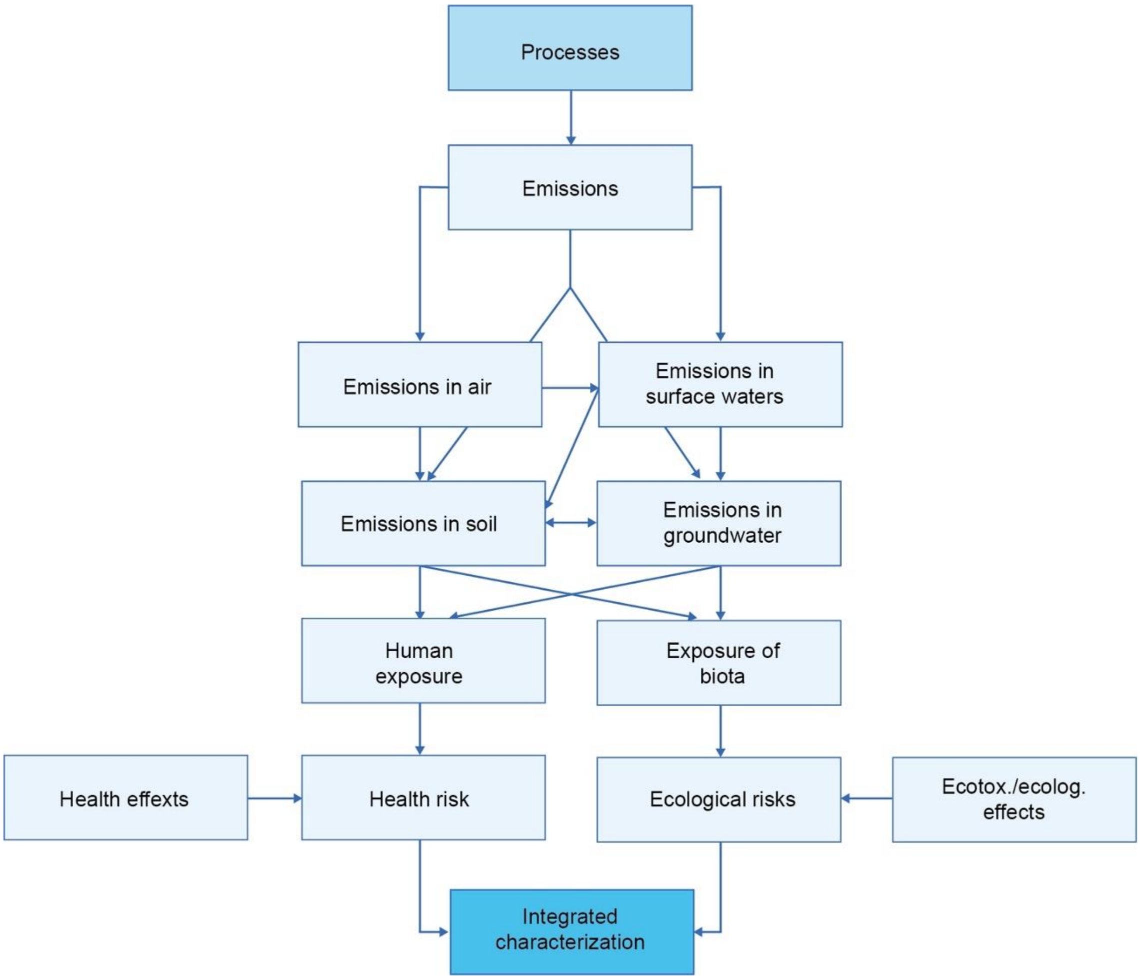


Figure 7-1 *Generic model for environmental risk assessments (ERA analyses) used to assess new mining projects. Source: Kemakta Konsult (2014).*

When rare earth elements are produced from IA deposits, environmental challenges are primarily linked to the liquids used at the site to release the rare earth element ions. In China, where IA deposits are particularly prevalent, the in-situ method is the most widely used (see section 5.1.3). Here, ammonium sulphate solutions (3-5 %) are pumped into the near-surface deposits, or the clay is dug up and mixed with the solution in excavated basins. If these methods are used, there is a great risk that the liquids will contaminate the groundwater (Yang et al. 2013). As a result of these environmental problems, the Chinese authorities have shut down many IA productions over the past 10 years (Adamas Intelligence 2014).

As mentioned above, environmental challenges to produce rare earth elements differ from most other mines and processing plants in that many REE minerals contain naturally occurring uranium and thorium, often referred to as NORM (Naturally Occurring Radioactive Materials). The process steps in which minerals containing rare earth elements are separated from the other minerals will inevitably mean that a smaller proportion of the minerals with rare earth elements and uranium and thorium are not separated and therefore end up as tailings. However, the majority of the radioactive elements – uranium, thorium and some of the decay products such as protactinium and actinium – are released (dissolved) from the minerals in the process step where the rare earth elements are released from the minerals (see also Figure 5-4). This residual material is radioactive and will typically be deposited in a pool of chemical residues near the processing plant. In some cases, this process step is carried out near the mine, in other cases the mineral concentrate is sold, and the extraction is carried out elsewhere. It is typically the location of the plant that determines at which authority-approved location the radioactive chemical residues can be deposited. For example, the plans for the two Greenlandic projects, Kvanefjeld/Kuannersuit and Kringlerne//Killavaat Alannguat are different; the Kvanefjeld project plans to carry out the process locally and deposit the chemical residues locally, whereas the project at Kringlerne plans to ship the mineral concentrate to a production site outside of Greenland, which is why the chemical residues must also be deposited outside of Greenland.

The risk constituted by radioactive elements depends on, amongst other things, the mineral composition, the concentrations, the oxidation conditions and the chemical composition. The biggest challenges with radioactive residues are related to deposits with a high content of xenotime and monazite, where there may be up to 2 % uranium and 1 % thorium (Table 7-1). By comparison, the ore from Kvanefjeld/Kuannersuit contains about 0.03 % uranium and 0.07 % thorium, which is mainly found in the mineral steenstrupin; the ore from Kringlerne, which is dominated by the mineral eudialyte, contains only approx. 0.0012 % uranium, which is consistent with eudialyte's generally low content of uranium and thorium. Alkaline deposits, which are dominated by the minerals parisite, synchisite, fergusonite and loparite, also generally have low uranium and thorium deposits, while IA deposits are characterised by containing only insignificant amounts of uranium and thorium.

Table 7-1 *Advantages and disadvantages of different methods of separating uranium and thorium from rare earth elements. Source: Garcia* et al. *(2020).*

Method	Advantages	Limitations	Recovery (%)
Leaching	Th and U are removed simultaneously from REE Cheap process Easily scalable process	The ore/concentrate must be very fine-grained The method only works on solids	Th: > 68 % U: 65-95 %
Precipitation	Th and U are removed simultaneously from REE Th and U can be separated Cheap process	Recovery highly dependent on pH, temperature and reagents REE can precipitate with U and Th at the wrong pH Difficult to perform in one process step without reducing recovery	Th: > 98 % U: 65-95 %
Solvent extraction	Very selective towards U and Th High recovery for U and Th in the single process steps Easily scalable process	Low recovery of Th and U if they are separated together Several process steps are needed to achieve high recovery Expensive reagents	Th: > 70 % U: > 55 %
Ion chromatography	Th and uranium can be removed in one process step High recovery of both Th and U	Low flow rate When scaled up, the process will either become batches or columns Anion exchangers only extract uranium	Th: > 90-99 % U > 90-99 %

In general, during the separation process of the individual rare earth elements, there may be a concentration of the radioactive substances, which can be found in many of the parts of the value chains.

When comparing the NORM load of different deposits, it must be ensured that the calculations are made on the basis of the values of the individual rare earth elements, as two deposits with the same NORM value may have different NORM loads if there are differences in the mineral composition. If, for example, two deposits contain 1 % and 2 % neodymium respectively, the NORM load is twice as large for the first occurrence measured in relation to the amount of neodymium produced.

There are several examples of insufficient regulatory control over the production of rare earth elements leading to major environmental damage. This applies to, for example:

- Asia Rare Earth and Mitsubishi Electric's chemical plant in Bukit Merah, Malaysia, which in the period from 1979 to 1994 produced rare earth elements from monazite. Here, more than 10.000 residents in the area contracted fatal diseases that could be linked to the radioactive residual material. The protracted course of the incicent must be attributed primarily to weak local environmental and raw material authorities (Consumers Association Penang 2011).
- In the areas around the town of Krasnoufimsk in the Sverdlovsk region of Russia, large amounts of radioactive monazite-remains have been deposited since the 1970s; work to minimise environmental damage is still ongoing (Buynovskiy et al. 2014; Idolova 2019).
- In the Ganxhou region of Southern China, environmental impact to humans, soil and groundwater have been found as a result of the exploitation of an IA deposit. Chinese authorities estimate that it will take 50-100 years to remedy the damage (Standard 2019).
- After the military junta took power in Myanmar in 2021, illegal productions of IA deposits near Pangwa and Chipwi increased significantly with major environmental damage as a result (The Irrawaddy 2021). A few months later, production stoppedbut in December 2021, it was reported that production and exports will resume.

Examples of typical processing of mineral concentrates, where rare earth elements, uranium and thorium are precipitated, are shown in Figure 7-2, Figure 7-3, and Figure 7-4.

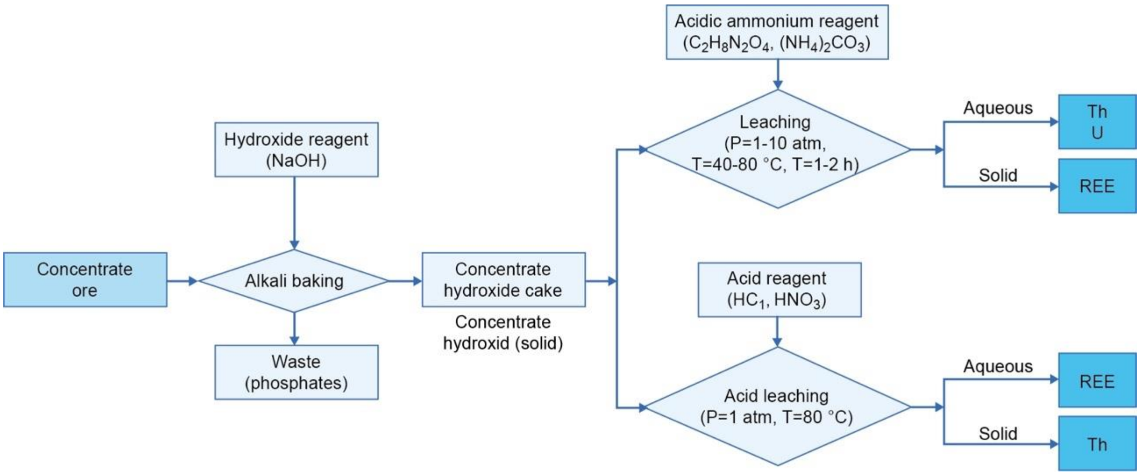


Figure 7-2 *Example of the processing of REE mineral concentrate with precipitation of uranium and thorium. Source: Garcia* et al. *(2020).*

The different technologies have different advantages and disadvantages, and there are big differences in how effective the methods are. As shown in Table 7-1, the efficiency varies greatly (55-99 %). For low efficiency processes, the process must be repeated in a significant number of sequences to ensure that the radioactive substances are collected in one section that can be handled properly.

The environmental problem associated with the radioactive material were the reason why the USA decided in 2002 to stop the production of rare earth elements from monazite in particular, after which production moved to China, thus laying the groundwork for China's dominant role in the rare earth element industries (see Chapter 11). In Australia, uranium mining must be approved by the federal government, and Lynas Corporation, which owns the Mt. Weld mine, has not been allowed to process its products from the mine due to the content of uranium and thorium, which has resulted in minerals mined from the Mt. Weld mine being processed at Lynas' plant in Malaysia (where discussions on environmental issues are ongoing between Lynas and the Malaysian authorities) (see section 13.1.2).

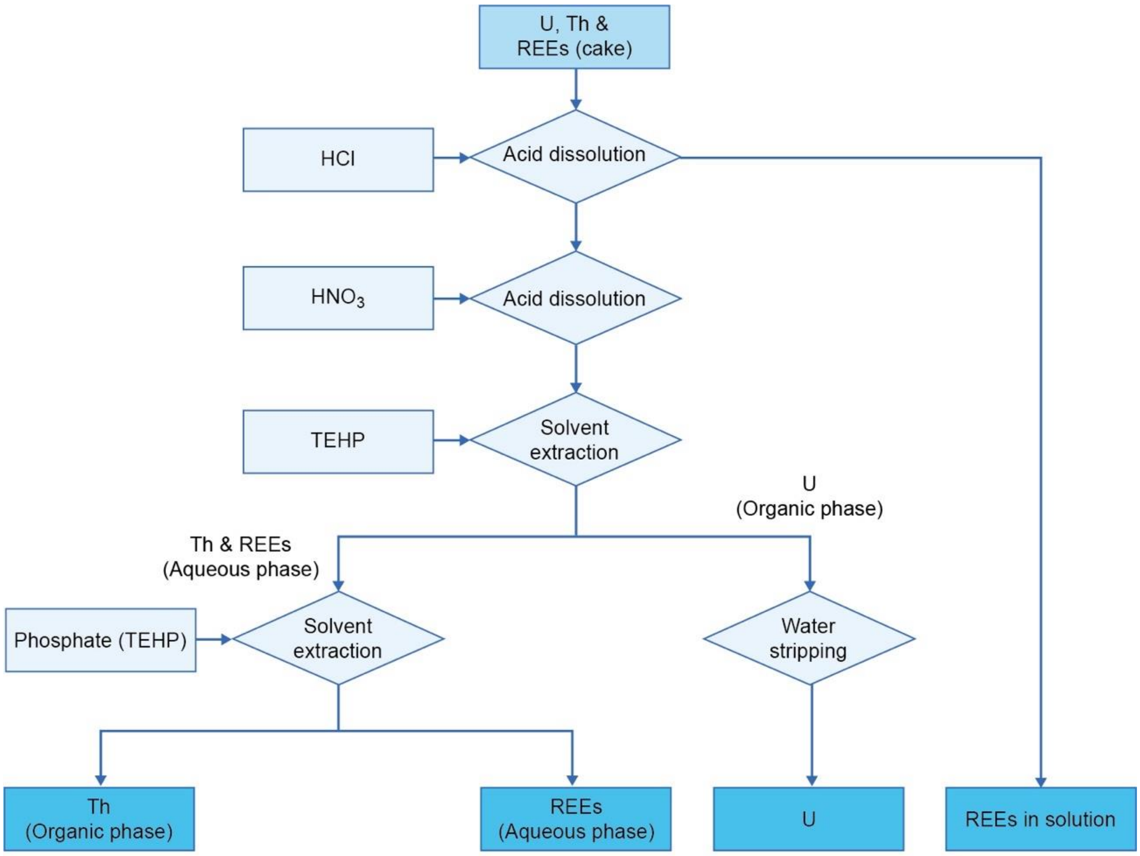


Figure 7-3 *Example of the processing of REE concentrate with precipitation of uranium and thorium during chemical 'opening' of the mineral and subsequent separation. Source: Garcia* et al. *(2020).*

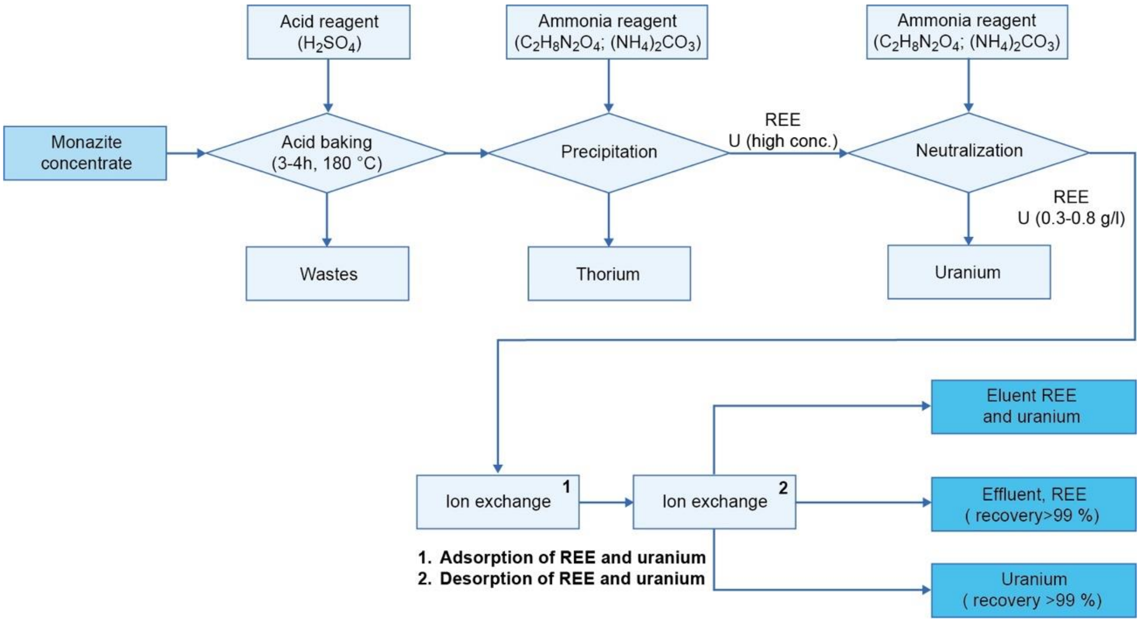


Figure 7-4 *Example of the processing of monazite with precipitation of uranium and thorium. Source: Garcia* et al. *(2020).*

7.2 REE production's climate footprint

Climate footprints from the primary production of rare earth elements are determined by both the composition and quality of the ore. From when mine construction begins until the mine closes, the quality of the mined ore will often decline, and both the environmental and climate footprint will typically be higher the older the mine is (Pell *et al*. 2019b). Pell *et al*. (2019b) have compared a number of climate footprint parameters between the Bear Lodge project (USA), the Mountain Pass mine (USA), the Bayan Obo mine (China) and IA deposits (China) (Table 7-2). The main data in the study is from 2014 and 2015 and improvements may have been made subsequently.

Table 7-2 *Comparison of environmental indicators between four different deposits of rare earth elements. Source: Pell* et al. *(2019b).*

Environmental indicator	**Unit**	**Bear Lodge**	**Mountain Pass**	**Bayan Obo**	**IA deposits (China)**
Acidification	kg SO_2 eq.	6.00E-02	1.70E-01	3.08E+00	1.70E-01
Ecotoxicity	CTU e	1.45E+00	n/A	3.76E+01	2.79E+0,2
Eutrophication	kg N eq.	1.30E-02	1.50E-01	1.80E-01	3.00E-01
Global warming	kg CO_2 eq.	1.21E+01	1.40E+01	2.30E+01	2.09E+01
Health	kg PM2,5 eq.	1.60E-02	n/A	1.70E-01	2.59E-02
Carcinogen effect	CTU h	1.30E-08	1.30E-08	2.27E-06	3.00E-02
Non-carcinogen	CTU h	1.20E-06	1.20E-06	7.70E-06	1.04E-05
Ozone depletion	kg CFC 11 eq.	2.40E-09	2.30E-09	3.80E-06	2.40E-09

Haque *et al*. (2014) have estimated a number of environmental footprints for the production of selected rare earth elements (Table 7-3). In general, the estimated energy consumption is relatively low, which is attributed to the fact that consumption is only included until the production of REO, which is one of the first semi-finished products, and that the energy consumption for the production of, for example, REM is not included. At the same time, Haque *et al*. (2014) states that water consumption is significantly higher than for other metals.

Table 7-3 *Environmental footprints for the production of selected rare earth elements. Source: Haque* et al. *(2014).*

REO	Energy MJ/kg	GHG* kg CO_{2e}/kg REO	Water Litre water/kg	Toxicity DALY**/kg x 10^6
La	177	9.3	300	1.65
Ce	157	8.3	300	1.46
Pr	798	41.4	1,320	7.36
Nd	743	38.5	1,230	6.86
Mix of Sm+Eu+Gd	1,074	55.6	1,750	9.89

* GHG – Greenhouse gas
** DALY – Disability-Adjusted Life Years

The total global CO_2 load due to the extraction of rare earth elements is shown in Table 7-4 and is based on the average composition of production in 2019 (European Commission 2020) and a production of 240,000 tonnes, roughly equivalent to 2020. As can be seen from Table 7-4 and Figure 7-5, the environmental footprint is generally smaller for LREE than HREE, which is consistent with the fact that it is more difficult to separate HREE than LREE (see section 5.2.1). Haque *et al*. (2014) also calculated the amount of greenhouse gas (GHG) that is formed in the individual process steps and found that a significant part of the GHG footprint is related to the consumption of hydrochloric acid. They therefore point out that if the GHG factor is to be reduced, the focus should be on both acid and energy consumption.

Jiabao & Jie (2009) have calculated that to produce 1 tonne of TREO at the plant in Bayan Obo, also produced is approx. 60,000 m^3 of gas containing sulphur and hydrochloric acid, approx. 200 m^3 of water containing acid and 1.4 tonnes of radioactive material, when all processes from mining, processing and refining are included.

Table 7-4 *Estimates of the CO_2 load for selected rare earth elements based on distribution data for 2019 (European Commission 2020, Table 176), as well as an estimated global production of 240,000 tonnes REO and load figures from Haque* et al. *(2014).*

	La	Ce	Pr	Nd	Sm/Eu/Gd
%	24.5	44.3	4.7	15.8	4.0
Tonne REO	58,800	106,320	11,280	37,920	9,600
Tonne CO_2/tonne REO	10	9	44	39	58
Tonne CO_2 total	588,000	956,880	496,320	1,478,880	556,800

From a climate perspective, it can therefore be concluded that where possible, the strategy should aim to substitute relatively heavier rare earth elements with relatively lighter rare earth elements. The process sequence of the separation processes and the natural distributions of the individual rare earth elements favour this. In some cases, substitution may be, for example, the replacement of Pr and Nd with Ce, where the environmental footprint will still be smaller as long as the additional consumption of the relatively lighter rare earth element < 400 % compared to the relatively heavier rare earth elements. These substitutions are important, since the green transition will lead to a markedly increased consumption of Pr and Nd (see Chapter 14).

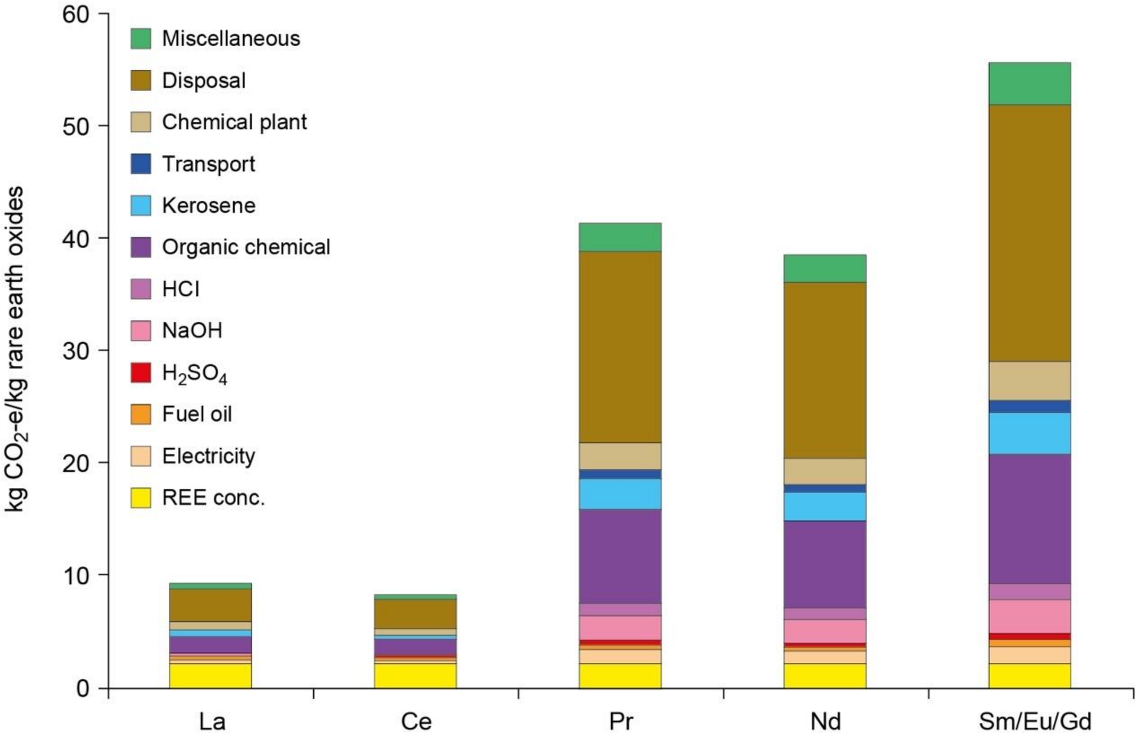


Figure 7-5 *CO_2 emissions for the production of selected rare earth elements. Source: Haque* et al. *(2014).*

8. Global Production of Rare Earth Elements

This chapter assesses the annual, global production of rare earth elements extracted from the primary producers - the mines. It is these quantities that determine how much can be delivered to the downstream parts of the value chains. There are no national inventories of how much the industries use, and the global annual consumption is considered equal to the volume of the outputs of the mines.

The annual production of rare earth elements measured as tonnes of TREO from mines is registered on a national basis by e.g. United States Geological Survey (USGS). Figure 8-1 shows the results from the USGS (2001 to 2021) statements for the period from 2000 to 2020, from which it appears that the total production in the period has increased approx. 200 %, and that the growth primarily occurred in the period 2017-2020.

These registrations are only approximate, as there are many small contributions from a large number of producers of heavy sand products with a by-product of monazite, which is not included, and because, especially in China, there is significant unregistered illegal production, despite China having worked purposefully to reduce illegal productions in the country. In addition, national reports are also affected by political conditions, both positively and negatively; for example, Chinese production reportedly declined for a number of years after the political crisis between China and Japan in 2010 (see section 4.3.2), but has been rising again since 2017 (Figure 8-1).

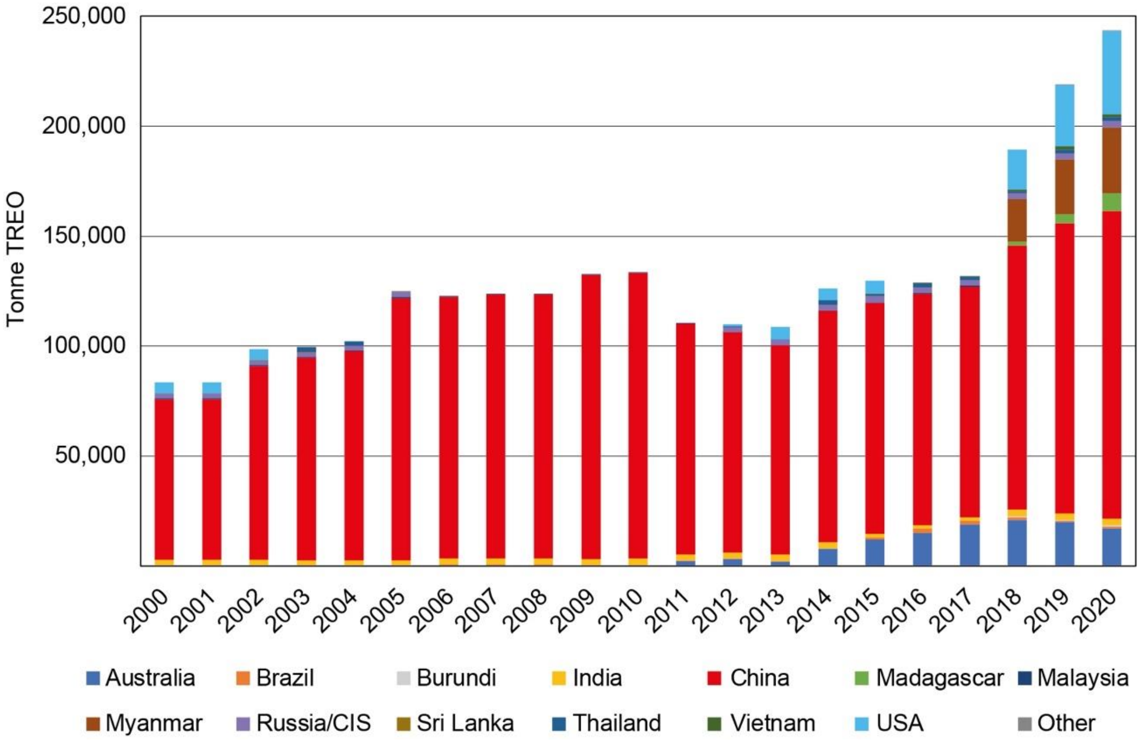


Figure 8-1 *Developments in the global production of minerals containing rare earth elements (converted to tonnes of TREO) by country. Source: USGS (2001 till 2021).*

Table 8-1 *Comparison between annual records of global production of TREO in tonnes/year made by USGS (2016 to 2020) and World Mining Data (WMD) respectively (Reichl & Schatz 2021).*

	2015		2016		2017		2018		2019	
	USGS	**WMD**	**USGS**	**WMD**	**USGS**	**WMD**	**USGS**	**WMD**	**USGS**	**WMD**
	tonne/year TREO	**tonne/year TREO**	**tonne/year TREO**	**tonne/year TREO**	**tonne/year TREO**	**tonne/year TREO**	**tonne/year TREO**	**tonne/year TREO**	**tonne/year TREO**	**tonne/year TREO**
Australia	12,000	10,916	15,000	13,872	19,000	17,264	21,000	18,556	20,000	17,613
Brazil	880	1,040	2,200	2,900	1,700	1,700	1,100	1,100	710	600
Burundi						31	630	631	200	68
India	1,500	956	1,500	2,265	1,500	2,724	2,900	4,215	2,900	4,200
China	105,000	105,000	105,000	105,000	105,000	105,000	120,000	120,000	132,000	132,000
Madagascar							2,000		4,000	
Malaysia	500	565	300	1,876	300	302		86		114
Myanmar		230		2,730		5,000	19,000	20,400	25,000	17,100
Russia	2,800	2,312	2,800	3,063	2,600	2,500	2,700	2,596	2,700	2,620
Thailand	760		1.600		1,300		1,000		1,900	
Vietnam	250		220		200		920		1,300	
USA	5,900	3,678					18,000	14,000	28,000	28,000
Others									66	
Total	**129,790**	**124,697**	**128,620**	**131,706**	**131,600**	**134,521**	**189,250**	**181,584**	**218,776**	**202,315**

During this period, China has clearly been the largest producer of rare earth elements and the only country that has produced throughout the period with a varying production share of around 90 % until 2013, since when other countries have begun production, which has meant that China's share in 2020 amounted to approx. 60 % of global production. U.S. production is predominantly from the Mountain Pass mine in California, which has been closed for some time. MP Materials reopened the Mountain Pass mine in 2017 with the Chinese company Shenghe Resources as a minority shareholder. Production was increase and in 2020 amounted to approx. 40,000 tonnes. During President Trump's tenure in 2017, the US government authorised the export of mineral concentrates from Mountain Pass to China, which continues to be part of the Chinese supply chains. Production in Australia (approximately 17,000 tonnes of TREO) is based on Lynas Corporation's Mt. Weld mine in Western Australia, from which the mineral concentrate is exported for processing at the company's plant in Malaysia. Reportedly, Russia has a fairly small but constant production of 2,000-2,700 tonnes of TREO, which are predominantly by-products of the Lovozero mines, which are processed in Kazakhstan and Estonia. Since 2018, a large annual production (approximately 30,000 tonnes of TREO) has been established in Myanmar, which has so far been exported for processing in China, but in the autumn of 2021, Myanmar's military junta have stopped nearly all exports to China; in total, around 24,000 tonnes of TREO were exported from January to October 2021 (The Rare Earth Observer 2021e), which is a significant reduction from 2020. Small, although growing volumes stems from heavy mineral sand deposits in Madagascar (8,000 tonnes of TREO) and India (3,000 tonnes of TREO).

There are significant discrepancies between the various institutions' inventories regarding the global production of rare earth elements. For example, for the five-year period 2015-2019, there are major differences between the USGS and World Mining Data (WMD) (Table 8-1). WMD, unlike the USGS, has not registered production of rare earth elements in Madagascar, Thailand, and Vietnam, but instead registered production in Myanmar already by 2015; sbustantial discrepancies also occur between, for example, production in Myanmar (USGS data) and exports to China, which, cf. The Rare Earth Observer (2021c), is larger than the production USGS indicates. Overall, it can be stated that the databases for the global production of rare earth elements are inaccurate in regard to the quantities produced in individual countries. The deviations are significant to a degree which may have an impact on the results in Table 8-2 and scenario calculations in Chapter 14.

China's reduced share of global production in recent years does not mean that China has a less crucial role as a world leader in rare earth element supply chains. Although the primary production outside China is growing, only minerals from Australia and Russia are processed at plants outside China, and China has a decisive influence on the other productions outside China. The challenges of establishing alternative value chains to the Chinese are described in Chapter 13.

Increased production in recent years reflects the global shift to fossil-free energy sources and electrification, for which neodymium, praseodymium, terbium, and dysprosium are in particular demand. This has led to a particularly high level of interest in the deposits that best meet these needs, such as deposits with e.g. monazite.

There is no published data on how large tonnages of the individual rare earth elements constitute the primary productions. As this information is important for assessing supply and demand, these compositions are estimated on the basis of a combination of the USGS' (2021) global production data for 2020 (Table 8-2) and the author's knowledge of the mineralogical compositions of the main mines. However, for Myanmar, the Tantalus deposit data has been used as a proxy for the ion adsorption deposit. For China, the estimates are based on the published production quotas for 2020, which were allocated to 'The Big Six' (see section 12.1).

The estimates for the distribution of the rare earth elements produced in individual countries are shown in Table 8-2 and are only indicative, which is why quantities below 100 tonnes/year are not included; also, more countries produce heavy rare earth elements than are shown in the table. Despite the above stipulations, the estimates clearly indicate that China and Myanmar dominate the production of the important magnetic metals praseodymium, neodymium, terbium, and dysprosium.

8.1 China’s production of rare earth elements

The distribution of China's rare earth element production in 2020 is estimated on the basis of the quota allocations to the consortia in The Big Six (see section 12.11 and Appendix V) and compositions of the rare earth elements in the provinces involved (Table 8-3). The sum of the estimates differs from the quota distribution; the estimates are approx. 5 % higher and 31 % lower for light and heavy rare earth elements respectively; it is unclear to what extent actual production differs from quotas and estimates.

Table 8-2 *Estimates for the global distribution of REOs in 2020. Sources: USGS (2021), Appendix III and Appendix IV; method explained in the text. Light blue: LREE, dark blue: HREE.*

	La_2O_3	Ce_2O_3	Pr_2O_3	Nd_2O_3	Sm_2O_3	Eu_2O_3	Gd_2O_3	Tb_2O_3	Dy_2O_3	Ho_2O_3	Er_2O_3	Tm_2O_3	Yb_2O_3	Lu_2O_3	Y_2O_3	Total
	tonne	tonne	tonne	tonne	tonne	tonne	tonne	tonne	tonne	tonne	Tonne	tonne	tonne	tonne	tonne	Tonne
Australia	4,000	8,000	1,000	3,000	400	100	200	-	-	-	-	-	-	-	100	**16,800**
Brazil	-	-	-	-		-	-	-	-	-	-	-	-	-	-	**-**
Burundi	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	**-**
India	1,000	1,000		1,000	100	-	-	-	-	-	-	-	-	-	-	**3,100**
China	38,000	60,000	6,000	24,000	2,600	400	1,600	300	1.000	100	500	-	100	-	6,400	**141,000**
Madagascar	2.000	4,000	-	1,400	200	-	200	-	-	-	-	-	-	-	100	**7,500**
Myanmar	2,000	-	6,000	10,000	-	2,100	600	1,500	4,800	-	300	300	300	-	2,100	**30,000**
Russia	1,000	1,000	-	-		-	-	-	-	-	-	-	-	-	100	**2,100**
Thailand	1,000	1,000	-	-		-	-	-	-	-	-	-	-	-	-	**2,000**
USA	13,000	19,000	2,000	4,000	300		100	-	-	-	-	-	-	-	-	**38,400**
Vietnam	-	1,000	-	-	-	-	-	-	-	-	-	-	-	-	-	**1,000**
Total	**62,000**	**95,000**	**15,000**	**43,000**	**3,600**	**2,600**	**2,700**	**1,800**	**5,800**	**100**	**800**	**300**	**400**	**-**	**8,800**	**241,900**

Table 8-3 *Estimates for the distribution of REO in China in 2020. Based on quota allocations to The Big Six. Light blue: LREE, dark blue: HREE.*

The Big Six	Quota	La_2O_3	Ce_2O_3	Pr_2O_3	Nd_2O_3	Sm_2O_3	Eu_2O_3	Gd_2O_3	Tb_2O_3	Dy_2O_3	Ho_2O_3	Er_2O_3	Tm_2O_3	Yb_2O_3	Lu_2O_3	Y_2O_3	TLREO	THREO
	tonne	tonne	tonne	tonne	tonne	tonne	tonne	tonne	tonne	tonne	tonne	tonne	tonne	tonne	tonne	tonne	tonne	tonne
China Northern Rare Earth	**73,700**	19,000	37,000	3,000	13,000	1,100	100	300	100	100	-	-	-	-	-	-	7,.000	1,700
China Southern Rare Earth	**32,800**	10,000	16,000	1,000	5,000	400	100	200	-	100	-	-	-	-	-	-	32,000	800
	9,000	3,000	-	1,000	2,000	400	100	400	100	300	-	200	-	-	-	1,500	6,000	3,000
China Xiyou Rare Earth (Chinalco)	**14,300**	4,000	7,000	1,000	2,000	200	-	100	-	-	-	-	-	-	-	-	14,000	300
	2,800	1,000	-	-	1,000	100	-	100	-	100	-	-	-	-	-	500	2,000	800
Xiamen Tungsten	**2,900**	-	-	-	-	100	-	200	-	200	100	200	-	100	-	2,000	-	2,900
Guangdon Rare Earth	**2,800**	1,000	-	-	1,000	100	-	100	-	100	-	-	-	-	-	500	2,000	800
Minmetal Rare Earth	**1,400**	-	-	-	-	100	-	100	-	100	-	100	-	-	-	1,000	-	1,400
Total	**139,700**	**38,000**	**60,000**	**6,000**	**24,000**	**2,500**	**300**	**1,500**	**200**	**1,000**	**100**	**500**	**-**	**100**	**-**	**5,500**	**128,000**	**11,700**

9. The Importance of Geology for the Supplies of Rare Earth Elements

Rare earth elements are found in many different rocks and geological environments, but the average content of most rocks is far below what is economically profitable to mine. Therefore, extraction can only take place where geological processes have concentrated the rare earth elements. This has resulted in rare earth elements being found in a variety of different minerals and geological deposit types that either already contribute, or could potentially contribute, to the global production and supply of these raw materials.

Deposits of rare earth elements are divided into different geological types, each of which has its own characteristics in terms of the distribution of the rare earth elements, resource sizes and values. The deposits are divided into two main groups: (i) deposits which are formed in the depths of the Earth and that, in this context, include both igneous and hydrothermal deposits; and (ii) secondary deposits formed as residues from chemical and physical degradation of rocks and minerals on or near the Earth's surface, and where rare earth elements have subsequently been concentrated by natural processes. Geologists use slightly different type divisions; in this report a subdivision is used in which the rare earth elements have been concentrated in eight different ways (Table 9-1).

Table 9-1 *Geological typology of rare earth elements.*

REE main group	Subgroup of REE deposits related to the following geological environments
Magmatic	Alkaline magmatic intrusions
	Carbonatite intrusions
	Granite and pegmatite intrusions
	Hydrothermal (vein and skarn)
	Iron ore deposits of Iron-Oxide-Copper-Gold (IOCG) or Iron Oxide-Apatite type
Secondary	Heavy sand deposits (alluvial; coastal/coastal adjacent; fossil heavy sand deposits
	Laterite/bauxite related deposits
	Weathering deposits (IA deposits)

Appendix I of this report includes an overview of 1,040 known deposits of rare earth elements (Appendix I) in 86 countries (Figure 9-1). The overview is by no means exhaustive, but the great number of deposits listed demonstrates that the first part of the concept of 'rare' earth elements is misleading.

Classification of different types of deposits is of practical importance for mineral exploration, as each type indicates the composition of the rare earth elements that can be expected, the quality that can be found, the size of the deposits that can be expected, and whether there might be other elements that may become by-products of the production of rare earth elements - or, conversely, the rare earth elements may constitute by-products of the production of another mineral. It should be noted, however, that many of the deposits have often been affected by subsequent geological events, which may have both augmented or weakened some of the classical type characteristics. The classification system is, therefore, often a simplistic image, and many of the deposits are combinations of several types.

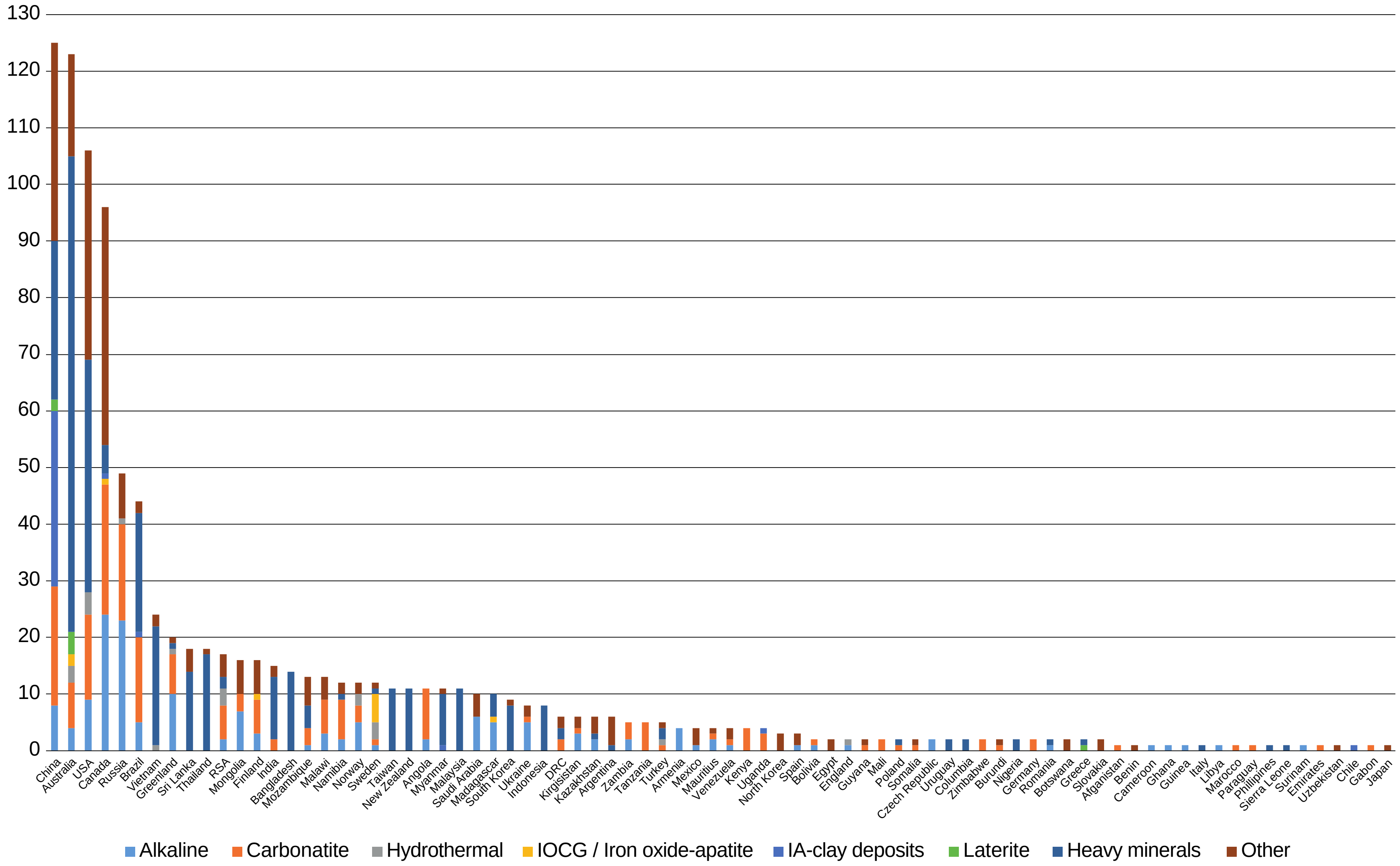
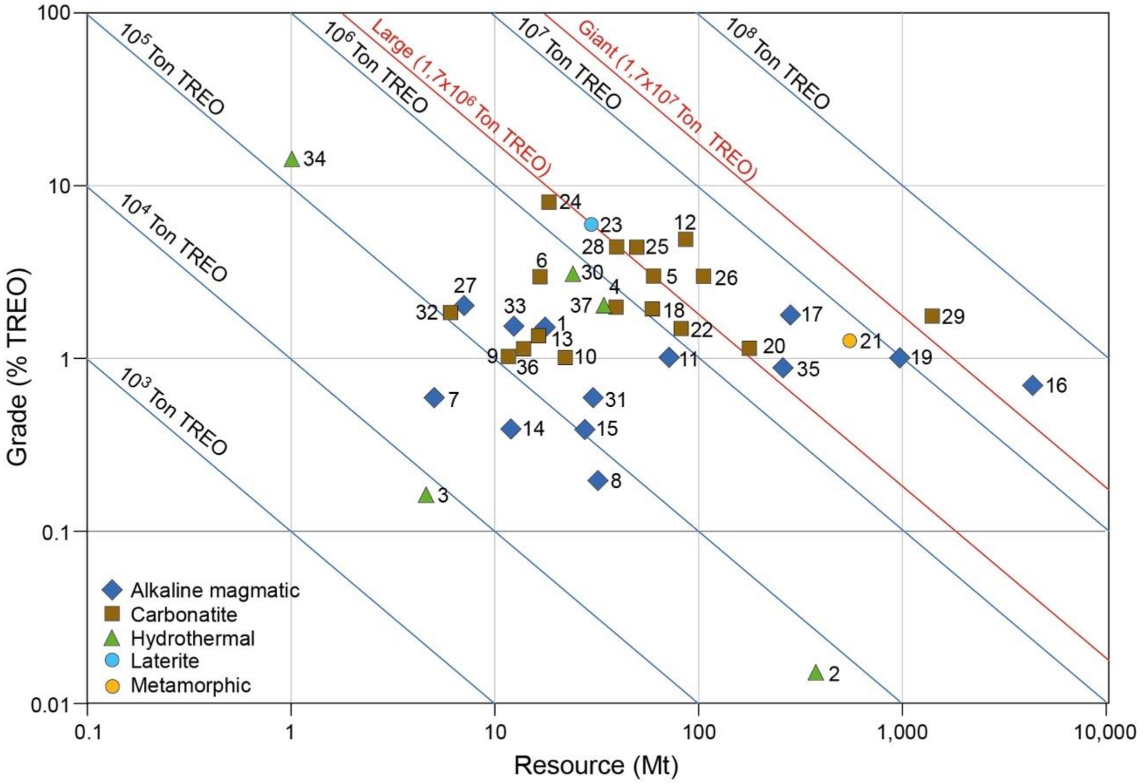


Figure 9-1 *Country-wise distribution of known deposits with rare earth elements distributed according to the geological types. An overview of the geological types used is shown in Table 9-1. Source: Appendix I.*

The greatest resources are typically associated with deposit types formed deep in the Earth, such as carbonatites and alkaline intrusions. This is illustrated in Figure 9-2, where selected resource data from Appendix IV is used. As can be seen, carbonatites often have slightly higher grades than alkaline deposits; the most prominent, however, are alkaline, which usually also have a slightly more favourable distribution of rare earth elements, i.e. a slightly higher proportion of the most in-demand rare earth elements.



1	Nechalacho Lower
2	La Pass
3	Browns Range
4	Araxa
5	Bayan Obo East
6	Bear Lodge
7	Boakan Mountain
8	Brockmans
9	Cummins Range
10	Daluhala
11	Dubbo
12	Fen
13	Glenover
14	Khibiny
15	Kipawa
16	Kringlerne
17	Kvanefjeld
18	Longonjo
19	Lovozero
20	Maniuping
21	Mau Xe
22	Montviel
23	Mount Weld (Duncan)
24	Mountain Pass
25	Mrima Hill
26	Mushgia Khudug
27	Nechalacho Upper
28	Ngualla
29	Niobec
30	Nolans Bore
31	Norra Kärr
32	Sarfartôq
33	Songwe Syenite
34	Steenkampskrall
35	Strange Lake
36	Yangibana North
37	Zankopsdrift

Figure 9-2 *Exploration projects by tonnage and quality (% TREO) with indication of geological type. Source: Appendix IV.*

The following is a summary of the characteristics of the groups. Detailed descriptions of rocks and REE minerals associated with the various subgroups can be found in Orris & Grauch (2002) and Verplanck et al. (2014) amongst others.

9.1 Primary deposits of rare earth elements

9.1.1 Alkaline magmatic deposits

Alkaline magmatic deposits are formed from alkaline rock melts, which penetrate from the Earth's mantle and through the crust (Figure 9-3 centre), typically when the Earth's stable continents break up. During intrusion, the melt is affected by lower pressures and temperatures higher up in the crust. At some point, the melt reaches areas with pressures and temperatures that induce some of the melt's elements to form minerals. The chemical composition of the residual melt changes constantly as minerals form, since the elements that enter minerals are no longer present in the residual melt. Due to large ion radius and charge, the rare earth elements do not fit into the ordinary rock-forming minerals and tend to remain in the melt only to be incorporated into minerals late in the crystallisation process. At this time, the melt's content of rare earth elements has become significantly concentrated relative to the initial level in the melt, and therefore these late crystallised minerals have a significantly higher content of rare earth elements than the mantle-derived melts. In alkaline deposits predominant minerals include bastnäsite, eudialyte, loparite, xenotime, monazite, and fergusonite.

Known alkaline deposits with rare earth elements include the Greenlandic deposits Kvanefjeld/Kuannersuit (steenstrupin), Kringlerne/Killavaat Alannguat (eudialyte) and Motzfeldt (pyrochlore), the Russian Lovozero (eudialyte, loparite and apatite), the Swedish Norra Kärr (eudialyte), the Canadian Strange Lake (bastnäsite, monazite, gadolinite) and Nechalacho (bastnäsite, monazite, allanite, fergusonite) and the South African complex Pilansberg (eudialyte, fergusonite, britholite). Alkaline rocks are often characterised by also having a relatively higher content of zircon, titanium, niobium, and tantalum as well as uranium and thorium, which can be by-product potential. In Appendix I, 152 deposits of the alkaline magmatic type have been recorded.

The alkaline deposits are often large resources with a typical content of 0.7-1.2 % TREO, of which LREE constitutes 60-80 % (Figure 9-2). Of the above-mentioned deposits, only the Lovozero deposit is in production, producing approx. 10,000 tonnes of REO per year, the majority of which is from the mineral loparite. There is exploration activity on the other deposits, however the activities on the Kvanefjeld project have been suspended because of the introduction of a zero tolerance ban on uranium production (2021), and the Norra Kärr project has also been temporarily shut down as a result of negative public discussions about the project.

9.1.2 Carbonatite deposits

Carbonatites are rocks that are dominated by carbonate minerals (> 50 %) and where the silica content is low (< 20 %). Carbonatites are often found in alkaline complexes, in geological rift zones and in areas where two continental plates have collided (Figure 9-3). Carbonatite deposits are found as plugs, intrusive breccias and in veins. Appendix I lists 200 carbonatite deposits, most of which are found in China, East Africa, Eastern Canada, California, the Kola Peninsula in Russia, Norway, and Sweden. Several carbonatite deposits are also found in Greenland, *e.g.* Sarfartoq, Qaqarssuk, Qassiarsuk, Niaqonakavssak and Tikiusaaq.

The most common REE minerals in the carbonatite deposits are monazite and bastnäsite as well as minor amounts of huanghoit, parisite and cebait. The carbonatite related REE deposits are characterised by being large, having a high content of rare earth elements (typically 1-9 % TREO), and being dominated by LREE. Most of the production of rare earth elements from this type of deposit comes from two major carbonatite deposits, Bayan Obo (bastnäsite, monazite) in China and Mountain Pass (bastnäsite, monazite) in the United States. However, Bayan Obo is geologically an iron deposit with rare earth elements and niobium as by-products (see section 9.1.4).

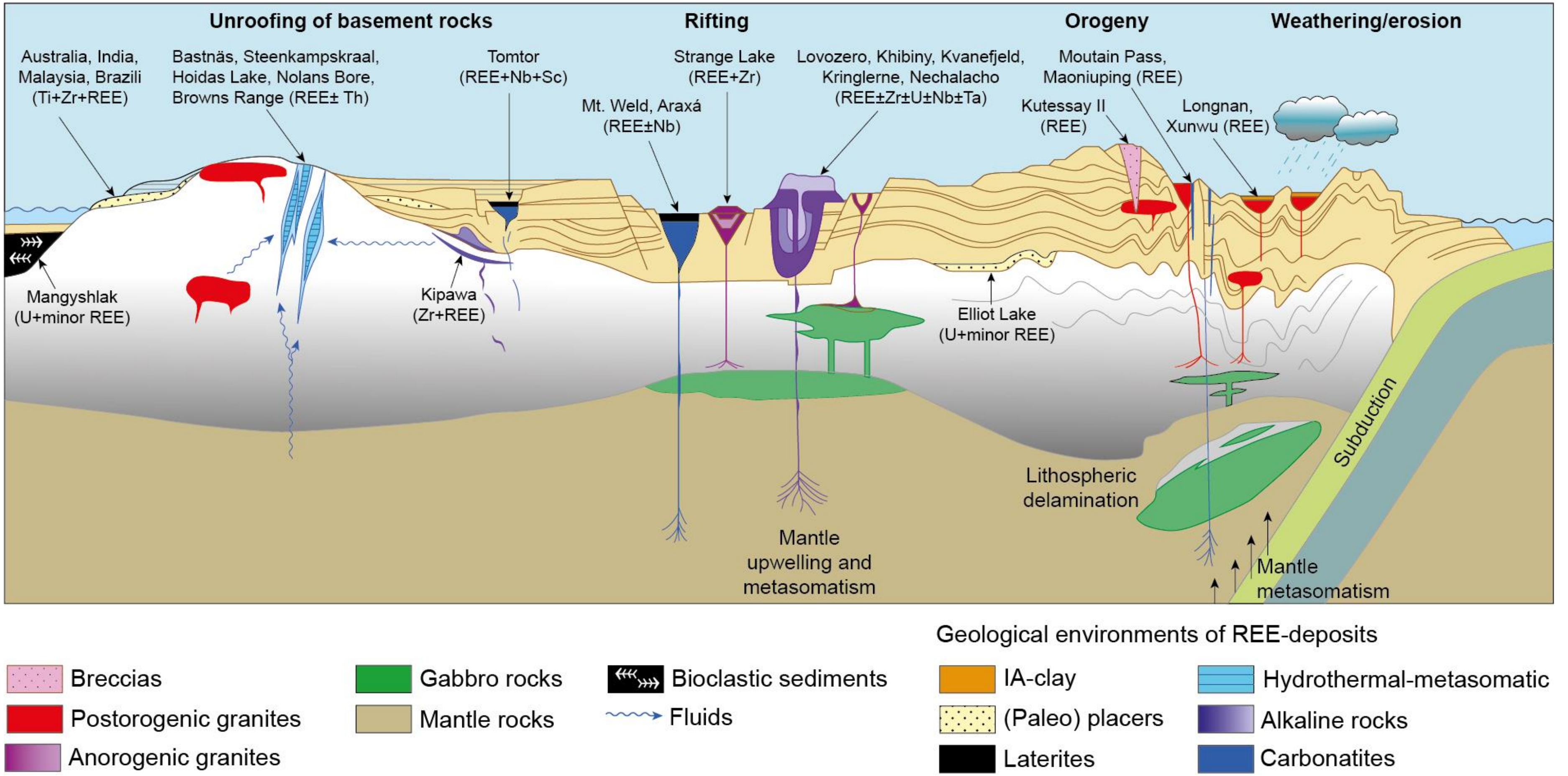


Figure 9-3 *Principle outline for the most important geological deposits with rare earth elements and their formation environments. Based on Chakhmouradian & Wall (2012), Goodenough* et al. *(2016), Liu (2016) and Elliott* et al. *(2017).*

9.1.3 Hydrothermal deposits (vein and skarn)

Hydrothermal deposits are formed where hot, aqueous solutions containing dissolved rare earth elements, penetrate other rocks and dissolve them, after which the rare earth elements precipitate as REE minerals upon cooling. This type of deposit may be associated with granites, carbonatites and alkaline intrusions. The group includes two historic Swedish deposits, Ytterby north of Stockholm and Bastäs at Riddarshyttan west of Stockholm, as well as Nolan's Bore (Australia) and Steenkampskraal (South Africa).

The hydrothermal deposits are generally small (< 1 million tonnes) but can have high values (up to about 4 % TREO), and by-products such as beryllium, niobium and fluorine are often available.

9.1.4 Iron Oxide-Copper-Gold (IOCG) and Iron Oxide-Apatite deposits

Iron-Oxide-Copper-Gold (IOCG) deposits are characterised by a high content of the iron minerals magnetite and hematite and generally also have a high content of barium, fluorine and phosphorus and may have a high content of rare earth elements. The Bayan Obo mine in China, the world's largest producer of rare earth elements, geologically belongs to this type. Large mines such as Olympic Dam, Australia, and Kiruna, Sweden, have discovered rare earth elements and are thus potential producers of rare earth elements. Although the Swedish deposits in Kiruna, Malmberget and Grängesberg-Blötberget are actually iron ore deposits, they are also generally classified as iron oxide-apatite deposits. The iron oxide-apatite group also includes the Milo (apatite) in Australia, which is a large but low-value resources, where rare earth elements will typically be able to contribute as a by-product only.

Rare earth elements are not currently mined from mines with these two deposit types, as the Bayan Obo mine is considered a carbonatite deposit.

9.2 Secondary deposits of rare earth elements

9.2.1 Heavy sand deposits (placer deposits)

Some of the minerals that contain rare earth elements can, after the weathering of the host rocks, resist physical and chemical degradation and be deposited together with other relatively heavy minerals to form heavy sand deposits. Heavy sand deposits are often divided according to their mode of formation, i.e. in alluvial (river) and marine (coastal and near-coastal) deposits as well as fossil deposits (deposits in alluvial or marine environments that are no longer active). Heavy sand deposits are characterised by containing various minerals with economic potential, *e.g.* titanium (ilmenite, rutile, etc.), zirconium (zircon), tin (cassiterite) and in some cases minerals containing rare earth elements (predominantly monazite), which will usually only constitute a by-product in a production.

The most important REE mineral in this group is monazite, which also contains uranium and thorium, but the heavy sand deposits can also contain the REE minerals xenotime, fergusonite, allanite, pyrochlorite and loparite. In general, these deposits are large, but the content of rare earth elements is low (< 0.05 % TREO). The grades are usually stated in relation to how much of the mineral there is (e.g. % monazite).

In Appendix I, 344 heavy sand deposits were registered, which makes this the most common type of deposit, but they do not necessarily contain the most resources. Utilisation of heavy sand deposits takes place in, amongst others, Australia, India, Madagascar, Malaysia and the United States, where monazite and xenotime are extracted as REE by-products for tin, titanium and zircon production. In the Nordic countries, this deposit type is found at Olserum in Sweden and in East Greenland in Milne Land; none of these are currently producing. Figure 9-4 shows areas with significant deposits of heavy sand with monazite.

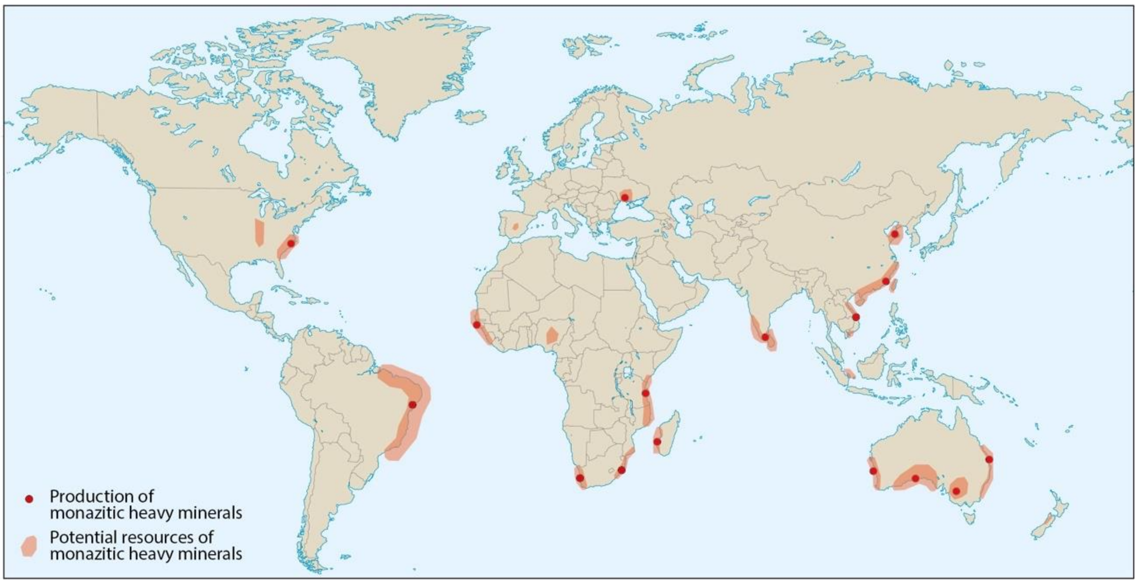


Figure 9-4 *Areas with significant deposits of heavy sand with monazite. Source: Saxon (2021).*

For heavy sand deposits, resources and production size are often reported simply as the amount of the mineral containing the rare earth elements, and only rarely are resource inventories made specifically for this group. The reason is probably that the production of rare earth elements is a by-product that is not of great importance for the main production, and that the extraction of heavy sand deposits in many cases does not require large construction investment, so there is less need for the extensive studies needed to establish actual resource inventories. When converting from the amount of a monazite concentrate to the content of rare earth elements, it is often estimated that the concentrate contains about 10 % non-REE minerals and that monazite contains about 50 % TREO (in places up to about 60 %).

9.2.2 Ion adsorption deposits

Ion adsorption (clay) deposits (IA deposits) are formed in tropical-subtropical wet climates, where seeping rainwater over thousands of years has dissolved the minerals in granitic and volcanic rocks and released the rare earth elements, which due to electrostatic forces are subsequently adsorbed to the surfaces of the clay minerals formed as part of the decomposition of the rocks. This type of deposit is often found in areas less than 200 km^2 and is generally low-grade (0.03-0.4 % TREO) with small resources (typically < 100,000 tonnes TREO). However, their composition is relatively enriched in heavy rare earth elements, including terbium and dysprosium amongst others, making them industrially attractive as HREE are used in magnets (see section 3.2.1). A typical profile in IA deposits is shown in Figure 9-5; the depths down to the enriched zone vary from a few meters to approx. 30 m below the surface; the highest content is approximately in the middle of this zone. The deposits are also easy to utilise by adding, for example, ammonium sulphate or sodium chloride directly into the deposit or by excavation and treatment in a basin or tank (O'Callaghan 2012) (see also section 5.1.3).

Ion adsorption deposits are predominantly found in a belt between 30 °S and 30 °N and are the basis for production in, for example, China (*e.g.* Ganzhou, Jiangxi, Guangdong, Longnan, Hunan, Fujian, Xunanwu), in the Nujiang Lisu area of Myanmar and in the exploration projects Araxa in Brazil, Penco in Chile, Tantalus in Madagascar and Makuutu in Uganda. Over the last 20 years, about 170 deposits have been produced in south-eastern China, and they still constitute an important group for HREE production in the country (Xie et al. 2016). However, the production method has significant environmental challenges, and for the same reason, Chinese small-scale production is being phased out. Countless examples of this type of deposit are known, but as many are small in terms of tonnage, they are not officially registered. In Appendix I, 62 of the projects described are IA deposits. Detailed description of the formation of the IA deposit at Serra Verde, Brazil, is given by Pinto-Ward (2017). Figure 9-6 shows selected IA deposits.

The distribution of the rare earth elements in these deposits varies considerably due to the very different source rocks. In China, they are divided into LREE and HREE, typically in relation to the Y_2O_3 content, where the LREE type contains < 50 % Y_2O_3 and the HREE type contains > 50 % Y_2O_3.

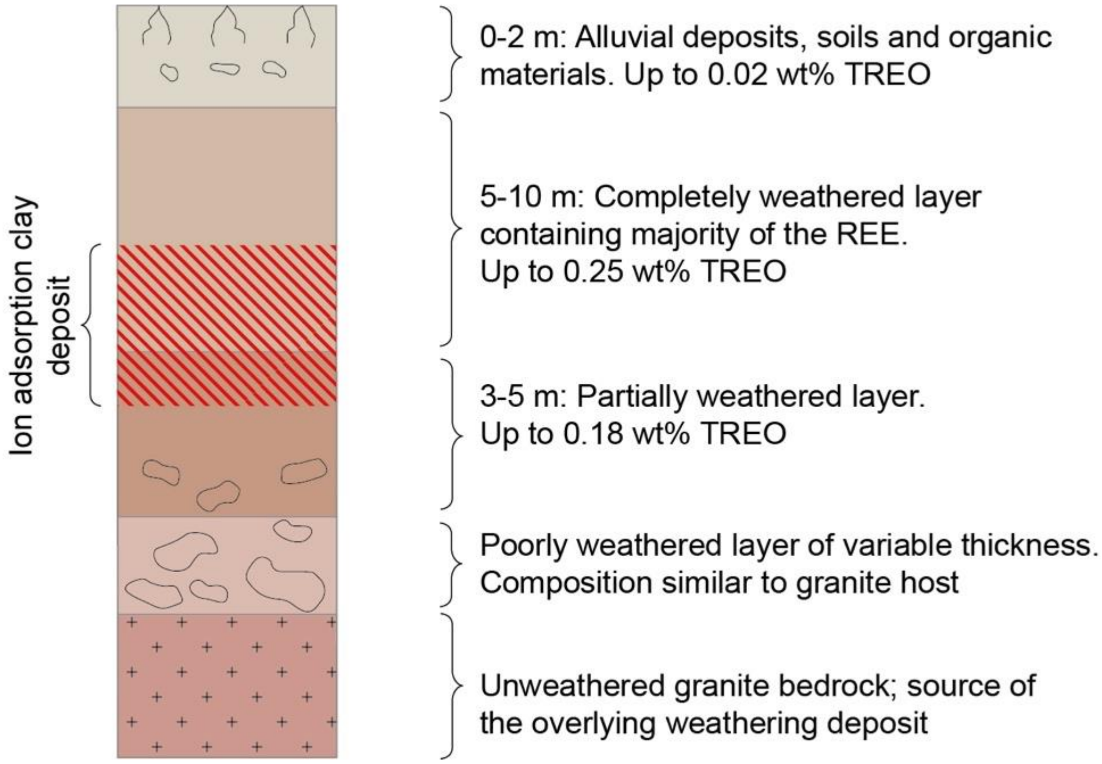


Figure 9-5 *Principle sketch for ion adsorption deposits. Source: O'Callaghan (2012).*

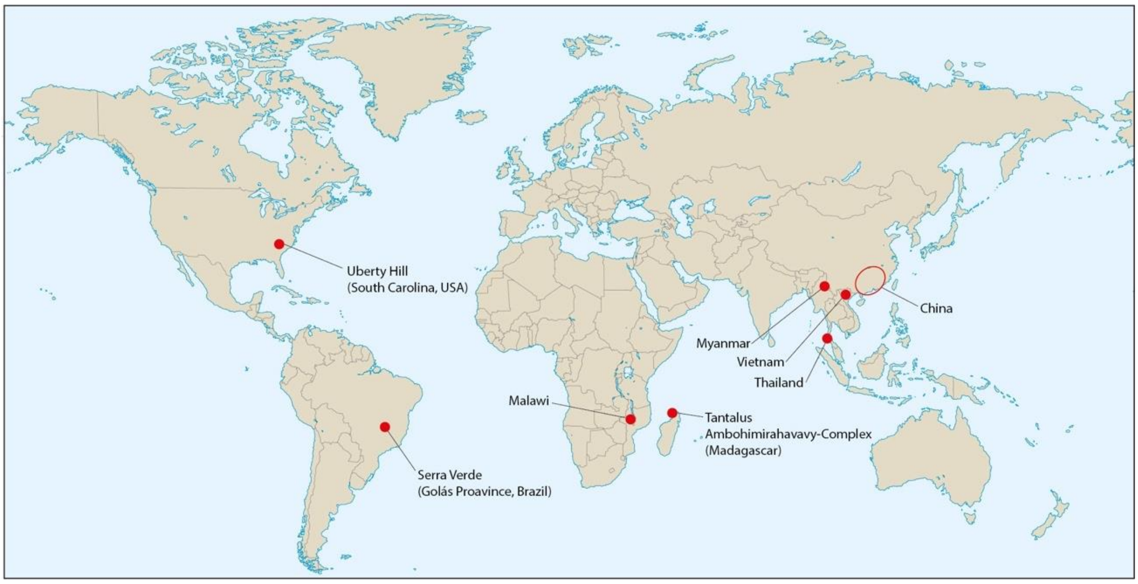


Figure 9-6 *Selected IA deposits. Source: Appendix I.*

9.2.3 Laterite (bauxite) deposits

Laterite deposits originate from the extraction of eroded bauxite rocks (which is an aluminium ore) and are therefore also called bauxite deposits. Laterite (bauxite) deposits are typically near-surface deposits, formed as a result of chemical erosion of granitic rocks, where the rock's initial low content of rare earth elements has been dissolved and subsequently precipitated as secondary minerals in thin, near-surface layers, enriched with rare earth elements (often bastnäsite). The deposits are very variable in size and quality but are rarely larger than 50 million tonnes; the values are typically 0.1 to 10 % TREO. The Mt. Weld deposit in Australia partly belongs to this type, as parts of the original carbonatite have subsequently been lateritised.

When bauxite is used as a raw material for aluminium, large amounts of ‘red mud’ appear after processing; this type of tailings constitutes a potential low-value resource of rare earth elements, but there is a particular focus on exploiting scandium from ‘red mud’, and a few projects are under consideration, including some in Greece (Panias et al. 2014).

9.3 Other geological types of rare earth elements

9.3.1 Metamorphic deposits

Metamorphic deposits with rare earth elements are primary deposits that, due to the Earth's plate tectonic movements, have in some cases been affected by subsequent geological events, where they have been exposed to high temperatures and/or high pressure, which may have led to the concentration of rare earth elements. There are no examples of producing deposits of this type.

9.3.2 Phosphorite deposits

Phosphorite deposits are sedimentary carbonate rocks that contain phosphate-rich concretions/nodules containing francolite and fluorapatite, both of which have high content of rare earth elements, commonly with the heavy rare earth elements relatively enriched (Emsbo et al. 2015). Such deposits are one of the world's most important resources to produce nitrogen-phosphorus-potassium fertilisers, which are produced in large quantities (in the USA alone about 30 million tonnes in 2014 (Emsbo et al. 2015)). Generally, the REE content does not exceed 0.2 %. In the United States, phosphorite deposits are found in sediments from the Proterozoic to the Pleistocene. The content of rare earth elements is often high in deposits of Upper Mississippian-Upper Devon, where the values can be up to about 1 %. Emsbo et al. (2015) point out that it is technically simple to release the rare earth elements by a leaching process, even with a high yield.

9.3.3 Manganese nodules – the deep ocean

Rare earth elements are found deep in the ocean in two different geological environments: (i) in the form of ferro-manganese nodules, which precipitate on the seabed at a depth of 4,500-6,000 m; and (ii) as iron-manganese crusts formed in association with seamounts[3] and oceanic spreading zones. The content of rare earth elements varies considerably between the various known deposits. In seamounts off the Mid-Pacific there are approx. 0.2 % TREO in the polymetallic nodules; at Scotia Sea there are approx. 0.3 % TREO in the ferromanganese modules and in marine mud in the Indian Ocean there are approx. 0.09 % TREO. The deposits are considered to be very large (Takaya et al. 2018), but are not mapped in detail, as exploration in this field is relatively new and any recovery will be technically challenging. The International Seabed Authority (https://www.isa.org.jm/) issues frameworks and licenses for exploration in the deep seas.

9.4 The importance of minerals in the economy of deposits

None of the rare earth elements are found naturally as metals proper but are found only as main or trace elements in minerals. More than 200 minerals are known to contain rare earth elements, but only about 20, which primarily belong to the mineral groups carbonates, oxides, phosphates and silicates, are considered to be commercially interesting (Table 9-2). The rare earth elements often replace cations in the crystal structure, such as in the mineral apatite ($Ca_5[PO_4]_3[F,Cl,OH]$), where the rare earth elements substitute for calcium in the crystal structure.

If a mineral has a high content of rare earth elements, it is clear from the chemical formula of the mineral. This applies, for example, to the mineral xenotime, where the heavy rare earth elements dominate, and in bastnäsite, where cerium and lanthanum dominate. Since each of the rare earth elements has approximately the same ionic radius and valence, they can to some extent replace each other in the crystal structure, and the ratio between them can therefore vary in the same mineral formed in two different deposits. If a mineral contains only very small amounts of rare earth elements, it is not usually stated in the chemical formula of the mineral.

The abundance of various elements in the Earth's crust decreases with increasing atomic number and according to Oddo-Harkin's law, the abundance of a given element with an even atomic number is greater than that of the previous one with an odd atomic number (see section 2.3). Thus,

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[3] Seamounts are underwater mountains formed by volcanic activity

there is a higher content of light rare earth elements than heavy, and more cerium than lanthanum in the Earth's crust.

The individual REE minerals are characterised by a given HREE/LREE ratio. As shown in Figure 9-7, both bastnäsite and monazite have a relatively low HREE/LREE ratio, while minerals such as eudialyte, gadolinite, fergusonite and steenstrupin have a slightly higher HREE/LREE ratio; xenotime has the highest ratio.

Figure 9-7 *The distribution between the individual rare earth elements in different minerals and between the same type of mineral but formed in different locations. Figure from Machacek & Kalvig (2017).*

Table 9-2 *Overview of the most common minerals with rare earth elements. The parentheses in the first column indicate whether they are predominantly light or heavy rare earth elements. Sources: O'Calaghan 2012, Goodenough* et al. *2016 and Chakhmouradin & Wall 2012.*

Mineral	**Mineral type**	**Chemical formula**	**TREO (wt%)**	**ThO_2 (wt%)**	**UO_2 (wt%)**	**Geological REE type**
Aeschynite (Ce)	Oxide	$(Ce,Ca,Fe,Th)(Ti,Nb)_2(O,OH)_4$	32			Hydrothermal
Alllanite (Ce)	Silicate	$CaNdAl_2Fe_2^+(Si_2O_7)O(OH)$	23	0.2-1.5	0.1	Alkaline
Ancylite (Ce)	Carbonate	$SrCe(CO_3)_2(OH)H_2O$	46-53	0.1-0.4	0.1	Carbonatite
Apatite	Phosphate	$Ca_5(PO_4)_3(F,Cl,OH)$	12-19	0.1-10	0.001	
Bastnäsite (Ce)	Carbonate	$CeCO_3F$	53-75	< 2.8	0.09	Carbonatite/hydrothermal
Brannerite	Oxide	$(U,REE,Th,Ca)(Ti,Fe,Nb)_2(O,OH)_6$				
Britholite (Ce)	Silicate	$(Ce,Ca,Sr)_2(Ce,Ca)_3(SiO_4PO_4)_3(O,OH,F)$	23			Hydrothermal
Brockite	Phosphate	$(Ca,Th,Ce)(PO_4)H_2O$				Hydrothermal
Burbankite	Carbonate	$(Na,Ca)_3(Sr,Ba,I,REE)_3(CO_3)_5$				Carbonatite
Cebait (Ce)	Fluoride	$Ba_3Ce_2(CO_3)_5F_2$	32			
Cerite	Silicate	$(LREE,Ca)_9(Mg,Ca,Fe)(SiO_4)_3(SiO_3OH)_4(OH)_3$				
Cerianite (Ce)	Oxide	CeO_2	90	< 5		
Cheralite	Phosphate	$CaTh(PO_4)_2$				
Churchite(Y)	Phosphate	YPO_42H_2O	43-56	< 0.3		
Columbite	Niobate	$FeNb_2O_6$				
Eudialyte	Silicate	$Na_{15}Ca_6Fe_3Zr_3Si(Si_{25}O_{73})(O,OH,H_2O)(Cl,OH)_2$	9	0.01	0.002-0.09	Alkaline
Euxenite	Oxide	$(REE,Ca,U)(Nb,Ta,Ti)_2O_6$	20-30	4-5	8-9.5	Alkaline
Fergusonite (Ce)	Niobate	$REENbO_4$	43-52	< 8	< 2.4	Alkaline
Florencite (Ce)	Phosphate	$(Ce)Al_3(PO_4)_2(OH)_6$	32	-		
Fluocerite (Ce)	Fluoride	CeF_3	83	-		Hydrothermal
Gadolinite (Ce)	Silicate	$Ce_2Fe^{2+}Be_2O_2(SiO_4)_2$	60	< 0.3	< 0.3	Hydrothermal/alkaline
Gerenite (Y)	Silicate	$CaNdAl_2Fe^{2+}(SiO_4(Si_2O_7)O(OH)$	44	-		
Huanghoit (Ce)	Carbonate/fluorocarbonate	$BaCe(CO_3)_2F$	40	-		
Iimoriite	Silicon-Carbonate	$Y_2SiO_4CO_3$				
Kainosite (Y)	Silicate	$Ca_2Y_2(SiO_3)_4(CO_3)H_2O$	38	-		
Keiviite (Y)	Fluoride	$Y_2Si_2O_2$	69	-		

Mineral	**Mineral type**	**Chemical formula**	**TREO (wt%)**	**ThO_2 (wt%)**	**UO_2 (wt%)**	**Geological REE type**
Loparite (Ce)	Oxide	$(Ce,La,Nd,Ca,Sr)(Ti,Nb)O_3$	28-38	0.65-0.85	0.1	
Monazite (Ce)	Phosphate	$CePO_4$	38-71	< 30	0.2-2	Carbonatite, heavy sand, hydrothermal, alkaline
Mosandrite	Phosphate	$(Ca,Na,REE)_{12}(Ti,Zr)_2Si_7O_{31}H_6F_4$				
Parisite (Ce)	Carbonate/fluorocarbonate	$CaCe(CO_3)_3F_2$	58-63	< 4	0-0.3	Carbonatite
Pyrochlore	Niobate	$(Na,Ca)_2Nb_2O_6(OH,F)$				Carbonatite
Rinkite	Silicate	$(Na,Ca)_3(Ca,Ce)_4Ti(Si_2O_7)_2OF_3$				
Samarskite	Oxide	$(Y,Ce,U,Fe,Nb)(Nb,Ta,Ti)O_4$				
Steenstrupin (Ce)	Silicate	$Na_{14}Ce_6(Mn^{2+})_2(Fe^{3+})_2Zr(PO_4)_7Si_{12}O_{36}(OH)_{23}H_2O$	20-30	0,2	0.4-0.8	Alkaline
Synchysite (Ce)	Carbonate/fluorocarbonate	$CaCe(CO_3)_2F$	48-52	< 1	0.02-0.03	Carbonatite, hydrothermal
Xenotim (Y)	Phosphate	YPO_4	43-65	< 8.4	< 5.8	Hydrothermal
Yttropyrochlore (Y)	Oxide	$(Y,Na,Ca,U)_{1-2}Nb_2(O,OH)$	17			

When making an economic assessment of an ore with rare earth elements, the following two factors are especially important: (i) the concentration of rare earth elements in the ore (REO grade) and (ii) the ratio between LREE and HREE. As mentioned above, the HREE/LREE ratio is determined by the selection of REE mineral(s) present in the ore, while the grade is determined by the concentration of the minerals containing the rare earth elements. At the current technological regime, one of the most economically important applications of REEs is for permanent magnets and hence minerals with a high content of praseodymium, neodymium, terbium and dysprosium are in high demand. Based on this ratio alone, apatite is more profitable to extract than *e.g.* monazite and allanite (Figure 9-8), but the total content of rare earth elements in apatite is significantly lower than in monazite and allanite, which makes the latter two more commercially interesting.

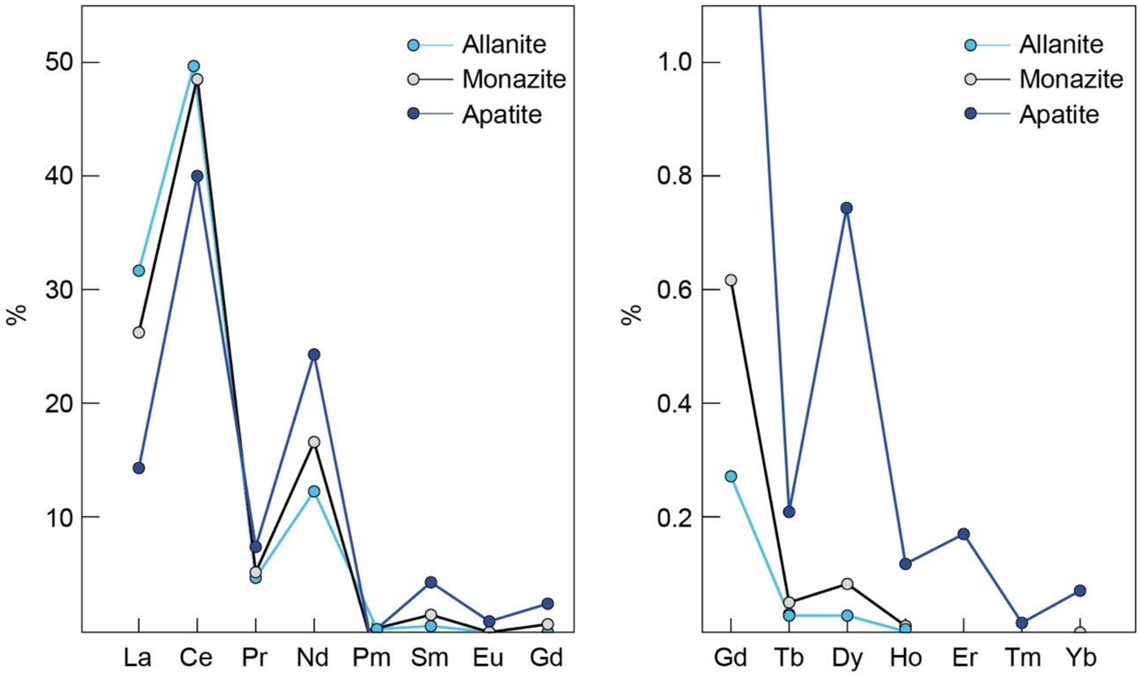


Figure 9-8 *The distribution of rare earth elements in allanite, monazite, and apatite. Source: Papunen & Lindsjö (1972).*

9.4.1 The balance problem

From a commercial point of view, there is generally an unfavourable relationship between the natural distribution of REEs in REE minerals and the industrial demand for the individual REEs. This is because the extraction of rare earth elements from the mineral assumes that the entire mineral is dissolved, whereby the 16 rare earth elements (promethium is excluded, see section 2.1) are recovered in the same ratio as they were in the mineral. The subsequent separation takes place by atomic number from the light to the heavy rare earth elements. Light rare earth elements are more abundant in nature than the heavy rare earth elements, but the needs of industry do not match the natural distribution so an overproduction of light earth elements such as lanthanum and cerium take place. This mismatch between industrial demand and the natural compositions is often referred to as the ‘balance problem’ (Binnemans et al. 2013). The balance problem expresses the tendency towards overproduction of LREE and an underproduction of HREE, and the consequences of this for the pricing of the individual rare earth elements and thus for how economically profitable the deposits are.

It is currently not technically possible to circumvent the balance problem by targeted extraction of individual rare earth elements. The balance problem is linked to the minerals in the deposit, and some minerals present greater challenges than others. For example, bastnäsite is a mineral with a high content of lanthanum and cerium and has a negative effect on the balance problem; conversely, deposits with *e.g.,* eudialyte, xenotime and monazite present fewer challenges in relation to the balance problem (Figure 9-7). IA deposits often contribute in a positive way to the balance problem, as the content of light rare earth elements is typically low, while the content of the heavy rare earth elements, especially yttrium, is very high, which can have an impact on the pricing for smaller niche markets.

Table 9-3 shows the significance of the mineral composition to produce two different deposits: (i) bastnäsite from the Mountain Pass deposit in the USA and (ii) eudialyte from the Kringlerne/Killavaat Alannguat deposit in Greenland. For the two deposits, the quantities of the individual rare earth elements are calculated with the aim of producing one tonne of europium or one tonne of neodymium, respectively. Production of one tonne europium means that large quantities of lanthanum and cerium will also be produced; for deposits with eudialyte this amount is about two-thirds less than for bastnäsite deposits. Similarly, when it comes to bastnäsite, more than 800 tonnes of lanthanum and cerium will be produced for every tonne of europium produced and approx. 200 tonnes of lanthanum and cerium for the example with eudialyte.

Table 9-3 *Example of the importance of minerals for the economy of a deposit. The product composition for bastnäsite from Mountain Pass, USA, and eudialyte from Kringlerne/Killavaat Alannguat, Greenland, is compared; we assume that it is the aim to manufacture one tonne of europium and one tonne of neodymium, respectively.*

	Mountain Pass (bastnäsite)	**Kringlerne (eudialyte)**	**Mountain Pass (bastnäsite)**	**Kringlerne (eudialyte)**
	1 tonne Eu gives (kg)	**1 tonne Eu gives (kg)**	**1 tonne Nd gives (kg)**	**1 tonne Nd gives (kg)**
La_2O_3	332.0	72.6	2.8	1.5
Ce_2O_3	491.0	135.7	4.1	2.7
Pr_6O_{11}	43.4	13.2	0.4	0.3
Nd_2O_3	12.0	49.8	1.0	1.0
Sm_2O_3	8.0	9.6	0.1	0.2
Eu_2O_3	1.0	1.0	0.0	0.0
Gd_2O_3	1.7	10.5	0.0	0.2
Tb_4O_7	0.2	1.9	0.0	0.0
Dy_2O_3	0.3	11.7	0.0	0.2
Ho_2O_3	0.0	2.6	0.0	0.1
Er_2O_3	0.0	9.8	0.0	0.2
Tm_2O_3	0.0	1.3	0.0	0.0
Yb_2O_3	0.0	8.3	0.0	0.2
Lu_2O_3	0.0	1.2	0.0	0.0
Y_2O_3	1.0	79.1	0.0	1.6

The mineralogical composition is therefore determined the magnitude of balance problem and is important to assess how attractive any given deposit will be. It follows that REE deposits dominated by bastnäsite will generally be less attractive compared to deposits dominated by monazite, xenotime and REE silicates. REE deposits can therefore not only be assessed on the basis of the total quality of the deposit for all the rare earth elements (TREO) in the same way as, for instance, gold, iron or copper deposits. In the assessments of deposits with rare earth elements, it is also necessary to consider the composition of the minerals that host the rare earth elements.

The mineralogical composition of the ore is also important for the technical processes that are used for separating minerals with rare earth elements from the other minerals in the rock, just as the mineralogy of the ore is important for how easily the rare earth elements can be released from the minerals. Both factors affect the operating economy of a REE mine. Most production of rare earth elements has been based on bastnäsite, monazite and xenotime, and there are well-developed techniques for separating these minerals from the other minerals, and for how the minerals can subsequently be dissolved and the rare earth elements extracted. The growing interest in rare earth elements has led to the development of methods for the treatment of REE silicates since the 2000s, but as no deposits are mineralogically identical, bespoke extraction protocols may be needed to produce each new deposit. The most common methods are described in Chapter 5.

Many rare earth deposits contain a certain amount of uranium and thorium, which presents a particular problem in connection with the extraction of REEs and the storage of tailings, as weel as because radioactive substances may be found in the lower parts of the value chains. In the deposits, uranium and thorium are found either engrained in the minerals or as independent uranium or thorium minerals. The problem with the radioactive materials is specifically related to alkaline intrusion, carbonatite intrusion and heavy sand deposits. For example, the mineral monazite often contains significant amounts of thorium, while the mineral steenstrupin, which is found in, for instance, Kvanefjeld/Kuannersuit in Greenland, contains both uranium and thorium. In the processing of minerals from such deposits, uranium and thorium will also be extracted and can contribute to radioactive contamination of both tailings and process water, as well as potentially the REE concentrate. When producing rare earth elements, special precautions must therefore be taken to ensure that there is no radioactive contamination in either tailings, process water or in mineral concentrates. This is described in more detail in Chapter 7.

10. Resources and Reserves

Mineral exploration projects typically undergo a series of standard development phases, which are organised step by step so that new information, at a minimum cost, helps to reduce the investment risk, and to cancel projects being considered not economically attractive in its present form. A central part of all exploration projects is the mapping and assessment of the project's resources, which are 'in stock' for the company/mine, and thus determine the economy and the life of the mine. Data from the mineral exploration is also included as information for investors and for the authorities' assessments of whether the companies are fulfilling their licensing obligations. The typical procedure for new projects is shown in Table 10-1 and for large mining projects can last more than 10 years. The greatest commercial risks come in the initial stages, but generally the cost of each step the exploration takes increases. The project phases in Table 10-1 and Figure 10-1 show how the development of the mineral reserve typically proceeds. In this report, the project phases are used subjectively in assessments of the status of the exploration projects listed in Appendix I.

Table 10-1 *Typical project steps for the development of mineral deposits, including deposits with rare earth elements.*

Project phases	Activities
Prospecting	Collection of field data from the surface (samples, geochemistry, geophysics, etc.), often covering a significant area of the license The deposit is identified/detected
Exploration	Collection of surface samples, detailed geophysics, and geochemistry Initial drilling Preliminary Economic Assessment (PEA) Scoping Study (SS)
Advanced exploration	Detail drilling Resource/reserve detection Pre-Feasibility Study (PFS) Metallurgical tests Commercial Project Assessments (Feasibility Study (FS); Definitive Feasibility Study (DFS)) The work is target licenses and investor agreements Bankable Feasibility Study (BFS) Design of mines and facilities
Development of the mine	Construction of mines and associated infrastructure Pre-production
Production	The mine begins production (usually with less production in the first years)
Decommissioning	In countries with responsible raw material management, conditions for decommissioning are agreed upon when the exploitation permit is granted. Not mentioned further.

Scoping Study (SS): Summary assessment of the project early in the project process on the basis of initial geophysics, geochemistry and drilling; often includes an outline for a possible mining project. The purpose is to determine whether there is a basis for follow-up studies and what risks the project may include. Many exploration projects are shut down after the SS.

Pre-Feasibility Study (PFS): Technical and economic study (profitability study) that is used to assess the probability that the project can lead to an economically profitable mining project; is usually carried out midway through the project. The study is based on collected surface samples, detailed geophysics, and geochemistry as well as a significant number of boreholes, which have formed the basis for the detection of a probable ore reserve; in addition, a project sketch is carried out for the mine and the associated facilities for processing the ore. The PFS also contains a financial analysis of the expected operating costs, capital requirements and financial risks. Some projects are shut down after PFS.

Feasibility Study (FS): Technical, economic, and commercial analysis that is used to assess whether the project should continue and as a basis for the preparation of detailed construction and process plans, environmental studies, etc. In FS, the ore body is classified as the ‘proven reserve’ and ‘probable reserve’ (see section 11.1), and FS also contains schedules, action plans and expectations for financial development for a multi-year period after the mine opens. A few rare earth element projects have reached the FS phase but are awaiting a final decision on project status for a variety of undisclosed reasons (Appendix I).

Basic Engineering (BS): A positive result of FS will typically lead to a need for further studies, including a final statement of the ore reserve (‘mineable reserve’). This includes calculations of the total quantities available for mining, and of the quality of the ore that is blasted, and which must subsequently be treated. In addition, proposals for technical solutions of all stages are included in any future production.

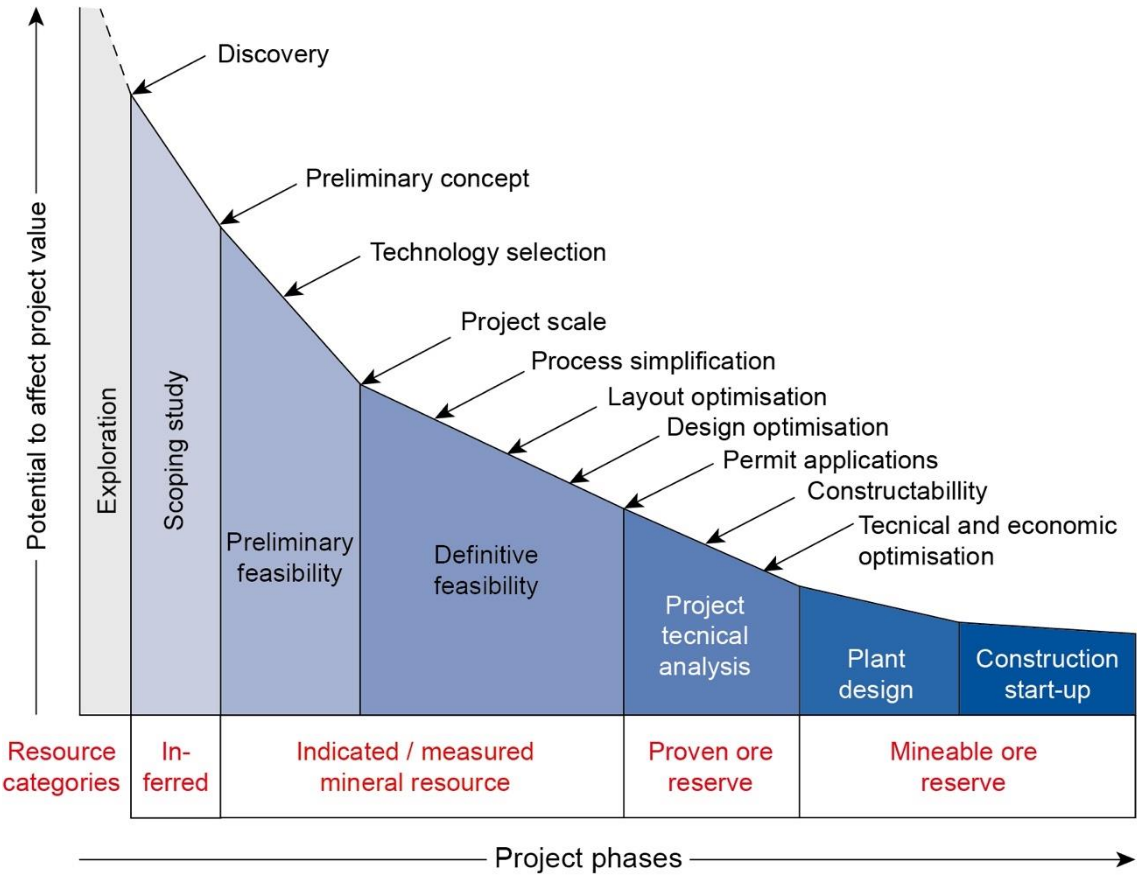


Figure 10-1 *Typical phases in mineral exploration projects which also apply to deposits with rare earth elements. The figure also indicates at which stages the resources and ore reserves of the deposit are determined.*

10.1 Definitions

Overall, the concept of resources is used for everything from estimated amounts of raw materials to proven reserves. The term resources is almost always used in connection with exploration projects, where the companies on the basis of basic data state estimates of whether a project could be profitable if follow-up studies confirm the volume and grade of the resource. The term *reserves* indicate the amount of ore that is securely determined with varying degrees of certainty.

The mining industry has developed various standards (classification systems) for the use of the terms resources and reserves, which must ensure that the values below the surface - the ore - are well determined, both in terms of how much there is of the desired raw material and the prevalence of the ore body. Such standards are developed by mining industry organisations to secure investors. The most widely used standards are JORC (Australia), SME (USA), NI43-101 (Canada), SAMREC (Africa), PERC (Europe) and CRIRSCO, which aims to become the global classification system. Determinations of ore quantities and grades are made in accordance with internationally recognised guidelines and must in all cases be carried out by independent experts. Efforts are also under way to introduce a United Nations Framework Classification for Resources (UNFC), which, in addition to classifying resources, also indicates the economic and technical status of a project.

A schematic overview of resources and reserves is shown in Figure 10-2. The inventory distinguishes between 'possible' (inferred), 'probable' (indicated) and 'safe' (measured) mineral resources, which in line with increasing geological information can be classified as one of these categories. If the exploration and economic analyses show that a given part of the resource can be utilised profitably, this part will be included as a 'proven' (proven and measured) mineral reserve, while the part of the resource which is just as well determined, but which due to the current technology and/or economy won't necessarily work economically, will fall into the category of probable mineral reserves. This means that increases in raw material prices, or new, cheaper production methods, can turn probable reserves into safe reserves (proven/measured); and vice versa with falling prices. Changes in technological possibilities can similarly affect the reserve inventories.

Descriptions of resources and reserves are shown in Table 10-2.

Table 10-2 *Description of mineral resources and reserves.*

Resource	The part of the ore, which is determined uncertain, or where the merits of the present technology or prices, do not provide a basis for an economic production, is referred to as the resource. If prices change in an upward direction or further exploration activities can detect, with great certainty, an ore body, all or part of the resource can be transferred to the reserve.
Reserve	The part of the ore where (i) the tonnage and the average grade are determined with high geological confidence / certainty; (ii) it has been shown that it is technically and economically profitable to mine and process the ore; and (iii) licenses and administrative permits are aquired, referred to as the reserve. Falling prices may mean that parts of the reserve can no longer be produced economically, and this part must be downgraded from safe reserve to probable reserve.

The quality of rare earth element deposits is often stated as the content of the total amount of all rare earth elements, which is found in a tonne of ore/reserve and is stated as TREO %. In order to be able to assess the ore's commercial value, however, it is necessary to assess the ore's individual composition of rare earth elements.

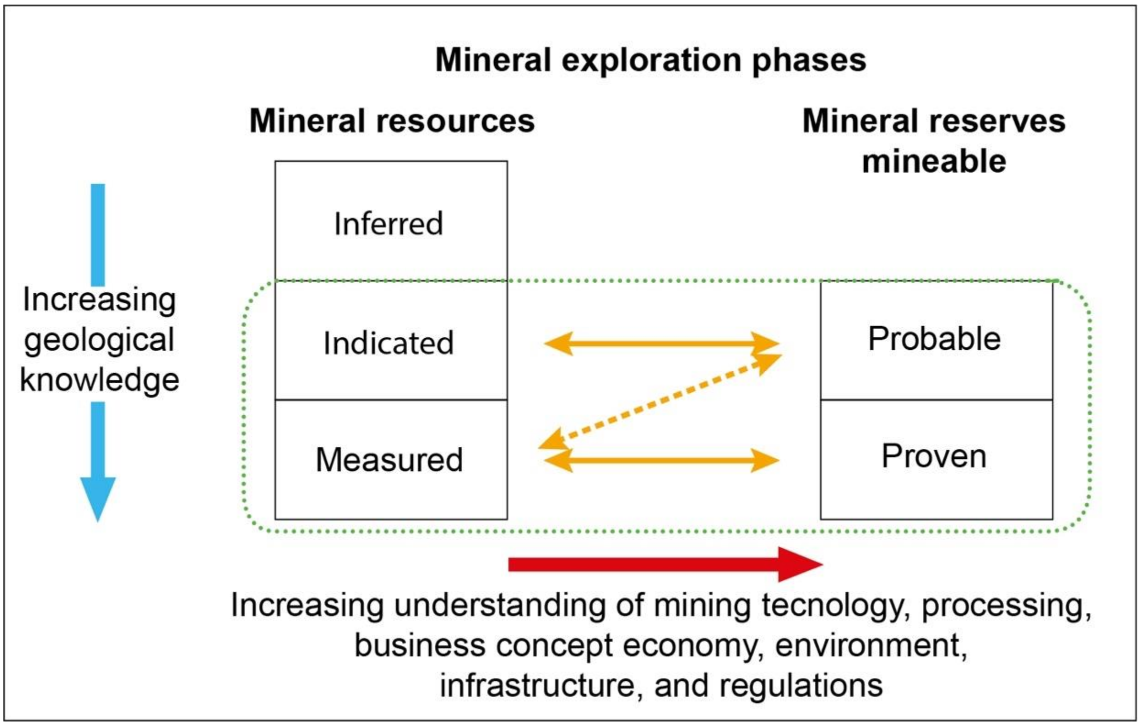


Figure 10-2 *CRIRSCO's definitions for resource inventories. Source: CRIRSCO (2019).*

The exploration industry uses, amongst other things, resources and reserves for assessments and comparisons of various projects; the resource inventories are dynamic in relation to results from the exploration activities and therefore change over time. In a number of cases, research companies emphasise that their resource is particularly large, and suggest that this is a quality in itself. But exploration projects with very large resources, sufficient for e.g. > 30 years of production, are not in themselves more economically attractive than smaller deposits with a shorter timeframe, as the long-term future cannot be capitalised on. Investors in the mining industry want secure investments with a manageable timeframe that correspond to the uncertainties built into the business models.

10.2 Global REE resources and reserves (top-down)

Most countries compile annual statements of national resources, which includes international organisations' estimates of global resources and reserves and estimates of how many years of production there are reserves of for a given mineral raw material.

The national inventories are based on information from the exploration and mining companies, and the data quality, therefore, reflects errors and omissions from both authorities and companies as well as in some cases national, politically determined omissions of data (exemplified below).

The United States Geological Survey (USGS) prepares annual inventories of global secure reserves for rare earth elements in the form of total TREO (tonnes) for each country (see e.g. Table 8-1). However, the USGS does not report the size of the possible (inferred) and probable (indicated) resources, and in general, the inventories of the REE reserves can only be considered as a guideline due to a number of reservations, which are reviewed below. In addition, the USGS does not publish information about the individual deposits, their reserves, grade or mineralogy.

Figure 10-3 shows the development of the mineral reserves in the period 2000-2020 based on the USGS (2001 to 2021). It appears that the total reserves vary somewhat over time, which is primarily due to some countries not having been included for a number of years, e.g. Russia/CIS in 2012-2015. The inventories show that Brazil, India and Vietnam have increased their reserves significantly, while the USA and China have both downgraded their reserves of rare earth elements during this period. US changes are presumably due to the closure/opening of the Mountain Pass mine, while China has reduced reserves in line with closures of IA explorations in Southern and Eastern China. Experts on China also believe that China's reserves are significantly overestimated (Kruemmer pers. Comm. October 2021). On the other hand, there are only very small reserves for Canada and Greenland, both of which are known to have some of the world's largest deposits, which are still in the category of probable and therefore not covered by the USGS' inventories. In addition, reserves for newly producing countries, which includes Myanmar and Madagascar, are not included, presumably due to lack of knowledge about the IA deposits in Myanmar and about the heavy sand deposits in Madagascar, which only produce rare earth elements as a by-product of ilmenite and zircon. The USGS (2001 to 2021) statements must therefore be considered conservative.

Seen over the period 2000-2020, the total reserves varied between approx. 85 and 130 million tonnes of TREO (Figure 10-3). As the consumption of the reserves during this period was very small in relation to the total amount of reserves, the varying reserve sizes are not due to changes in the consumption during this period. Most of the variations can presumably be attributed to price variations, as the low prices of the 2000s may have shifted reserves from the category of safe to probable, and therefore not included; similarly, the growth of reserves may be a combination of rising prices and the inclusion of new countries.

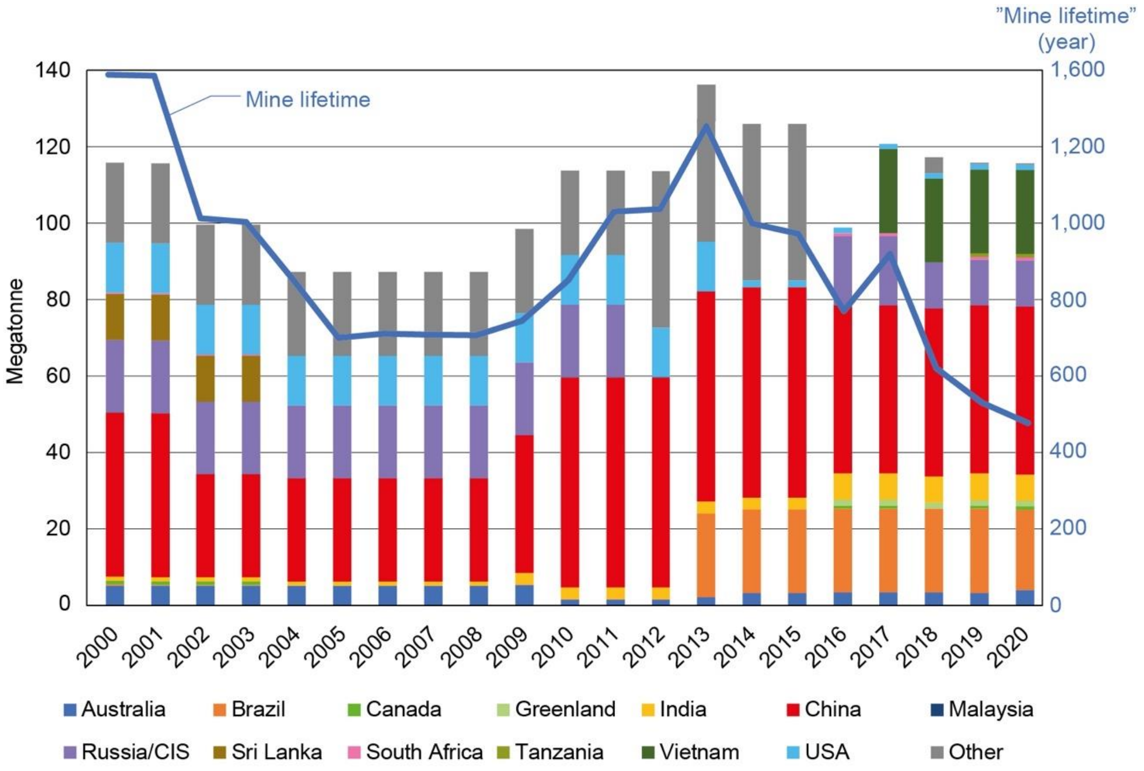


Figure 10-3 *Development in REE reserves (million tonnes TREO) in the period 2000-2020. The life of the reserves is calculated as the ratio between the year's calculated reserves and production (blue line). Source: USGS (2001 till 2021).*

The term ‘lifetime’ is often used for the timeframe the reserves for a given raw material can reach, seen in relation to a given production. The development in the lifetime of the rare earth elements is calculated on the basis of the reserves calculated by the USGS (2001 to 2021) and the annual production in the same period (blue line in Figure 10-3). It appears from this that the total life of the reserves has been reduced from about 1,600 years in the year 2000 to 450 years in 2020, which is primarily due to the increased consumption. With the expected large production increases in the coming years, life expectancy will probably fall to around 200 years up to 2025, however, any probable reserves from Greenland and Canada could have a positive effect on life expectancy. It should be noted that the estimated lifetimes of the rare earth elements are significantly higher than for most other metals (copper approx. 43 years; zinc approx. 19 years (USGS 2021)), and that very large tonnages in the resource classes are possible and probable, which at some point can be expected to be reclassified to safe reserves.

As the market conditions for the rare earth elements are dynamic and are currently shifting towards a rapid increase in the consumption of neodymium, praseodymium, terbium and dys-prosium, more accurate lifetime estimates should be based on the amount of these four magnetic metals in the reserves. The USGS does not disclose the reserves at either type, mineral or element level, and the desired relevant distinction is therefore not possible based on published data. This issue is discussed in Chapter 14 based on the data from Appendices Appendix I and Appendix IV. Overall, it can again be concluded that if the concept of ‘rare’ earth elements is assessed in relation to the very large known resources, the name is misleading.

10.3 Global resource assessments (bottom-up)

Based on publicly available information, MiMa has, as per. 22 December 2021, registered 1,040 rare earth elements occurrences/projects, situated in 86 countries. Based on available information and subjective estimates, the sites are divided into six categories: deposits, prospects, exploration, advanced exploration, mines under establishment and production, which indicate how advanced the projects are, see Figure 10-4. In English-language literature, a distinction is made between 'mineral occurrence' and 'mineral deposit'; in this report both groups are referred to as ‘deposits’. The geographical distribution of the deposits in the groups ‘production sites’, ‘advanced projects and mines under construction’, ‘prospects and exploration’ as well as ‘deposits’ is shown in Figure 10-5. The underlying data is shown in Appendix I and Appendix IV; as a result of subsequent adjustments to Appendix I, there may be minor discrepancies between Figure 10-4, Figure 10-5, Appendix I and Appendix IV.

We consider it likely that the registrations include all significant projects and thus are fairly accurate for the level of activity but are aware that a number of exploration projects are most likely not included, and that the registration is therefore incomplete.

As a result of increased targeted exploration activity, the number of REE deposits accounted for has increased significantly in the last 15 years, with the largest increases in countries that traditionally have significant mineral exploration activities for many different raw materials, such as Australia, Canada, China, and the USA, as well as a number of 'frontier zones', such as Africa, South America and Asia. This means that significant exploration activities are taking place outside China, although it is not possible to conclude on the basis of the present extent to what extent Chinese interests are involved in activities carried out outside China (see section 13.1, if applicable).

About half of the registered deposits in Appendix I are entirely without commercial interest, and/or there is no publicly available information about the deposits/projects. For many the other projects, the business models are based on the fact that rare earth elements constitute a by-product only, for example from monazite from heavy-sand deposits, from polymetallic deposits with niobium and tantalum and from apatite or other minerals from iron ore deposits. An overview of the projects by exploration stage and geological type is shown in Figure 10-5, from which it appears that in MiMa's registrations there are 136 projects which are assessed as 'advanced' and 130 which are assessed as exploration projects (i.e. a little earlier in the course of the exploration); it is expected that the new productions by 2030 will be found among these 266 projects.

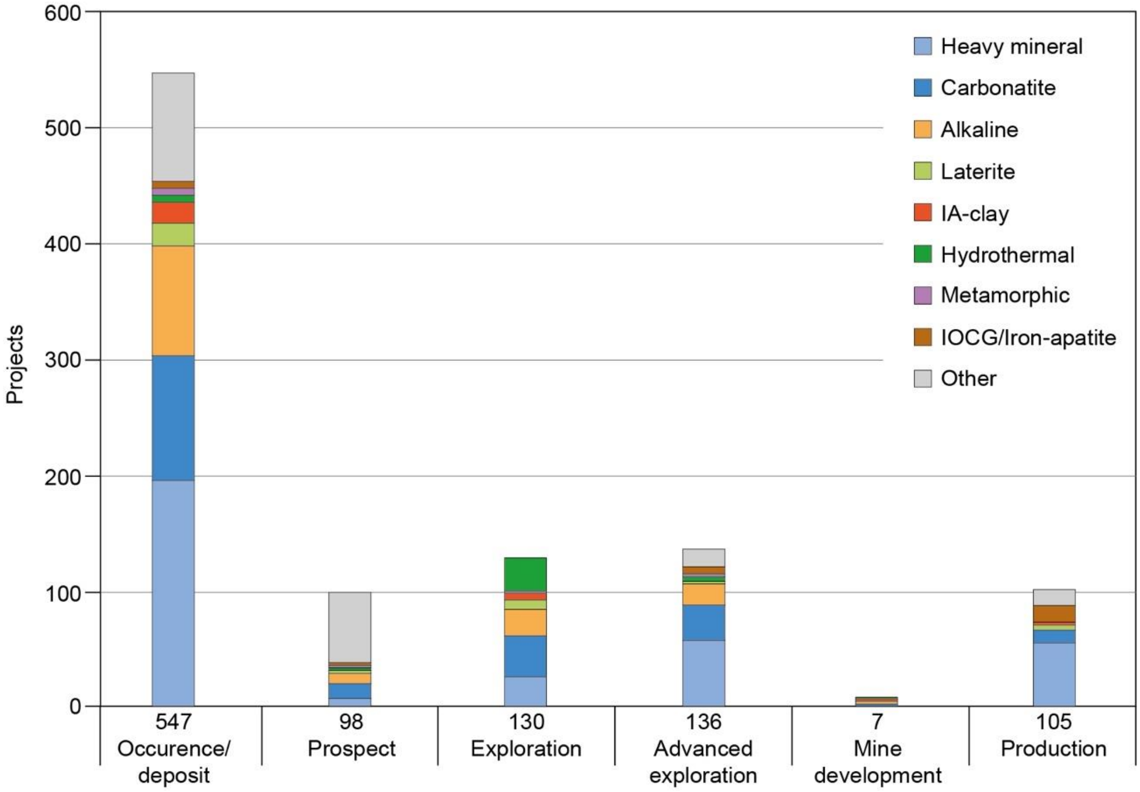


Figure 10-4 *The distribution of 1,023 of the 1,040 rare earth element deposits in Appendix I. The deposits are divided up on the basis of exploration stage. Data from Appendix I (calculated as of 22 December 2021).*

10.3.1 Global inventory of resources and reserves by country, geological type and exploration stage

MiMa's registrations in Appendix I and Appendix IV include the companies' reported resource inventories for the rare earth elements by country, resource class, geological type and exploration stage. On this basis, an inventory has been made that shows the total TREO resources amount to approx. 165 million tonnes, of which approx. 14 million tonnes are measured resources, 93 mill. tonnes are indicated resources, and 58 mill. tonnes are inferred resources; in addition to the latter group, North Korea is reported to have approx. 60 million tonnes (Table 10-3). The majority of the measured resources are in China, Australia, Greenland, and the USA. The indicated resources occur primarily in the following countries: Greenland, Canada, Vietnam, and Australia. A very significant part of the indicated resources is linked to deposits in Canada and Greenland, where in Greenland it is primarily the deposit at Kringlerne that affects the result. The total amount of the possible resources will be determined by the extent to which resources of REE-holding iron ore deposits should be included. The total amount of safe and probable reserves aligns with the statements made by the USGS.

Table 10-3 *Global bottom-up resource estimates divided into classes of safe, probable, and possible resources. North Korea's very large share of possible resources is not documented. Excerpts from Appendix I and Appendix IV.*

Land	**Safe resources tonne TREO**	**Probablesources tonne TREO**	**Possible resources tonne TREO**
China	6,410,000	2,350,000	2,160,000
Australia	1,690,000	3,650,000	3,070,000
Greenland	1,590,000	31,660,000	1,970,000
USA	1,440,000	780,000	30,000
Russia	1,040,000	10,050,000	-
Tanzania	900,000	90,000	70,000
South Africa	570,000	800,000	140,000
Canada	200,000	24,700,000	9,950,000
Brazil	80,000	1,080,000	1,330,000
Kyrgyzstan	40,000	50,000	-
Madagascar	40,000	-	-
Vietnam	-	7,800,000	-
Mongolia	-	3,150,000	790,000
India	-	3,150,000	-
Kenya	-	2,140,000	4,000,000
Angola	-	1,110,000	2,220,000
Malawi	-	320,000	140,000
Sweden	-	190,000	30,080,000
Uganda	-	50,000	150,000
Mozambique	-	20,000	-
Namibia	-	10,000	10,000
North Korea	-	-	*(59,840,000)*
Norway	-	-	990,000
Turkey	-	-	710,000
Zambia	-	-	260,000
Finland	-	-	140,000
Burundi	-	-	30,000
Germany	-	-	20,000
Total	**14,000,000**	**93,000,000**	**58,000,000** **(118,000,000)**

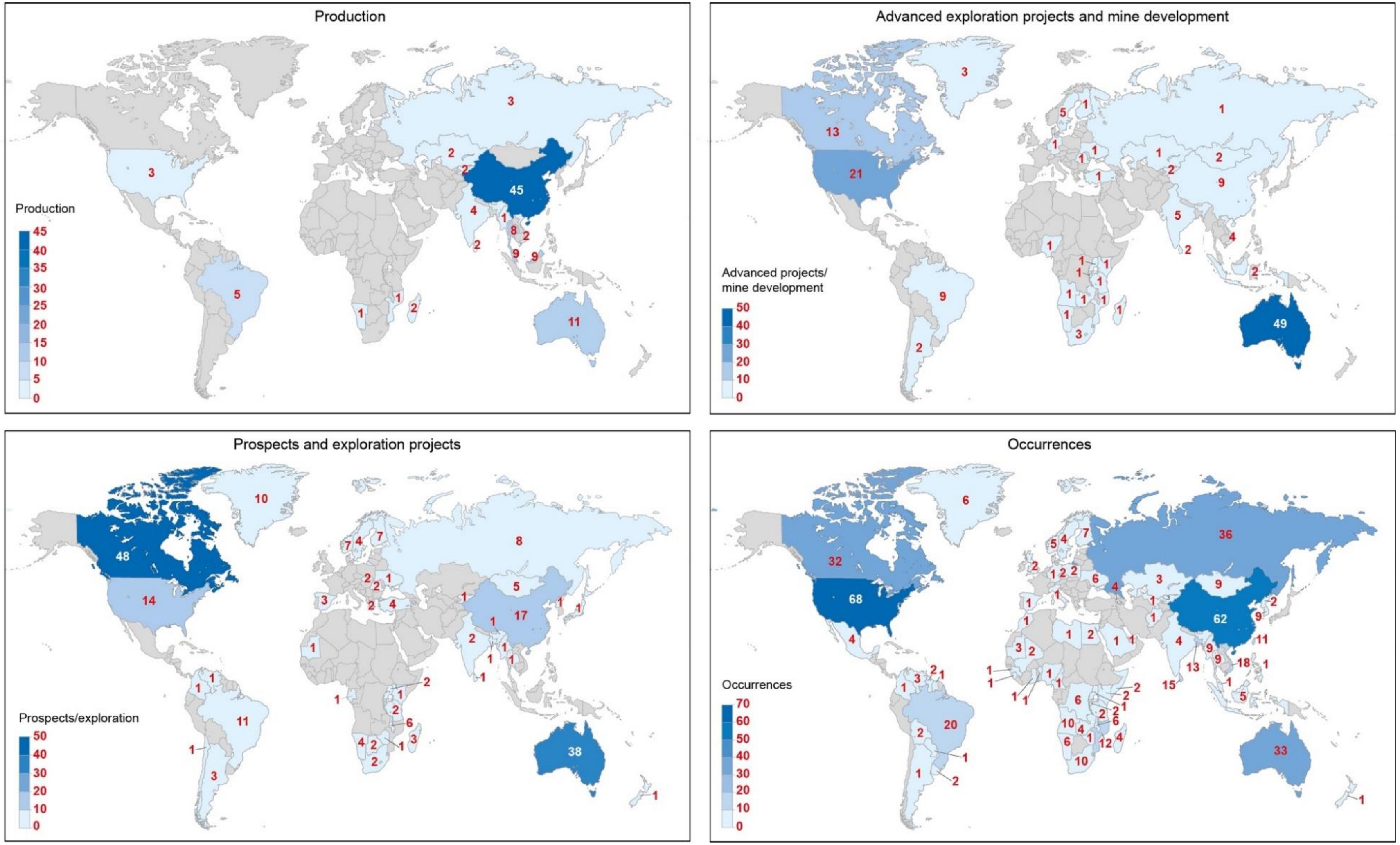


Figure 10-5 *Geographical distribution of known deposits and exploration activities of rare earth elements, divided by the progress of the project. Based on Appendix I.*

If the resources are assessed based on the geological types, carbonatites and alkaline magmatic deposits are the largest groups for the safe and probable resources (Figure 10-6).

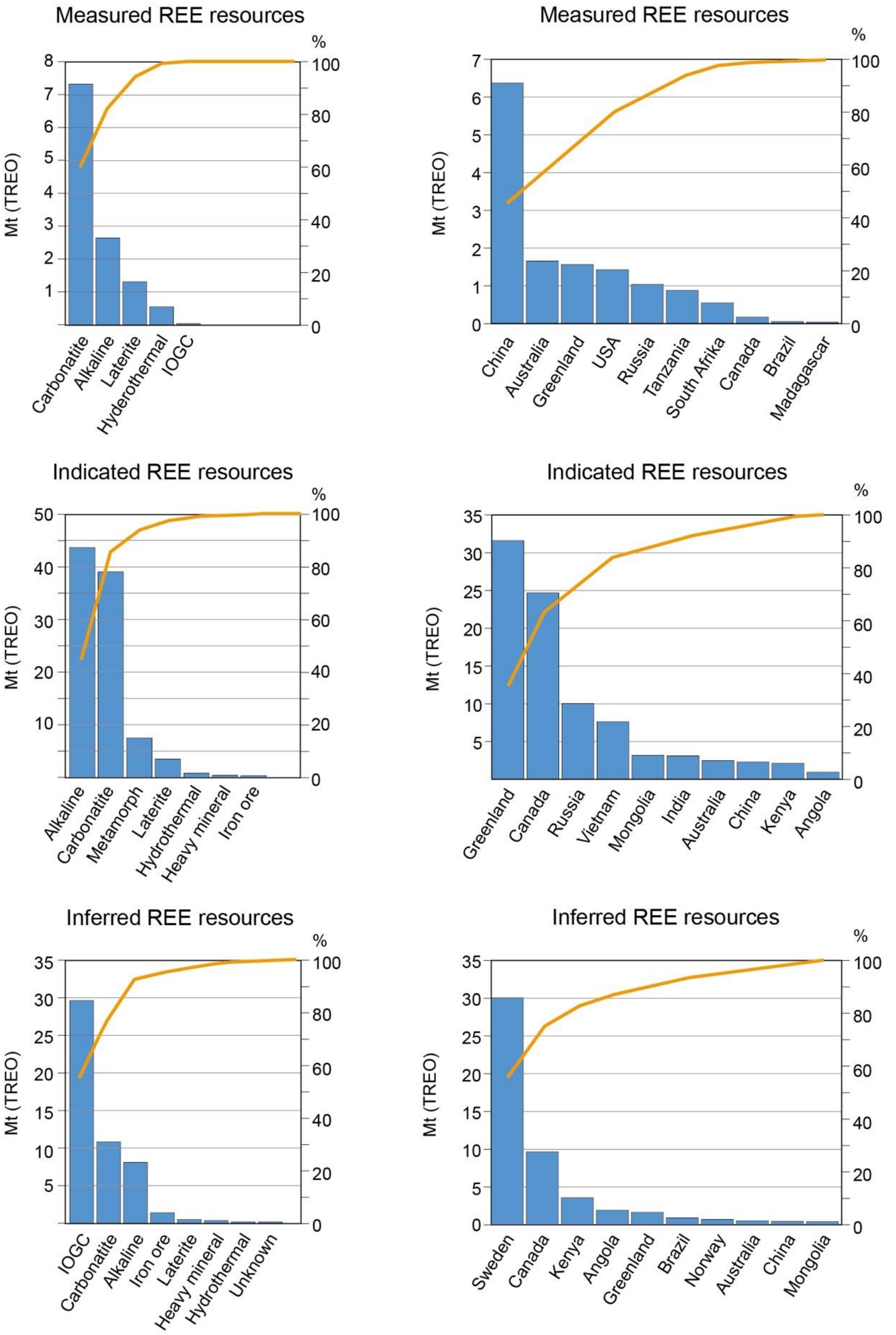


Figure 10-6 *Distribution of REE resources by country, resource class and geological type. Based on Appendix I.*

As previously mentioned, resource and reserve inventories are dynamic and change in line with REE-prices, the exploration activities, and the progress of the projects. When assessing rare earth element resources and reserves, it is also important to know the connection between the resources and the geological types, as this affects the composition of the ore and thus has significance for the commercial potential of the project.

Based on the USGS' (2021) calculation of global production in 2020 of approx. 240,000 tonnes of TREO, the estimated lifetime of the proven resources is approx. 50 years, for the probable resources approx. 400 years and for the possible resources approx. 450 years. However, with fluctuating demand for the individual rare earth elements, there may be significant deviations from these estimates.

As mineral exploration is economically driven, these activities are initiated only to the extent - and in those areas - where the companies consider themselves able to make money. For the same reason, it will never be possible to get an overall assessment of the Earth's resources of a given raw material, and the inventories should only be considered as snapshots.

10.3.2 Geographical distribution of geological resources (and exploration projects)

The following sections provide a brief description of a number of rare earth element projects, summarizing the status by country or continent. In the descriptions, the potential of existing mines from which rare earth elements may possibly be produced as by-products in the future, are not included. A comprehensive list of registered projects can be found in Appendix I.

10.3.2.1 Essential resources in Africa

The growing interest in the exploration of rare earth elements has also led to increased interest in Africa, also outside the large, known deposits in South Africa, Namibia and the secondary deposits in Madagascar; a summary of the deposits is given by Harmer & Nex (2016) and Kasay et al. (2012). The distribution of the selected deposits is shown in Figure 10-7.

MiMa has registered 124 deposits/prospects/projects in 27 African countries (Appendix I). Based on the same data, the safe resources amount to approx. 1.4 million tonnes of TREO, the probable approx. 4.5 million tonnes of TREO and the possible resources approx. 7 million tonnes of TREO. All geological types are represented in Africa; however, the number of carbonatites is particularly large and is predominantly linked to the development of the East African rift zone, which is found in Burundi, Kenya, Malawi and Tanzania. Alkaline intrusions are found in both North and West Africa, but there are relatively few exploration projects that include these geological types. A significant part of the REE exploration in Africa is targeted by-products from monazite bearing heavy mineral sand, as in Madagascar, for example, as well as ion adsorption/laterite deposits. Since the majority of the resources are carbonatites and laterites, the resources are dominated by light rare earth elements.

There are about 20 projects where the exploration has reached advanced exploration stage, and several have initiated mining on a small scale (Table 10-4). It is therefore considered likely that more African countries will be added to the list of primary producers of rare earth elements in the coming years. On the other hand, it is more uncertain which supply chains these will become part of, as several companies are trying to establish their own processing facilities, which the companies state are said to be without Chinese influence; this even though there are also examples of companies/projects that have entered into agreements with Chinese companies for technical and/or financial assistance and/or sales agreements (see Chapter 13 for examples). No plans have been announced for the establishment of companies in Africa for the preparation and processing of the rare earth elements from African mines.

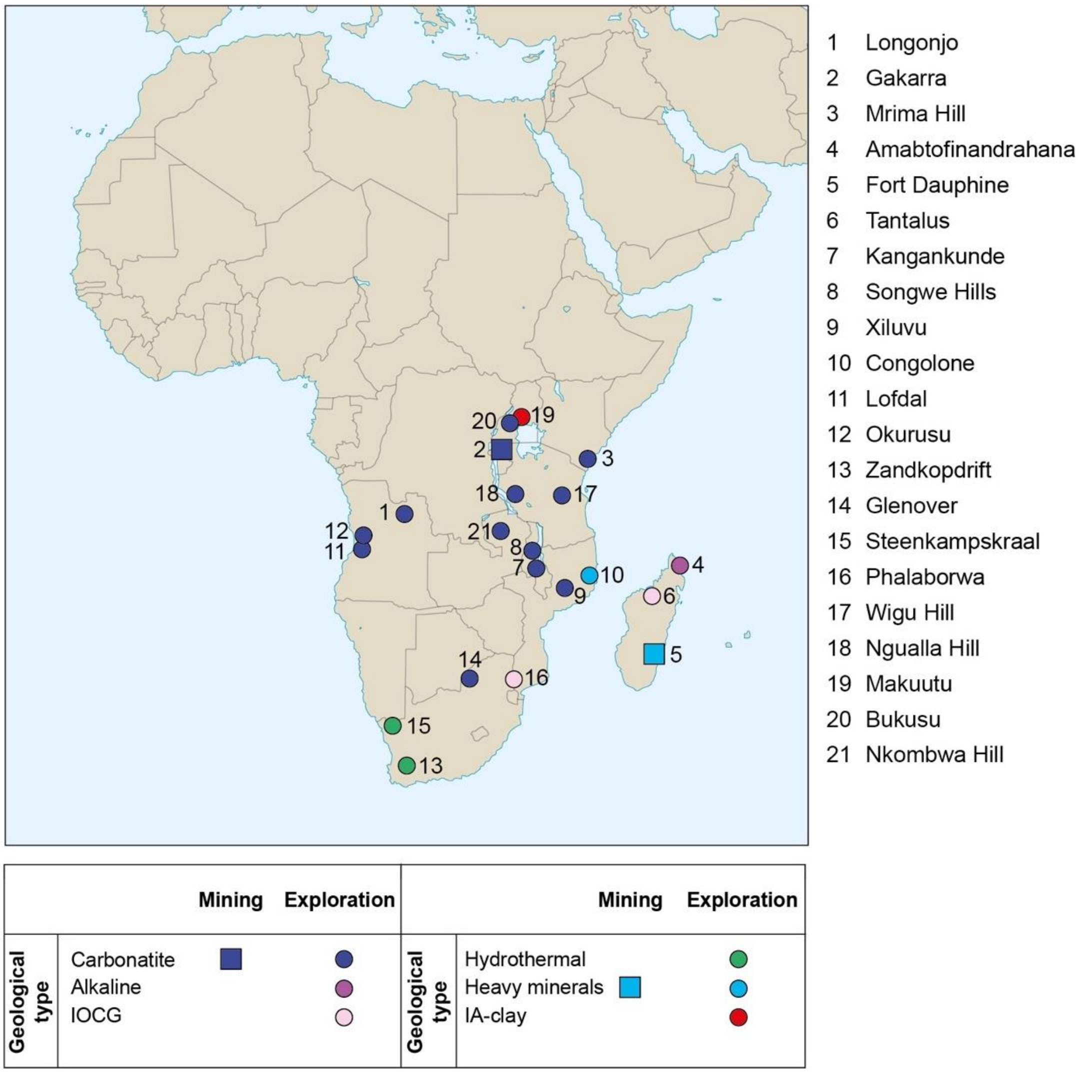


Figure 10-7 *Geographical distribution of selected mining and exploration projects in Africa, indicating geological type. Based on Appendix I.*

10.3.2.2 Essential resources in Asia (excl. China)

Publicly available information and data on exploration activities and resources in Asia is insufficient and Appendix I and the status below should therefore be assessed in this light. Appendix I includes 129 deposits in nine countries; among these deposits, heavy sand deposits with by-products of the rare earth elements (mostly monazite) dominate. The lack of a database, as well as the fact that the heavy sand sector in this region is dominated by smaller companies, which do not prepare resource inventories, means that the registered deposits only amount to approx. 13 million tonnes of TREO, which based on the geology is not a true picture of the region's resources for rare earth elements. Added to this underestimation, the region as a whole can be considered under-explored, and the overall resource potential is therefore assumed to be significantly underestimated. Figure 10-8 and Table 10-5 show some of the existing mines and advanced projects.

Table 10-4 *Overview of selected projects and mines for rare earth elements in Africa, incl. potential resource estimates. Excerpts from Appendix I and Appendix IV.*

Country	**Project**	**REE type**	**Status**	**Safe resources tonne TREO**	**Probable resources tonne TREO**	**Possible resources tonne TREO**
Angola	Longonjo	Carbonatite	Advanced	-	1,114,000	2,221,000
Burundi	Gakara (Karonge)	Carbonatite	Mine being established		-	26,000
Kenya	Mrima Hill	Carbonatite	Advanced	-	2,143,000	3,996,000
Madagascar	Amabtofinandrahana	Alkaline	Exploration	-	-	-
Madagascar	Fort Dauphine	Heavy sand	Production	-	-	-
Madagascar	Tantalus	IOCG	Advanced	39,000	-	-
Malawi	Kangankunde	Carbonatite	Exploration	-	106,000	-
Malawi	Songwe Hills	Carbonatite	Exploration	-	214,000	136,000
Mozambique	Xiluvo	Carbonatite	Advanced	-	23,000	-
Mozambique	Congolone	Heavy sand	Production – by-product		-	-
Namibia	Lofdal	Carbonatite	Advanced	-	9,000	10,000
Namibia	Okurusu Complex	Carbonatite	Production	-	-	-
South Africa	Zandkopdrift Mineral Resource	Hydrothermal	Advanced	476,000	330,000	17,000
South Africa	Glenover	Carbonatite	Exploration	-	243,000	119,000
South Africa	Steenkampskral	Hydrothermal	Advanced	17,000	67,000	-
South Africa	Phalaborwa	IOCG	Advanced	-	158,000	-
Tanzania	Wigu Hill	Carbonatite	Exploration	-	-	52,000
Tanzania	Ngualla Hill	Carbonatite	Advanced	898,000	92,000	22,000
Uganda	Makuutu	IOCG	Exploration	-	54,000	151,000
Uganda	Bukusu	Carbonatite	Advanced – formerly by-product	-	-	-
Zambia	Nkombwa Hill	Carbonatite	Advanced	-	-	255,000
Total				**1,430,000**	**4,553,000**	**7,005,000**

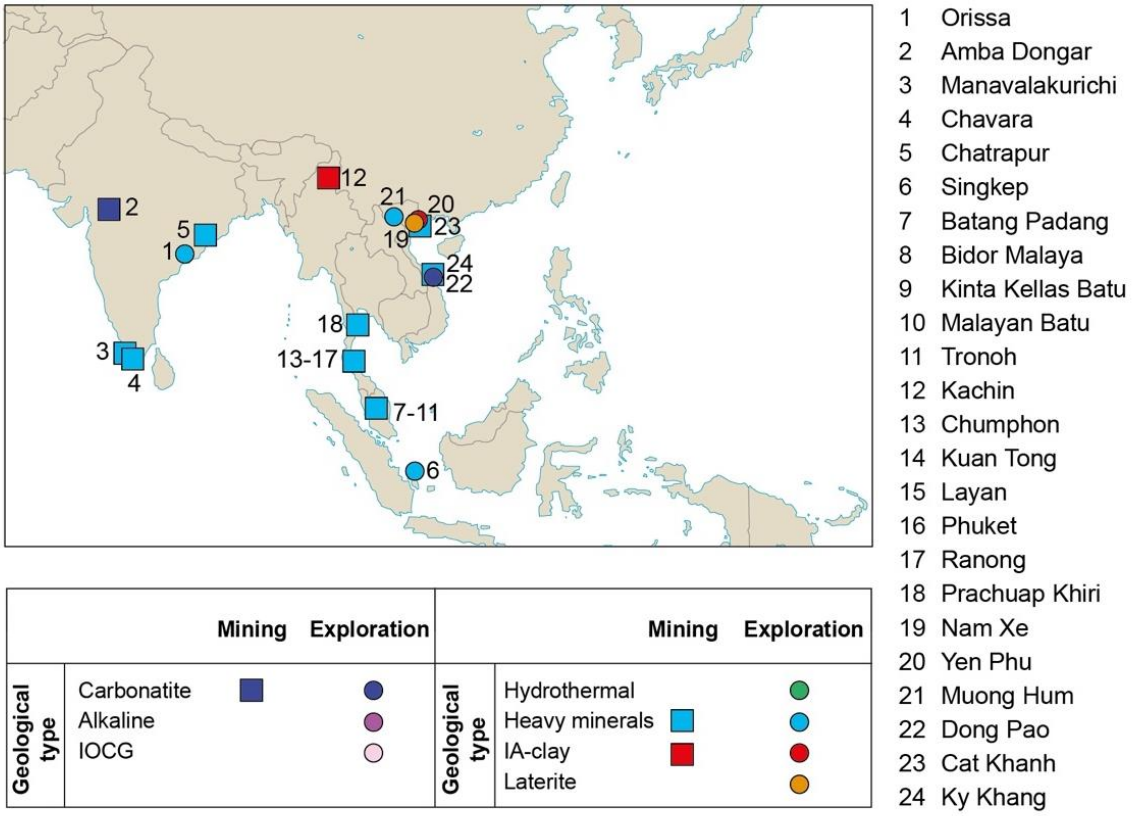


Figure 10-8 *Geographical distribution of selected mining and exploration projects in Asia (excluding China), indicating geological type. Based on Appendix I.*

India

India's deposits of rare earth elements are dominated by heavy sand containing monazite and are found mainly in the states of Andhra Pradesh, Kerala, Chattisgarh, Odisha, Jharkhand, West Bengal as well as in the North-eastern states. India's production of rare earth elements comes from the production sites of Tamil Nadu and Kerala. According to the USGS (2016, 2017, 2021), production in 2020 amounted to around 3,000 tonnes of TREO, while it was only approx. 1,700 tonnes in 2015 and 2016. In addition, there is a significant unregistered production of monazite concentrate.

Malaysia

Pengang Mining Company produces monazite and xenotime as a by-product of tin extraction in the Kinta Valley region. The processing is carried out at the company's plant in Menglembu. The production plant has a capacity of about 500 tonnes/year for each of the two concentrates (Adamas Intelligence 2014).

Myanmar

Myanmar has been producing rare earth elements since 2015 and has become a major supplier of heavy rare earth elements to the Chinese value chains. However, there is little information on the country's resource potential, which is partly due to there being no western exploration or mining companies involved and partly due to the majority of production being based on IA deposits, where there is generally no tradition of resource inventories. In addition, it may be to the advantage of the current military government to consider information about the resources as confidential data.

Vietnam

In 2011, the state-owned mining company Lavreco opened a production at the Dong Pao mine, where there has previously been significant illegal production of rare earth elements. The reserve is stated at approx. 5 million tonnes. The upper weathered zone contains approx. 10 % TREO, and the content of uranium and thorium varies between 0.01 and 0.001 %. The deposit predominantly consists of the minerals parisite, bastnäsite and apatite and is therefore dominated by light rare earth elements. The production began after the conclusion of agreements with, amongst others, Toyota Tsusho on sales to the Japanese market. In 2013, a production of 3,000 tonnes was planned (Adamas Intelligence 2014), but according to the USGS (2021), production has not exceeded that of 2019 which was 1,300 tonnes/year.

Table 10-5 *Overview of selected projects and mines for rare earth elements in Asian countries outside China. Excerpts from Appendix I and Appendix IV.*

Country	Project	REE type	Status
India	Orissa	Heavy sand	Mine being established
India	Amba Dongar	Carbonatite	Production
India	Manavalakurichi	Heavy sand, coastal deposits	Production
India	Chavara	Heavy sand, coastal deposits	Production – by-product
India	Chatrapur	Heavy sand, coastal deposits	Production – by-product
Indonesia	Singkep	Heavy sand, coastal deposits	Advanced – formerly by-product
Malaysia	Batang Padang	Heavy sand, coastal deposits	Production – by-product
Malaysia	Bidor Malaya Mine	Heavy sand, coastal deposits	Production – by-product
Malaysia	Kinta Kellas Batu	Heavy sand, coastal deposits	Production – by-product
Malaysia	Southern Malayan Batu Gajah Mine	Heavy sand, coastal deposits	Production – by-product
Malaysia	Tronoh Mines	Heavy sand, coastal deposits	Production – by-product
Myanmar	Kachin state	IA deposits	Production
Thailand	Chumphon	Heavy sand, coastal deposits	Production – by-product
Thailand	Kuan tong Mine	Heavy sand, coastal deposits	Production – by-product
Thailand	Layan	Heavy sand, coastal deposits	Production – by-product
Thailand	Phuket	Heavy sand, coastal deposits	Production – by-product
Thailand	Prachuap Khiri Khan	Heavy sand, coastal deposits	Production – by-product
Thailand	Ranong	Heavy sand, coastal deposits	Production – by-product
Vietnam	Nam Xe	Metamorphic/laterite	Advanced
Vietnam	Yen Phu	Heavy sand	Advanced
Vietnam	Muong Hum	Heavy sand, coastal deposits	Advanced
Vietnam	Dong Pao	Carbonatite	Mine being established
Vietnam	Cat Khanh	Heavy sand, coastal deposits	Production – by-product
Vietnam	Ky Khang	Heavy sand, coastal deposits	Production – by-product

10.3.2.3 Essential resources in Australia

Australia has a long tradition of mineral exploration, which has meant that mineral exploration of rare earth elements already began in the 2000s. In Appendix I, 128 prospects/projects are registered in Australia, where Mt. Weld is the only mine with rare earth elements as the main product; in addition, a number of companies extract heavy sand concentrates with monazite as a by-product, such as Eneabba (Figure 10-9 and Table 10-6).

In the inventory in Appendix I, 85 of the projects are heavy mineral sand deposits, followed by eight carbonatite deposits, four alkaline deposits, four laterite deposits, as well as some IOCG and hydrothermal deposits. There are 128 prospects/projects, of which 16 are either in production or can be considered as advanced projects with the potential to contribute to global production within five years. Several states in Australia do not allow production where uranium is a by-product, which was in part the reason why the company Lynas Corporation has established a processing plant in Malaysia as the ore in Mt. Weld contains uranium and thorium. Additionally, Australia has restrictions on the ownership of Chinese companies within mining and exploration companies, which has led to the rejection of some proposed corporate structures that include Chinese investors.

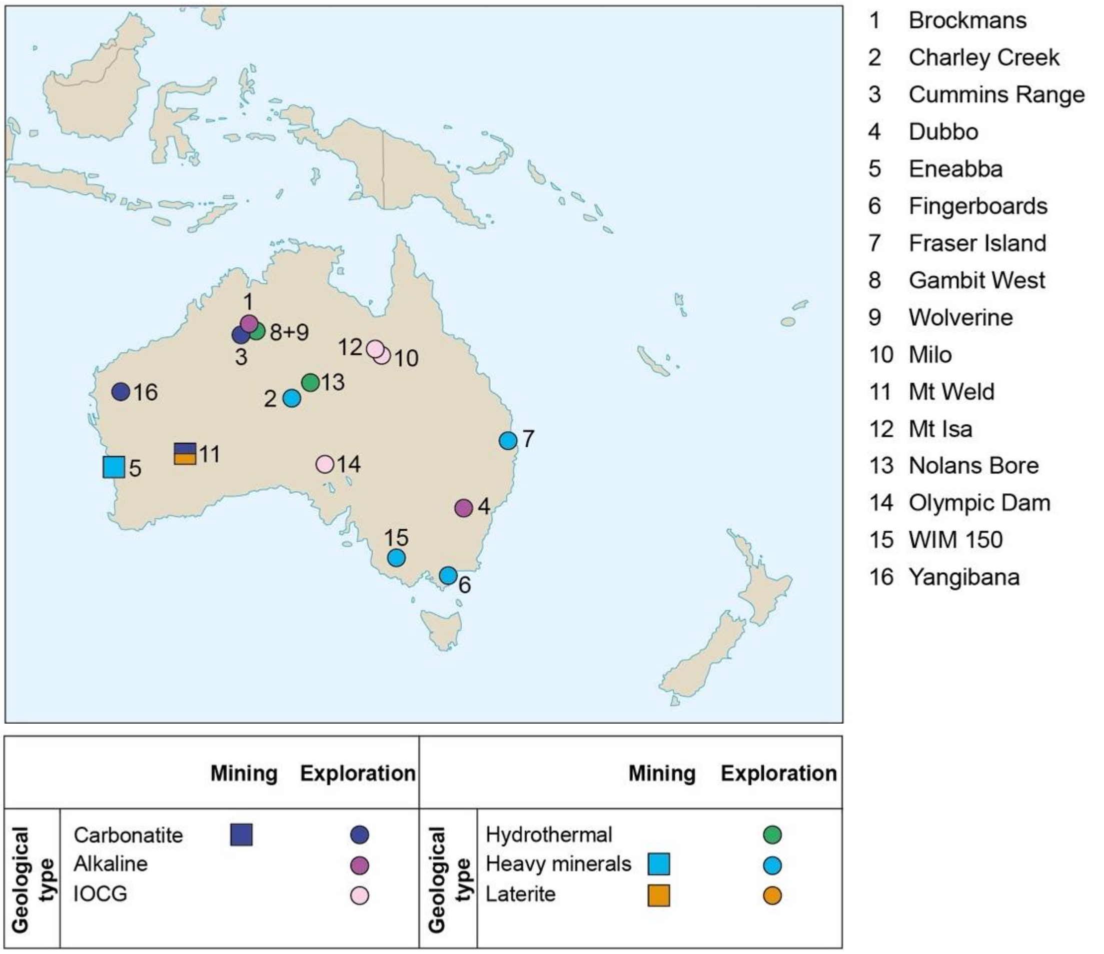


Figure 10-9 *Geographical distribution of selected mining and exploration projects in Australia, indicating geological type. Based on Appendix I.*

Lynas Corporation started production from Mt. Weld Central Lanthanide Deposit in 2011; the company also owns the REE deposit Duncan. According to Lynas' own information, the mining plant and the associated ore processing plant have a capacity of 240,000 tonnes/year of ore, corresponding to 26,500 tonnes/year of mineral concentrate.

Processing of the ore is carried out at the company's factory (Lynas Advanced Material Plant (LAMP)) in Gebeng, Malaysia, which was opened in 2012; the following REE products are produced: NdPr oxides, Ce carbonates, Ce oxides, LaCe carbonates and LaCe oxides, as well as SEG oxides (Lynas Corporation 2021); the company states that the production capacity is 22,000 tonnes/year TREO, of which only approx. 75 % is utilised. Production is sold to customers in Japan, Europe, the USA, and China (for more information on Lynas Corporation, see sections 13.1.2 and 13.1.21).

Table 10-6 *Overview of selected projects and mines for rare earth elements in Australia, incl. potential resource estimates. Excerpts from Appendix I and Appendix IV.*

Project	**Type**	**Project status**	**Safe resources tonne TREO**	**Probable resources tonne TREO**	**Poossible re-sources tonne TREO**
Brockmans	Alkaline	Advanced	-	68,000	-
Charley Creek	Heavy sand	Advanced	-	-	-
Cummins Range	Carbonatite	Advanced	-	147,000	85,000
Dubbo	Alkaline	Advanced	134,000	651,000	-
Eneabba	Heavy sand	Production	-	-	-
Fingerboards	Heavy sand	Advanced	-	-	-
Fraser Island	Heavy sand, coastal deposits	Advanced – formerly by-product	-	-	-
Gambit West (Browns Range)	Hydrothermal	Advanced	-	-	2,000
Wolverine (Browns Range)	Hydrothermal	Mine being established	-	24,000	18,000
Milo	IOCG	Advanced	-	112,000	112,000
Mt. Weld, Duncan	Carbonatite	Production	1,400,000	660,000	-
Mt. Isa	IOCG	Advanced	-	-	-
Nolans Bore	Hydrothermal/carbonatite	Advanced	142,000	546,000	528,000
Olympic Dam	IOCG	Production – by-product	-	-	-
WIM 150	Heavy sand, coastal deposits	Advanced	-	-	-
Yangibana North	Carbonatite/laterite	Advanced	5,000	35,000	5,000
Total			**1,681,000**	**2,485,000**	**750,000**

10.3.2.4 Essential resources in Europe and Greenland

In terms of resources, Europe, incl. Greenland, is one of the regions of the world that has the largest quantities of rare earth elements. Today, there are approx. 114 deposits of rare earth elements in Europe, incl. Greenland, several of which are world-class size (Appendix I). The deposits are divided into six main geological groups (Goodenough et al. 2016) (Figure 10-10):

- The Mesozoic-Cenozoic belt, which includes East Greenland, North-western Scotland, as well as the Rhine Rift Valley in Germany, the Central Massif in Southern France and the Anatolian rift zone in Turkey.
- The Palaeozoic Belt, which consists mainly of the Iberian Massif in Spain and Portugal, the Bohemian Massif in Germany, the Oslo Rift in Norway, and the Kola Peninsula in Russia.
- The Precambrian belt in Southern Greenland, which is dominated by the province of Gardar, the Svecofennian belt in Northern Sweden, and the Southern Swedish belt.
- Carbonatite intrusion, the largest of which are Fen in Norway, Sarfartoq in Greenland and Alnø in Sweden.
- Palaeozoic monazite deposits in Southern England, Belgium, France and Portugal.
- Paleo-Mesozoic carbonatites and alkaline provinces, such as Qaqarssuk and Tikiusaaq in Greenland, as well as Lock Loyal in Scotland, Delitzsch in Germany, Tajno in Poland and Ditrau in Romania.

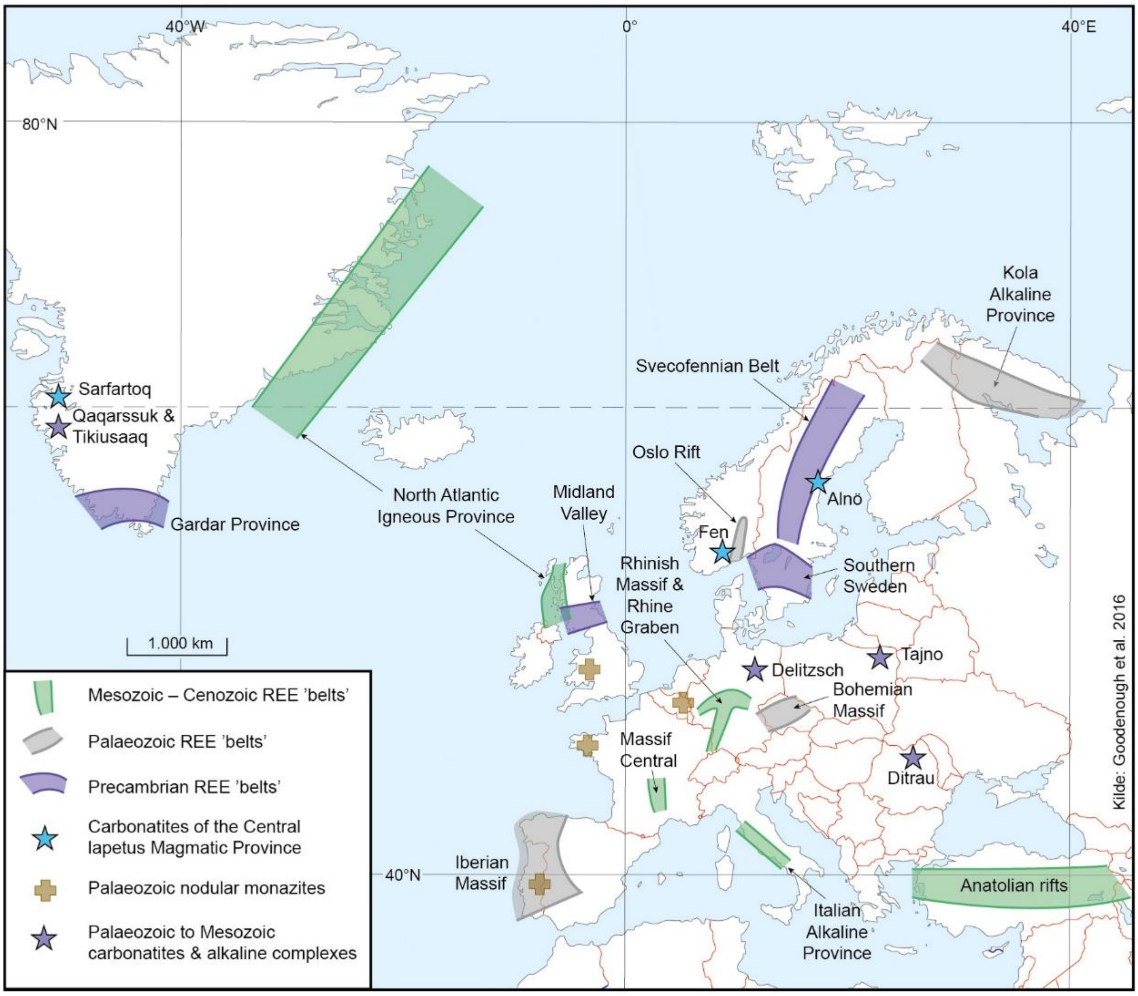


Figure 10-10 *Overview of focus areas for mineral exploration for rare earth elements in Europe. Source: Goodenough* et al. *(2016).*

In addition to the above, there are 15 laterite (bauxite) deposits in the Mediterranean area (Goodenough et al. 2016). Some of these deposits are used as raw material for aluminium, but the content of rare earth elements is not used. There are a number of research projects focusing on the utilisation of these untapped resources, including several with a special focus on scandium. The majority of European rare earth element deposits are not explored, as resource size and quality or logistical conditions do not make them commercially interesting.

The meassured resources in Europe, incl. Greenland, amounts to approx. 1.5 million tonnes of TREO, while the probable and possible resources constitute 32 and 34 million tonnes of TREO, respectively (Appendix IV); most of these resources are from the Greenland deposits. It should be noted, however, that inaccurate statements from Kringlerne in Greenland affect the resources in an upward direction.

For approximately the last 15 years, European REE mineral exploration has focused on deposits in Greenland, Sweden, Norway, and Finland, several of which are commercially interesting and where technical, economic and environmental studies are underway on the possibilities of bringing them into production. Particular attention is being paid to the alkaline deposits in Greenland (Kvanefjeld/Kuannersuit and Kringlerne/Killavaat Alannguat) and Sweden (Norra Kärr) as well as the carbonatite complex Fen in Norway, all of which were part of the EU research project EURARE (www.eurare.org/), which aimed to assess the possibilities of establishing supply chains in the EU (and the associated countries Greenland and Norway) (Table 10-7).

Greenland

The international mineral exploration of Greenland's potential for rare earth elements started in 2007 with a single license, which focused on the alkaline Ilímaussaq complex, which at this time was geologically well documented based on 50 years of scientific research and several years of uranium exploration. The rapidly growing global interest in rare earth elements led to a significant increase in exploration activities in Greenland. In 2015, there were 19 exploration licenses for rare earth elements, which covered an area of approx. 3,200 km^2 and at this time accounted for a significant percentage of the mineral exploration in Greenland.

Today, 20 rare earth elements deposits are known, and in addition four geological zone carry the potential to host rare earth deposits, such as (see also Figure 10-11):

- Alkaline rocks in the Gardar province in South Greenland (Kvanefjeld/Kuannersuit, Kringlerne/Killavaat Alannguat, Motzfeldt, Grønnedal-Ika and others) and the Gardiner complex in East Greenland
- Carbonatite deposits in West Greenland (e.g. Sarfartoq, Qaqarssuk, Qassiarsuk, Tikiusaaq)
- Heavy sand deposits (fossil) in East Greenland (Milne Land)
- Hydrothermal deposits in West Greenland (Niaqornakavsak)

In 2021, three of the licenses with the largest resources are still active (Tanbreez's license at Kringlerne/Killavaat Alannguat, Greenland Minerals 'license at Kvanefjeld/Kuannersuit and Hudson Resources' license at Sarfartoq); Tanbreez was granted a mining lease in 2020.

In 2016, Greenland Minerals applied for a mining lease for the deposit on Kvane-fjeld/Kuannersuit, but environmental challenges due to the content of uranium and thorium as well as the geographical proximity to Narsaq resulted in a multi-year application process. During this period, the political support for the project changed due to the concern of the uranium and thorium content, and in the autumn of 2021, the Naalakkersuisut (Greenland Government) introduced a law banning mineral exploration of uranium and exploitation of rocks containing more than 100 ppm uranium (U). Consequently, Greenland Minerals has decided to cease operations in Greenland (KNR 2021).

A comprehensive overview of the most important Greenland deposits with rare earth elements is shown in Figure 10-11. A review of Greenland's resource potential for rare earth elements is given in Paulick et al. (2015) and Goodenough et al. (2016).

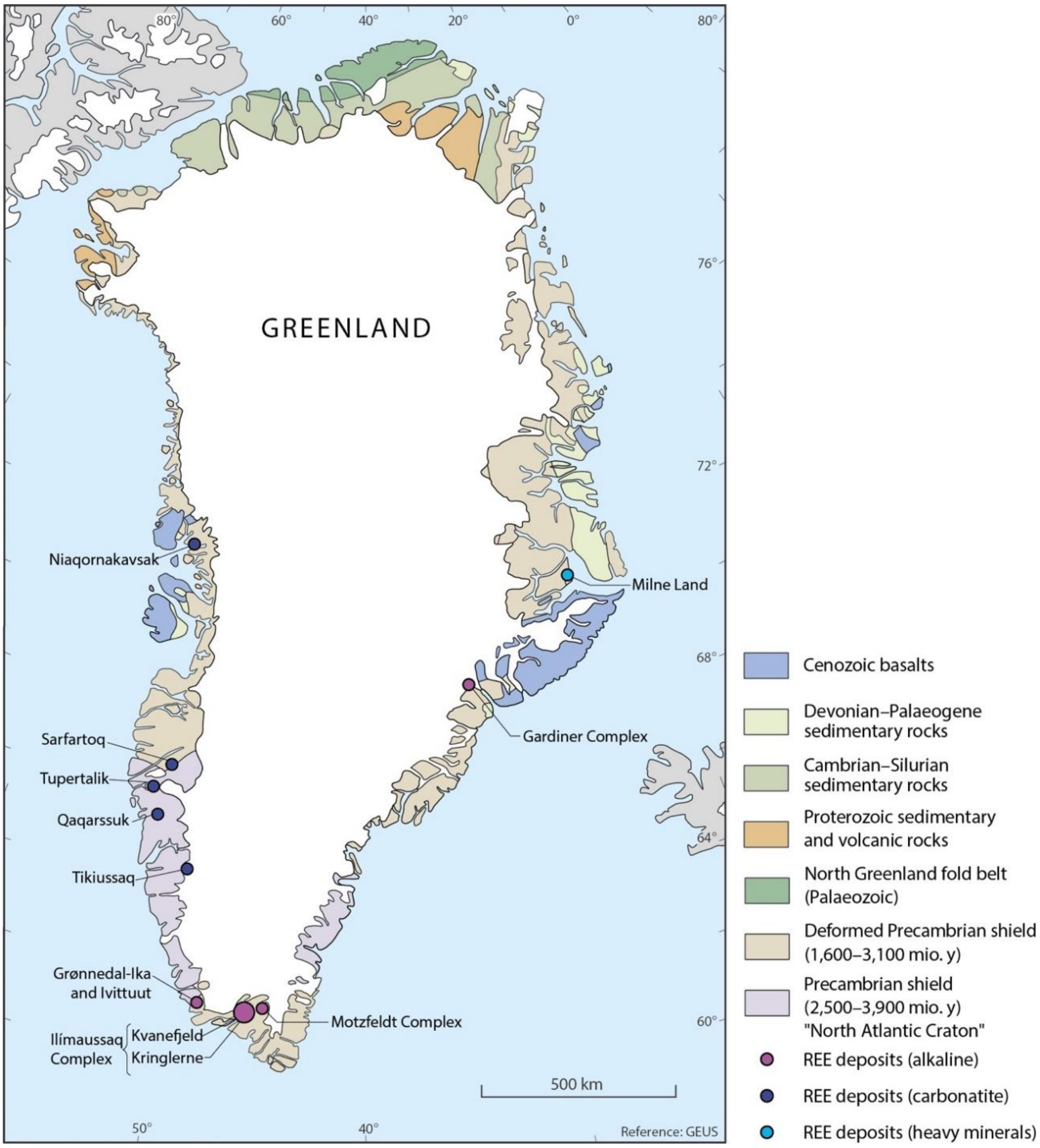


Figure 10-11 *Geological map with the most important deposits of rare earth elements in Greenland. Source: Goodenough* et al. *(2016).*

Table 10-7 *Overview of selected projects and mines for rare earths in the Nordic countries, incl. Greenland. Resource estimates are displayed, if available. Excerpts from Appendix I and Appendix IV.*

Country	**Locality**	**REE type**	**Company**	**Status (interpreted)**	**Safe resources tonne TREO**	**Probable resources tonne TREO**	**Possible resources tonne TREO**
Finland	Sokli	Carbonatite	Finnish Minerals Group	Advanced	-	-	-
Greenland	Kvanefjeld (main area)	Alkaline	Greenland Minerals A/S	Advanced (pause)	1,600,000	3,600,000	800,000
Greenland	Sarfartoq	Carbonatite	Hudson Resources A/S	Exploration (pause)	-	100,000	-
Greenland	Kringlerne	Alkaline	Rimbal Pty Ltd	Advanced	-	28,000,000	-
Norway	Fen	Carbonatite	REE Minerals AS	Exploration	-	-	900,000
Sweden	Olserum	Hydrothermal	Leading Edge Materials Ltd.	Advanced	-	-	-
Sweden	Kiruna	Iron-oxide-apatite	LKAB	Advanced – by-product	-	-	19,800,000
Sweden	Leveaniemi	Iron-oxide-apatite	LKAB	Advanced – by-product	-	-	2,000,000
Sweden	Malmberget	Iron-oxide-apatite	LKAB	Advanced – by-product	-	-	8,000,000
Sweden	Norra Kärr	Alkaline	Leading Edge Materials Ltd.	Advanced (pause)	-	200,000	200,000
Total					**1,600,000**	**31,900,000**	**31,700,000**

Norway

In Norway, there has been particular focus on the carbonatite complex Fen for the mineral exploration of rare earth elements, due to the large resource potential and logistical conditions with proximity to shipping and industrial areas. For almost 300 years, until 1927, iron ore was mined from Fen, and in the period 1953-1965, niobium was mined. Rare earth elements are found in several rock types, including 'rødbergite' and Fe-dolomite ('rauhaugite'), of which the latter is considered the most prospective (Dahlgren 2019). Mineral exploration for rare earth elements is still being carried out in the Fen field (Figure 10-12).

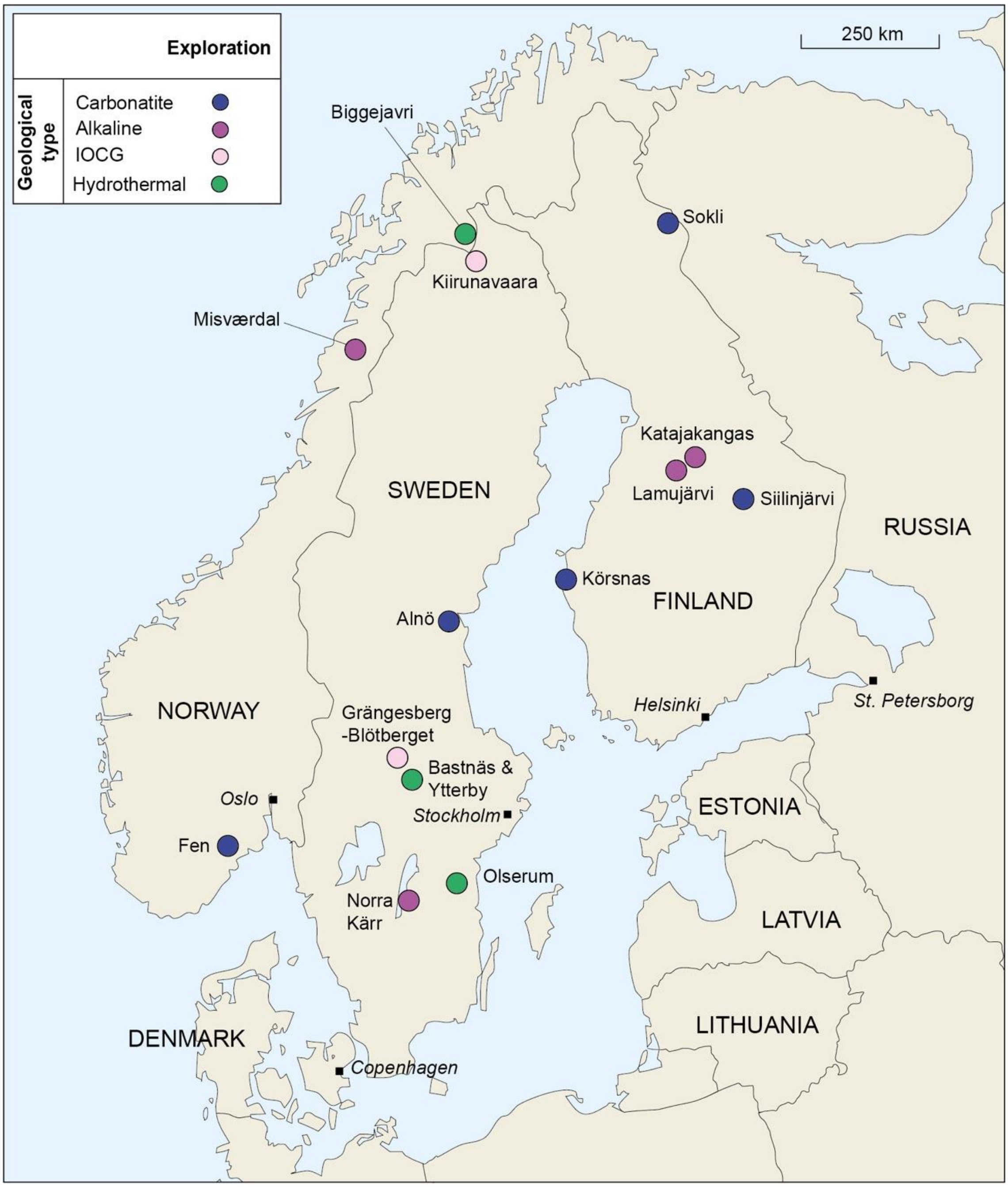


Figure 10-12 *Overview of some of the Scandinavian deposits of rare earth elements. After Goodenough et al. (2016).*

Sweden
Sweden is, as mentioned in section 2.2, the country where the rare earth elements were first identified, and after several hundred years of exploration, many deposits have been located (Figure 10-12). Most of these are found in Central Sweden and are all considered non-economic. Research in recent years has focused on the alkaline deposit Norra Kärr and the hydrothermal deposit Olserum. Leading Edge Materials Ltd., Canada, holds the rights to both deposits, of which the Norra Kärr deposit has attracted the most attention. However, the results of an EIA study in 2019 meant that activities had to be put on hold, as the submitted business model did not meet the imposed requirements from the authorities. In the autumn of 2021, work is underway on a concept where the ore is intended to be mined at Norra Kärr and subsequently shipped to Central or Northern Sweden, where heap leaching facilities will be established, which Leading Edge Materials Ltd. expects can meet the authorities' environmental requirements. The Olserum project is on standby.

The iron ore deposits at Kiruna and Biggejärvi in Northern Sweden both contain the mineral apatite with small amounts of rare earth elements. In the long run, it is possible to utilise these resources as a by-product of iron ore production. Utilising apatite from iron ore production is being researched in various parts of the world, and due to the large amounts of iron ore mined, could potentially contribute significantly to the supplies of rare earth elements.

Finland
In Finland, there are 16 deposits/prospects/projects for rare earth elements associated with carbonatite, alkaline and hydrothermal geological environments. None of the projects that have rare earth elements as main products can be classified as advanced projects (Figure 10-12, Appendix I), but among the deposits there are several with significant by-product potential, such as the phosphate deposits Sokli, Korsnäs and Kortejärvi (Al-Ani et al. 2018).

10.3.2.5 Essential resources in China

China is endowed with a large number of rare earth elements doposits that incorporate a variety of geological types; some of these are shown in Figure 12-1. In Appendix I, 152 deposits have been recorded (the actual number of deposits is presumably significantly higher), which are divided into the following geological types: 24 carbonatite deposits, 35 IA deposits and 28 heavy sand deposits, some of which are shown in Table 10-8 and in Figure 12-1. In terms of resources, it is largely the carbonatite deposits that contribute to the large quantities; IA deposits are generally relatively small (< 100,000 tonnes of TREO); heavy sand deposits contribute significantly to production, but make up only a small part of China's total resources.

China's largest resources are the carbonatite deposits at Bayan Obo and Maoniuping, both with bastnäsite as the dominating rare earth element mineral and thus is relatively enriched in light rare earth elements. As can be seen from Table 10-8, the measured resources from the two large carbonate mines are around DKK 6.3 million tonnes TREO. Appendix IV states that the probable and possible resources are approx. 2 million and 1 mill. tonnes TREO respectively; data in these inventories is from 2016 and is very conservative, also seen considering the large-scale exploration activities in China's carbonatite areas. However, there is generally great uncertainty about China's resources, which some believe are overestimated (Kruemmer personal communication October 2021b). Production in China is discussed in more detail in Chapters 11 and 12.

Table 10-8 *Overview of selected projects and mines for rare earth elements that significantly contribute to China's resources, incl. potential resource estimates. Excerpts from Appendix I and Appendix IV.*

Locality	REE type	Company	Status (interpreted)	Safe re-sources tonne TREO
Bayan Obo (East)	Carbonatite	China Northern Rare Earth Group/Baotou Steel	Production	-
Bayan Obo (Main and West)	Carbonatite	China Northern Rare Earth Group/Baotou Steel	Production	3,400,000
Bayan Obo (surrounding)	Carbonatite	China Northern Rare Earth Group/Baotou Steel	Advanced	300,000
Bayan Obo (West)	Carbonatite	China Northern Rare Earth Group/Baotou Steel	Advanced	1,200,000
Dalucao	Carbonatite	Dechang Houdi Rare Earth Mining Co. Ltd	Production	-
Fujian Jinlong	IA deposits	Fujian Changting Jinlong Rare Earth Co. Ltd.	Mine being established	-
Ganzhou	IA deposits	Ganzhou Mining Group	Production	-
Guandong	IA deposits	Guandong Rising NF	Production	-
Gupsehan	IA deposits	China Minmetals Corp.	Production	-
Longchuan Heping	IA deposits		Production	-
Longnan (Zudong)	IA deposits	People's Republic of China	Production	-
Longyan, Jiangxi	IA deposits	Xiamen Tungsten Industry Co. Ltd	Production	-
Maoniuping	Carbonatite	China Southern Rare Earth Group Co Ltd/ Sichuan Jiangtong Rare Earth Co. Ltd	Production	1,400,000
Mianning	Alkaline		Production	-
Miaoya	Carbonatite	n.a.	Advanced	-
Renju	IA deposits	Rising Nonferrous Metals Share Co. Ltd	Advanced	-
Tianzhuping Sha'ebo	Ingen information	Ganzhou Mining Group	Advanced	-
Xuanwu 1	IA deposits	Ganzhou Mining Group	Production	-
Xuanwu 2	IA deposits	Ganzhou Mining Group	Production	-
Total				**6,300,000**

10.3.2.6 Essential resources in North America

The North American resource potential for rare earth elements is one of the most significant in the world and includes more than 200 deposits (Appendix I lists 198 prospects/projects), several of which are world-class in size. It was also this region that dominated primary production, when industrial demand began around the 1950s up until 2002, when the United States decided to stop production due to environmental problems caused by uranium in tailings. After several years without production the United States, in 2015, once again became one of the few western countries to produce rare earth elements, which are, however, processed in China (see Chapter 13). Select mining and exploration projects in North America can be seen in Figure 10-13.

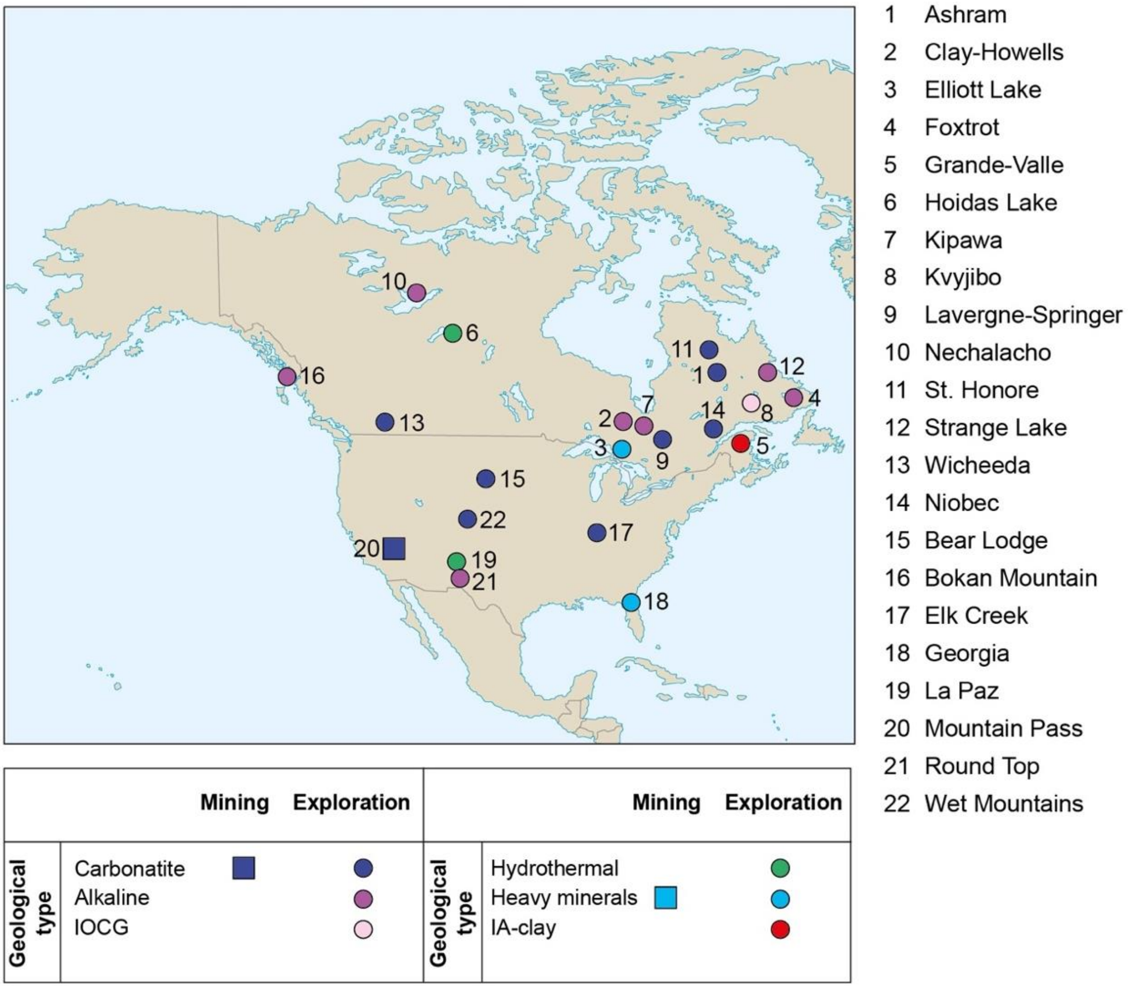


Figure 10-13 *Geographical distribution of select mining and exploration projects in North America, indicating geological type. Based on Appendix I.*

Canada

The majority of Canadian deposits/prospects/projects are located in Labrador, Quebec and Ontario and are linked to the Precambrian Canadian Shield area and the Appalachian fold chain areas, which have high potential for hosting alkaline deposits and rare earth element carbonatite deposits; these types also make up approx. half of the Canadian exploration projects and the majority of the known resources. The total resources of the exploration projects have been calculated at approx. 0.2 million tonnes of TREO, which is confirmed, as well as a potential resource of 25 million tonnes TREO and 10 million tonnes TREO that may be present. The largest resources are associated with the Strange Lake and Nechalacho deposits (Table 10-10).

USA

The potential for rare earth elements in the US is huge. Appendix I comprises 106 deposits/prospects/projects, of which heavy sand deposits constitute the largest group, while carbonatite and alkaline deposits, which dominate the potential resources, comprise 24 prospects/projects. US published resource data for secure and potential resources includes only the carbonatite deposit at Mountain Pass, which MP Materials mines, as well as a few exploration projects of other carbonatites and alkaline rocks, as the resource potential of the heavy sand deposits is not immediately available, similar to other countries. Based on Appendix I, the United States' secure reserves amount to approx. 1.4 million tonnes TREO, of which Mountain Pass contains approx. 1.3 million tonnes TREO, and the probable resources are approx. 0.8 million tonnes TREO. This is in all probability not a true picture of the US' resource situation, as knowledge of the geological conditions and ongoing prospects indicates that the resources are significantly larger.

10.3.2.7 Essential resources in Russia, Kyrgyzstan, and Kazakhstan

There is no tradition of western companies undertaking mineral exploration in Russia, Kyrgyzstan and Kazakhstan, and thus the publicly available information on the resources is limited and the geological resource potentials of the areas are generally not well described. However, the Murmansk region contains some of the world's largest geological deposits of rare earth elements and in 2016 was estimated at 22.4 million tonnes TREO in secure reserves and 36.2 million tonnes TREO in probable resources (Kalashnikkov et al. 2016). The resources are linked in particular to the titanite-apatite deposit Khibiny and the loparite-eudialyte deposit Lovozero, both of which have been exploited for a number of years, predominantly with rare earth elements as by-products (Cotting et al. 2019). The Tomtor deposit (niobium and rare earth elements) is a large high-grade deposit (6 million tonnes/13.5 % TREO).

In addition, there have been by-products of rare earth elements as part of uranium production in Kazakhstan and Kyrgyzstan, but overall, resource information for these countries is deficient (Appendix I). An overview of selected rare earth element projects and mines in Russia, Kyrgyzstan and Kazakhstan is shown in Table 10-9.

Table 10-9 *Overview of selected rare earth element projects and mines in Russia, Kyrgyzstan, and Kazakhstan; incl. potential resource estimates. Excerpts from Appendix I and Appendix IV.*

Project	REE type	Status	Safe resources tonne TREO	Probable resources tonne TREO	Possible resources tonne TREO
Abukalakskoe	No info	Advanced	-	-	-
Schevchenko	IOCG	Production (by-product)	-	-	-
Stepnogorsk	Tailings	Production	-	-	-
Aktyuz	No info	Exploration	-	-	-
Kutessay II	Alkaline	Production	37,000	47,000	4,000
Kutessiask	Unknown	Production	-	-	-
Elisenvaara	Alkaline	Production	-	-	-
Khibiny (apatite deposit)	Alkaline	Production	41,000	-	-
Lovozero (loparit deposit)	Alkaline	Production	57,000	10,000,000	-
Seligdar	Carbonatite	Exploration	15,000	-	-
Tomtorskoye	Carbonatite	Advanced	924,000	-	-
Azovske	Alkaline	Advanced (pause)	-	-	-
Mazurivske	Unknown	Exploration	-	-	-
Total			**1,071,000**	**10,047,000**	**4,000**

Table 10-10 *Overview of select projects and mines for rare earth elements in Canada and the United States, incl. potential resource estimates. Excerpts from Appendix I and Appendix IV.*

Country	Project	REE type	Company	Status (interpreted)	Safe resources tonne TREO	Probable resources tonne TREO	Possible resources tonne TREO
Canada	Ashram	Carbonatite	Commerce Resources Corp	Advanced	28,000	526,000	4,132,000
Canada	Clay-Howells	Alkaline		Exploration	-	-	62,000
Canada	Elliott Lake Teasdale	Heavy sand	Appia Rare Earths & Uranium Corp	Advanced	-	475,000	-
Canada	Foxtrot	Alkaline	Search Minrals Inc	Advanced	-	48,000	56,000
Canada	Grande-Vallee	IA deposits	Advance Energy Minerals	Advanced	-	605,000	-
Canada	Hoidas Lake	Hydrothermal	Star Minerals (?)	Exploration	25,000	70,000	-
Canada	Kipawa (Zeus)	Alkaline	Vital Metals Ltd/ Matamec Explorations Inc.	Advanced	-	77,000	-
Canada	Kwyjibo	IOCG	Investissement Quebec/Focus Graphite Inc.	Advanced	68,000	119,000	-
Canada	Lavergne-Springer	Carbonatite	Canada Rare Earths Corporation	Exploration	-	48,000	149,000
Canada	Nechalacho (Thor Lake)	Alkaline	Avalon Advanced Material	Advanced	63,000	248,000	-
Canada	Nechalacho Upper	Alkaline	Vital Metals Ltd	Mine being established	22,000	120,000	-
Canada	St. Honore (Niobec)	Carbonatite	IAMGOLD; Magris Resources Inc; Commerce Resources	Advanced	-	18,321,000-	-
Canada	Strange Lake	Alkaline	Quest Rare Minerals Ltd/Tongat Metals Inc.	Advanced	-	2,587,000	1,822,000
Canada	Wicheeda	Carbonatite	Defense Metals Corp/Marvel Discovery Corp.	Exploration	-	148,000	350,900
USA	Bear Lodge	Carbonatite	Rare Element Resources	Exploration (pause)	113,000	446,000	-
USA	Bokan Mountain	Alkaline/hydroth.?	Ucore Rare Metals	Mine being established	-	29,000	31,000
USA	Elk Creek	Carbonatite	Nio-Corp Development Ltd.	Advanced	-	-	-
USA	Georgia	Heavy sand	Chemours	Advanced	-	-	-
USA	La Paz	Hydrothermal	American Rare Earth	Exploration	-	297,000	-
USA	Mountain Pass	Carbonatite	MP Materials/Bhang Inc	Production	1,333,000	-	-
USA	Round Top	Alkaline	USA Rare Earth (80 %) JV Texas Rare Earth Resources (20 %)	Advanced	120	98	441
USA	Wet Mountains	Carbonatite	U.S. Rare Earths Inc.	Exploration	-	-	-
Total					**1,652,120**	**24,164,098**	**6,603,341**

10.3.2.8 Essential resources in South America

With only 64 registered deposits/prospects/projects, most of which are found in Brazil, South America is one of the regions with few identified resources of rare earth elements (Appendix I). Geologically, the region is dominated by heavy sand deposits as well as alkaline and carbonatite deposits. The publicly known resources are also few and are linked to deposits in Brazil (the carbonatite deposit Araxa and the heavy sand deposit Buena Norte), from which there is/have been by-products of rare earth elements. The resource potential calculated in Appendix I consists of a secure resource of approx. 30,000 tonnes TREO, and approx. 0.5 mill. tonnes and 1.4 mill. tonnes TREO in potential and possible resources (Table 10-11). The resource potential is expected to be significantly greater, because some of the deposits carries the potential to mine rare earth elements as a by-product.

10.3.3 Resource sizes are not the most important criteria for success

For projects with special metals, such as rare earth elements, where there is a limited market and where few producers can dominate the market, the size of the resources of a project is not a key parameter for assessing a project's commercial value, as it is typically sales that determines the production volume. A project with a resource that extends several decades is therefore not necessarily a more economically attractive project than a project with a somewhat smaller resource, if the resource will simply supply enough to give the project the necessary timeframe for the project to be economically attractive.

As mining and exploration projects for rare earth elements in investor circles are often marketed on the basis of e.g. resource size, the 20 largest deposits are measured in relation to secure and probable resources, compared in Table 10-12.

It appears that a number of the exploration projects that are often referred to as the (next) upcoming mines are not among the 20 largest resources. This applies to Songwe Hill (Malawi), La Paz (USA), Lofdal (Namibia) and Norra Kärr (Sweden), for example, and conversely, some of the projects that contain very large resources, such as Kringlerne/Killavaat Alannguat and Kvanefjeld/Kuannersuit (both in Greenland), Fen (Norway) and Montviel (Canada), have not – alone on a resource basis – been able to reach the decision-making level for starting a mine any faster. This is because such decisions also deal with many other factors, such as the composition of the rare earth elements, the ore's quality, sales opportunities, logistics, etc.

Table 10-11 *Overview of selected projects and mines for rare earth elements in Argentina and Brazil, incl. potential resource estimates. Excerpts from Appendix I and Appendix IV.*

Country	**Project**	**REE type**	**Status**	**Safe resources tonne TREO**	**Probable re-sources tonne TREO**	**Possible resources tonne TREO**
Argentina	Cueva del Chacho	Heavy sand	Exploration	-	-	-
Argentina	RioTercero	Heavy sand, river deposits	Advanced	-	-	-
Argentina	Rodeo de Los Molles	Unknown	Advanced	-	-	-
Brazil	Anitapolis	Carbonatite	Advanced – by-product	-	-	-
Brazil	Araxa	Carbonatite	Exploration	28,000	526,000	876,000
Brazil	Buena Norte	Heavy sand, coastal deposits	Production	-	-	-
Brazil	Catalao I	Carbonatite	Advanced – by-product	-	-	-
Brazil	Cumuruxatiba	Heavy sand, coastal deposits	Production – by- product	-	-	-
Brazil	Guarapari	Heavy sand, coastal deposits	Production – by- product	-	-	-
Brazil	Itapemirim	Heavy sand, coastal deposits	Production – by- product	-	-	-
Brazil	Jacupiranga	Alkaline	Advanced – by- product	-	-	-
Brazil	Matka Zul	Unknown	Exploration	-	-	-
Brazil	Morro dos Seis Lagos	Carbonatite	Exploration	-	-	-
Brazil	Northeast Dunes	Heavy sand, coastal deposits	Exploration	-	-	-
Brazil	Pitinga	Heavy sand, coastal deposits	Advanced – by- product	-	-	-
Brazil	Pocos de Caldas	Alkaline	Prospect	-	-	-
Brazil	Porto Sequro	Heavy sand, coastal deposits	Advanced – formerly by- product	-	-	-
Brazil	Prado area	Heavy sand, coastal deposits	Deposits – no data	-	-	-
Brazil	Sao Goncalo do Sapucai	Heavy sand, river deposits	Exploration	-	-	-
Brazil	sao Joao de Barr	Heavy sand, coastal deposits	Exploration	-	-	-
Brazil	Serra Negra	Carbonatite	Advanced – by- product	-	-	-
Brazil	Serra Verde	IA deposits	Exploration	46,000	552,000	449,000
Brazil	Tapira	Carbonatite	Advanced – by- product	-	-	-
Brazil	Vitoria District	Heavy sand, coastal deposits	Production – by- product	-	-	-
Venezuela	Cerro Impacto	Carbonatite	Exploration	-	-	-
Total				**74,000**	**1,078,000**	**1,325,000**

Table 10-12 *The world's largest resources of rare earth elements in the categories 'secure' and 'probable', by country and company. Excerpts from Appendix I and Appendix IV.*

	Country	Project	Secure resources tonne TREO		Country	Project	Probable resources tonne TREO
1	China	Bayan Obo (main area)	3,444,000	1	Greenland	Kringlerne	27,950,000
2	Greenland	Kvanefjeld (main area)	1,587,000	2	Canada	Niobec	18,321,000
3	China	Maoniuping	1,432,000	3	Russia	Lovozero	10,000,000
4	Australia	Mt. Weld, Duncan	1,400,000	4	Vietnam	Mau Xe	7,798,000
5	USA	Mountain Pass, CA	1,333,000	5	Greenland	Kvanefjeld (hovedområdet)	3,612,000
6	China	Bayan Obo (west)	1,213,000	6	India	Amba Dongar	3,150,000
7	Tanzania	Ngualla Hill	898,000	7	Mongolia	Mushgia Khudug	3,150,000
8	South Africa	Zandkopdrift Mineral Resource	476,000	8	Canada	Strange Lake	2,587,000
9	China	Bayan Obo (surrounding area)	329,000	9	Kenya	Mrima Hill	2,143,000
10	Australia	Nolans Bore	142,000	10	China	Maoniuping	2,116,000
11	Australia	Dubbo	140,000	11	Canada	Montviel	1,241,000
12	USA	Bear Lodge	113,000	12	Angola	Longonjo	1,114,000
13	Canada	Kwyjibo	68,000	13	Australia	Mt. Weld, Duncan	660,000
14	Canada	Nechalacho (Thor Lake)	63,000	14	Australia	Dubbo	651,000
15	Russia	Lovozero (loparite deposits)	57,000	15	Canada	Grande-Vallee	605,000
16	Russia	Khibiny (apatite deposits)	41,000	16	Australia	Nolans Bore	546,000
17	Madagascar	Tantalus	39,000	17	Canada	Ashram (samlet ressource)	526,000
18	Kyrgyzstan	Kutessay II	37,000	18	Brazil	Araxa	526,000
19	Brazil	Araxa	28,000	19	Canada	Elliott Lake Teasdale	475,000
20	Canada	Ashram (overall resources)	28,000	20	USA	Bear Lodge	446,000

11. China's Strategies and Practice(s)

All countries are dependent on imports of many different mineral raw materials; the degree of dependence varies from country to country due to the countries' different geological preconditions for mining, infrastructure and industrial structures. This also applies to large countries such as the United States and China, although there is a difference in the degree and nature of their dependence. Some of these differences are illustrated in Figure 11-1, which shows China's and the United States' dependence on a number of the raw materials that, *inter alia*, are important for the green transition. Some of these imports are not based on a lack of domestic raw materials, but more on the existence of the necessary infrastructure for processing the raw materials and markets to purchase the products. For example, in 2020, the United States accounted for approx. 15 % of world production of rare earth elements, which in principle could supply US industry. However, unprocessed mineral concentrates were and are instead exported for processing and consumption in China, as the United States does not have the necessary infrastructure to process the concentrates. Conversely, China's imports of rare earth elements, which the country itself has the resources and infrastructure to process, can be seen as part of a geopolitical strategy to maintain control over the global value chains, which are of great economic importance.

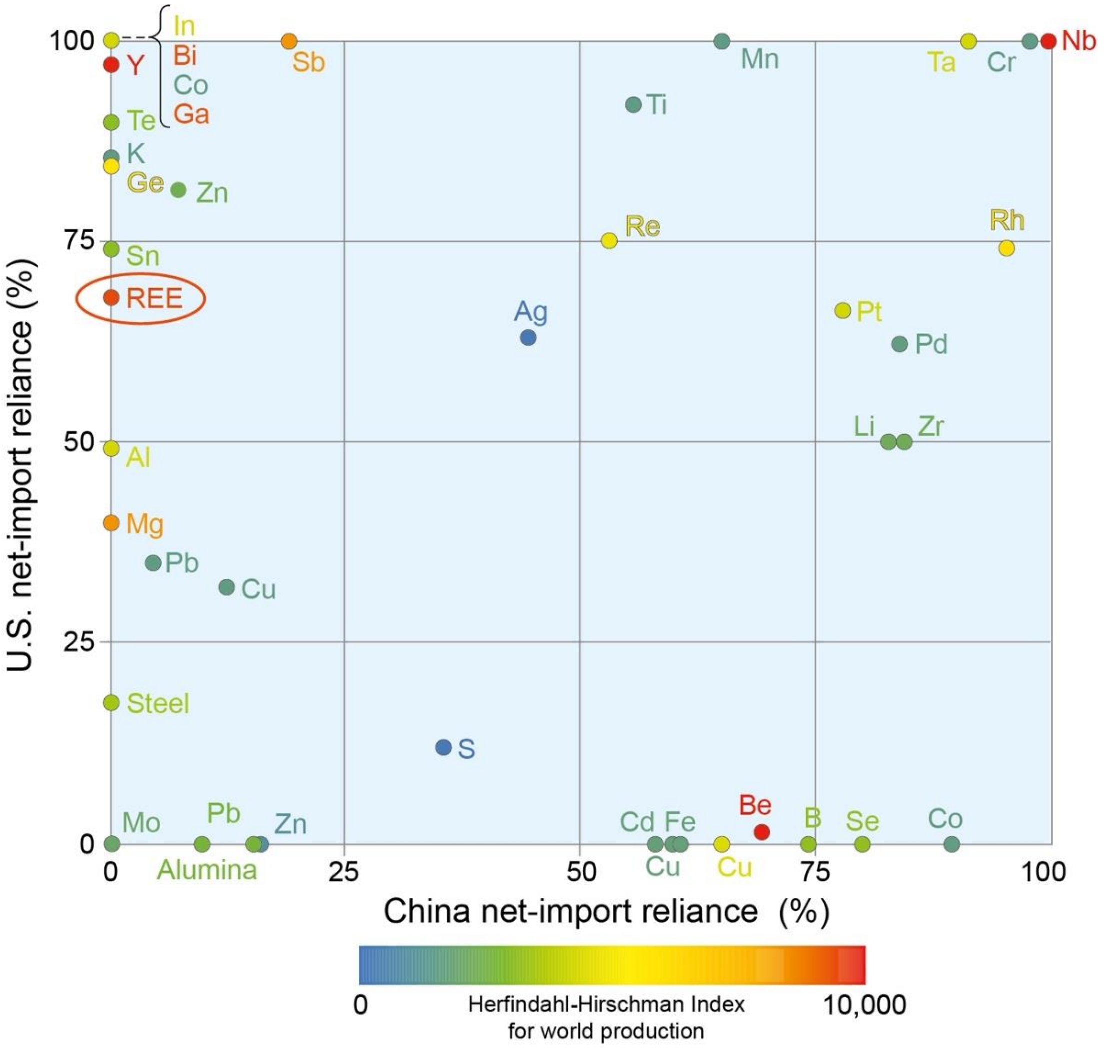


Figure 11-1 *US and China raw material dependence, indicating the importance of the raw material (HHI colour code). Source: Gulley et al. 2018.*

11.1 China’s road to becoming a mass producer

The first industrial use of rare earth elements was in the 1880s in the United States, where they were used to make the filament in light bulbs. The rare earth elements were initially only extracted from the mineral monazite from granitic pegmatites in Sweden and Brazil, but from the 1890s there was also production in the USA, and from around 1910 production began in India (Hedrick 2010). The USA began to utilise monazite from heavy sand deposits in the 1940s and in the 1960s began using the mineral bastnäsite from carbonatite rocks from, amongst others, The Mountain Pass mine in the United States, which became the world's largest producer of rare earth elements. However, low prices, rising competition and environmental challenges have meant that the mine has been intermittently closed. Today, the Mountain Pass mine is again one of the world's largest producers of rare earth elements, but the production of bastnäsite is exported to China and included in the Chinese value chains, facilitated by the Chinese minority shareholder Shenghe Resources Holding Co. Ltd. The history of the Mountain Pass mine is shown in Table 11-1.

In the late 1960s, China started a small production of rare earth elements that had already increased to around 5,000 tonnes TREO in the 1980s (Adamas Intelligence 2014). At this time, China began to extract rare earth elements as a by-product of the Bayan Obo iron mine, and as early as 1986, production had increased further to 15,000 tonnes. This made China one of the largest producers of rare earth elements (Adamas Intelligence 2014), a position that the country has continued to strengthen as a result of the implementation of a national raw materials strategy. The strategy aimed to secure raw materials for Chinese industries, and to ensure that value growth occurred in China. China's strategy for the development of the rare earth minerals industry was reportedly expressed as early as 1992 by Chinese Prime Minister Deng Xiaopeng at a meeting in Jiangxi, where he compared the geopolitical strength of the Middle East, due to large oil resources, with China's geopolitical strength due to the rare earth elements, and urged its compatriots to make the most of these resources economically.

Table 11-1 *The history of Mountain Pass mine. Source: https://en.wikipedia.org/wiki/Mountain_Pass_mine.*

Year	Owner	Activity
1949		Deposits discovered
1952	Molybdenum Corp. (Molycorp)	Small scale production
1960	Molybdenum Corp. (Molycorp)	Production expands to focus on europium; world leader
1977	Union Oil	Union Oil buys Molycorp
1998		The separation facility shuts down; production of bastnäsite continues
2002		The mine closes due to environmental issues and competition from China
2005	Chevron Corp	Chevron Corp buys Molycorp
2012		Production of bastnäsite resumes
2015		Molycorp goes bankrupt; company is removed from the list at the New York Stock Exchange
2016	Neo Performance Materials (NPM)	NPM takes over the bankruptcy. The relationship between NPM and MP Materials is unclear.
2018	MP Materials	The mine reopens with Shenghe Resources Holding Co. Ltd. owning 8 % of the shares Bastnäsite concentrate is exclusively sold to China

As early as 1990, China declared rare earth elements as *protected and strategic minerals*, one consequence of which is that foreign companies can only mine these raw materials in China in joint venture with Chinese-owned companies, and that foreign companies can only be involved in the processes that process the minerals into finished products. In practice, this meant that China had a strong focus on developing the necessary technologies and infrastructure to build industries within rare earth elements processing, and by 1999 China had reached the point where export quotas were introduced to strengthen the country's leading position in the production of REE raw materials for industries. China's main provinces for the exploitation of rare earth elements are discussed in section 12.1.

With production in Bayan Obo, China was already one of the world's largest producers of rare earth elements in the early 1990s, and China developed concurrently, in accordance with Deng Xiaoping's strategy, the industrial sectors that process the raw materials and produce raw materials and goods in which rare earth elements are included. This development was greatly aided by the relocation of industrial production by the western world to China, as part of its efforts to reduce production costs, and with that, competing industries disappeared. As a result of the foreign policy crisis with Japan, Chinese production was reduced in 2011, but after a few years returned to the previously high level with the majority coming from the Bayan Obo mine (Table 11-2). In 2020, China's production amounted to 140,000 tonnes TREO, corresponding to approx. 58 % of global production, which, together with China's long-term contracts for mineral concentrates and expanded raw materials processing infrastructure, enables China to retain control of its more technically complex and economically important value chains. China's rapidly growing production, and thus increased importance in the period from the late 1990s to 2013, is seen in Figure 11-2.

Table 11-2 *China's production of rare earth elements in 2004, 2006, 2008, 2010 and 2014. Source: Mancheri & Marukawa (2018).*

Year	Bayan Obo (bastnäsite) tonnes	Sichuan (bastnäsite) tonnes	IA deposits tonnes	Heavy sand (monazite) tonnes	Total Tonnes
2004	42-48,000	20-24,000	28-32,000	-	90-104,000
2006	45-55,000	22-26,000	40-50,000	9-12,000	115-143,000
2008	60-70,000	10-15,000	45-55,000	8-12,000	123-152,000
2010	55-65,000	10-15,000	35-45,000	4-8,000	104-133,000
2014	80-100,000	20-40,000	40-50,000	8-12,000	148-202,000

Up to the year 2000, China exported less than 10,000 tonnes of rare earth elements, and the sector only had a very limited economic significance. In 2000, exports increased dramatically (approx. 70,000 tonnes), but without a significant economic contribution, as value growth predominantly took place outside China. In the following years, China expanded a diversified industrial sector for rare earth elements and reduced exports, resulting in overall economic growth (Figure 11-2).

In 2010, China reduced its export quota by 37 % and completely stopped exports to Japan for a few months due to disputes between the two countries over territory in the East China Sea. The export restrictions were brought before the World Trade Organization (WTO) in 2012. China argued that the restrictions were due to reduced production because of environmental problems with productions of primarily IA deposits but in 2014, the WTO ruled that there was no basis for China's export quotas. China therefore abolished the export quotas in 2015, replacing them with a modified version of the production quotas introduced in 2006, stipulating the quantities of REE minerals permitted to be mined and the quantities of rare earth elements permitted to be separated. The quotas are allocated to six state-owned consortia referred to as ‘The Big Six’ (see section 12.1); further restructuring took place in 2016 because of significant competition between individual Chinese producers (Yi et al. 2021). China emphasises the need to see production quotas as a tool for more environmentally friendly and efficient production.

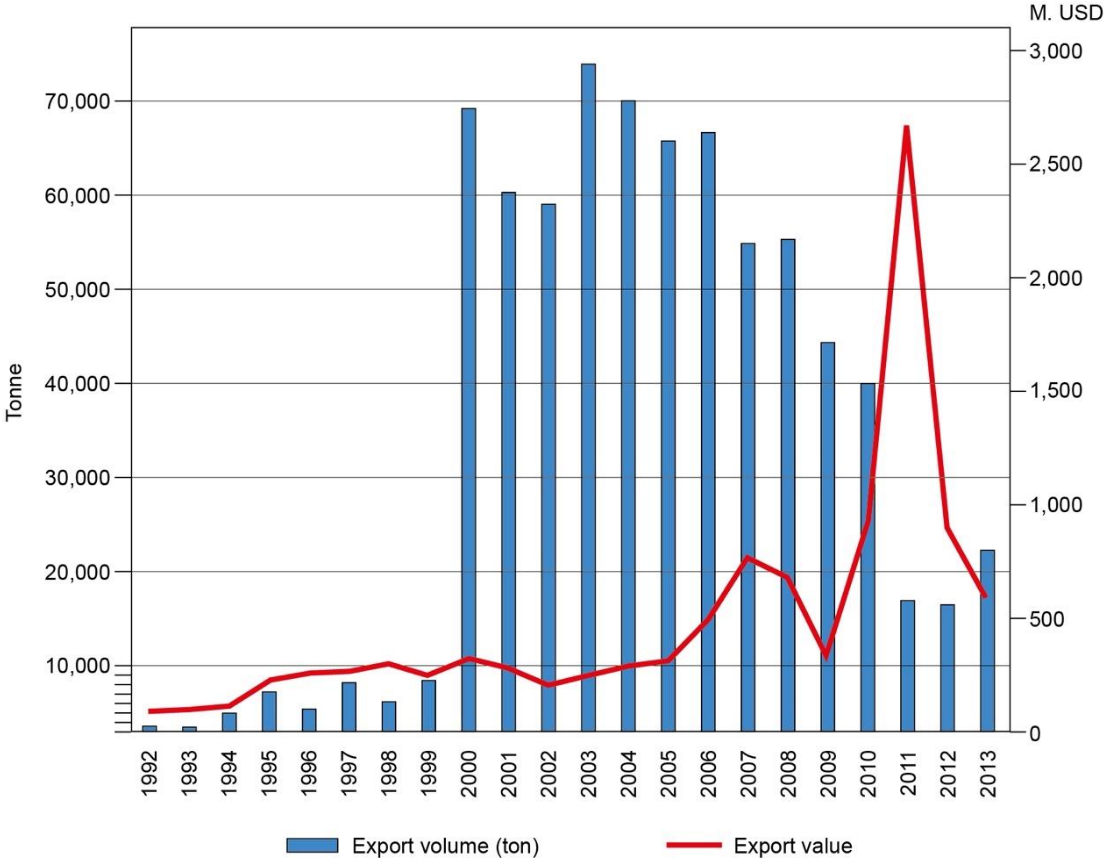


Figure 11-2 *China's exports of rare earth elements and associated export value from 1992-2013. Based on Mancheri & Marukawa (2018).*

The western world's response to China's control of supply chains for rare earth elements has focused more on opening new mines rather than on the establishment of the supply chains to process the REE minerals into industrial raw materials. This has resulted in massive mineral exploration activity, not least due to the fact that the United States' only producer of rare earth elements, the Mountain Pass mine, was closed in 2002 after accounting for approx. 24 % of global production in 1996. However, it was reopened in 2012, closed again in 2015 and reopened in 2018 (see Table 11-1 and section 13.1.21). In 2019, US production amounted to approx. 20 % of the global market for rare earth elements, but without domestic production to challenge China's control of the rare earth element value chains. The western countries' strategy of focusing on mineral exploration and not on the development of the necessary value chains has led a number of western exploration companies to enter into agreements of co-operation with Chinese companies in order to ensure sales of their products (see also Chapter 13).

Despite China's control of the TREO markets, the Australian company Lynas Corporation opened Mt. Weld Mine in Australia and established a separation plant in Malaysia to circumvent

Australian rules on the handling of radioactive materials. The arrangement was possible because the project had both political and economic backing from Japan (Lynas received 250 million USD in 2011 from Sojitz Corporation and JOGMEC) (see also section 13.1.2). In 2014, Australia was the largest non-Chinese producer of primary rare earth element raw materials with a production of approx. 8,000 tonnes TREO, corresponding to 6 % of global production; in 2020, Australia produced approx. 18,000 tonnes TREO with roughly the same share of world production, but was overtaken in volume by US production. Australia, in close co-operation with Japan, has managed to maintain its independence from China.

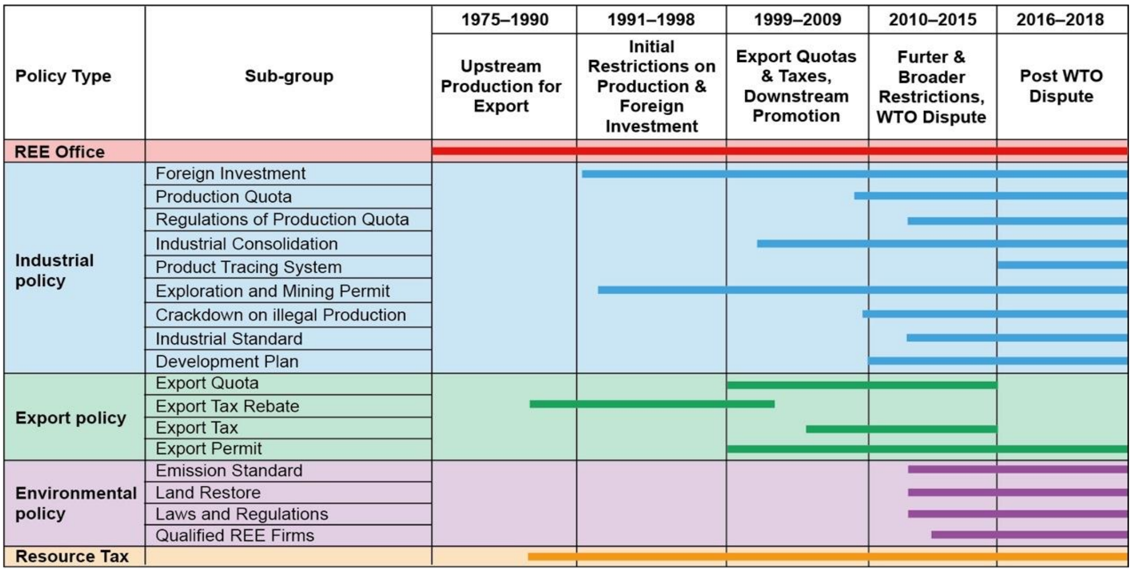
In 2019, then US President Trump declared the rare earth elements essential to national defence and that the US should ensure the establishment of its own productions, processing, and production to liberate the US defence industry from its dependence on China (Lasley 2019). The declaration opened financial support from the Department of Defense (DOD) for a number of projects, among which, in April 2020, was a joint venture financing agreement between Lynas Corp. and Blue Line Corp. (USA) on the establishment of a separation plant in Texas with the long-term goal that part of Lynas' production should be refined in Texas instead of, as presently, in China. Foreign projects are also part of the USA's efforts to reduce the USA's dependence on imports from China and, for example, the USA entered into an agreement with the Greenland Government in 2020 on a mineral exploration project in an area near the two large rare earth element exploration projects, Kvanefjeld/Kuannersuit and Kringlerne/Killavaat Alannguat, South Greenland.

There is still a strong focus on rare earth elements from both the Chinese and American side. For instance, in a statement from China's Natural Development and Reform Commission in May 2019, China threatens the United States with export sanctions if they seek to obstruct China's trade in rare earth elements (Hanke 2021). China has subsequently reiterated such threats, including in connection with the Biden administration's proposal (November 2021) to impose sanctions on NdFeB magnets for the United States using Section 232 of the Trade Expansion Act of 1962 (Lester 2021) as political aid to establish a national value chain for NdFeB magnets; an initiative that the EU does not support.

11.2 China’s political and administrative strategies

As mentioned above, China's value chains for rare earth elements were for some years characterised by competition between some of the larger consortia, which now make up The Big Six (see section 12.1), with low prices and overcapacity as a result, so in 2006 the first production quotas were introduced (Zeuthen 2021a). In 2010, when the World Trade Organization (WTO) considered the quotas barriers to trade, China introduced a new quota system, allegedly to allow China to combat illegal production and to ensure environmentally sound production. As part of the new initiatives, new tax systems were also introduced (Central People's Government of the People's Republic of China 2011). In 2015, the system was changed so that licenses are only issued to large companies, and the production quotas were allocated on a provincial basis to the six large vertically integrated consortia in The Big Six, whilst a central government agency would coordinate and manage the production of raw materials and finished products based on the geographical distribution of resources (Ministry of Land & Resources 2015). The production quota system, combined with the new tax system, now serves as an effective safeguard against international attempts to break China's monopoly-like supply chains (see Chapter 11). A historical overview of the political/administrative instruments is shown in Table 11-3.

Table 11-3 *Overview of China's political/administrative methods to regulate global production and trade in rare earth elements in the period 1975-2018. Source: Shen* et al. *(2020).*



Policy Type	Sub-group	1975–1990	1991–1998	1999–2009	2010–2015	2016–2018
		Upstream Production for Export	Initial Restrictions on Production & Foreign Investment	Export Quotas & Taxes, Downstream Promotion	Furter & Broader Restrictions, WTO Dispute	Post WTO Dispute
REE Office		■	■	■	■	■
Industrial policy	Foreign Investment		■	■	■	■
	Production Quota			■	■	■
	Regulations of Production Quota				■	■
	Industrial Consolidation			■	■	■
	Product Tracing System					■
	Exploration and Mining Permit		■	■	■	■
	Crackdown on illegal Production			■	■	■
	Industrial Standard				■	■
	Development Plan				■	■
Export policy	Export Quota			■	■	
	Export Tax Rebate	■	■	■		
	Export Tax			■	■	
	Export Permit			■	■	■
Environmental policy	Emission Standard				■	■
	Land Restore				■	■
	Laws and Regulations				■	■
	Qualified REE Firms				■	■
Resource Tax		■	■	■	■	■

11.2.1 China’s national quota system

The Chinese Ministry of Industry and Information Technology (MIIT) allocates semiannual quotas to the six major consortia in The Big Six, which then have one month to allocate their allocated quotas to their subsidiaries (at the time of writing, China is working to reduce The Big Six to two or three large consortia). To ensure the implementation of the government's industrial policy, the subsidiaries must meet the following requirements in order to receive the quotas: (i) they must have access to a mine; (ii) their separation capacity shall be > 2,000 t/year REO; (iii) they must meet environmental requirements for waste products, including radioactive material; and (iv) they must not have been shut down for an extended period of time. The companies are not allowed to buy or use ore from non-approved mines or products that are separated at central plants (after tolling) outside China, or that are not part of The Big Six. In addition, REE-recycling companies (i.e. not from mining) are not allowed to base their production on ore or mineral concentrates, in the event they experience shortage of REE-scrap material

The production quotas for the period 2018 to 2021 are shown in Table 11-4, from which it appears that in that period they increased from approx. 132,000 tonnes to 168,000 tonnes, and that the increases include production from solid rocks, which are dominated by light rare earth elements, and stagnant quotas for IA deposits. The quotas for separation and refining have increased accordingly.

11.2.2 Fiscal policy - instruments for maintaining control of supply chains

To protect against competition from western companies, China has introduced a special tax system that includes the following elements:

- All items in China are subject to 13 % VAT, which is not specified separately. This also applies to REE oxides, metals and magnets and the VAT imposed can thus be considered as a consumption tax, which is cost neutral for domestic producers.

Table 11-4 *Quota allocation for the production and treatment of rare earth elements in the period 2018-2021, awarded to The Big Six, as well as three specifications for their associated companies. Source: The Rare Earth Observer (Jan 21, 2022).*

	Mineral products (REO ton) 2018		**Mineral products (REO ton) 2019**			**Mineral products (REO ton) 2020**			**Mineral products (REO ton) 2021**		
The Big Six	**LREE + HREE**	**Smelting and sep. products**	**Minerals (LREE)**	**Ionic clay (HREE)**	**Smelting and sep. products**	**Minerals (LREE)**	**Ionic clay (HREE)**	**Smelting and sep. products**	**Minerals (LREE)**	**Ionic clay (HREE)**	**Smelting and sep. products**
China Xiyou Rare Earths Corp. (China Aluminium, Chinalco)	14,350	19,379	14,350	2,500	21,879	14,550	2,500	23,879	14,550	2,500	23,879
of which: China Steel Reseach Technology Group Co. Ltd			4,100		1,500	4,300		1,700	4,300		1,700
Minmetals Rare Earth Group Co. Ltd	21,010	5,658		2,010	5,658		2,010	5,658		2,010	5,658
China Northern Rare Earth (Group) High-Tech Co. Ltd	69,250	59,484	70,750		60,984	73,550		63,784	100,350		89,634
Xiamen Tungsten Co. Ltd	3,440	3,963		3,440	3,963		3,440	3,963		3,440	3,963
China Southern Rare Earth Group Co. Ltd	28,250	15,912	27,750	8,500	23,912	32,750	8,500	27,112	33,950	8,500	28,262
of which: Jiangxi Copper participations in Sichuan			27,750		16,320	32,750		19,520	33,950		20,670
Guangdong Rare Earth Industry Co. Ltd	2,700	10,604		2,700	10,604		2,700	10,604		2,700	10,604
of which: China Nonferrous Metals Construction Co. Ltd					3,610			3,610			3,610
Subtotal	**139,000**	**115,000**	**112,850**	**19,150**	**127,000**	**120,850**	**19,150**	**135,000**	**148,850**	**19,150**	**162,000**
Total	**139,000**		**132,000**			**140,000**				**168,000**	

- When a producer buys his REE raw materials in China, the international market price is paid, which includes 13 % VAT. If the buyer is a Chinese company, the VAT is subsequently refunded, but when exporting REE raw materials and raw minerals, VAT is not refunded; on the other hand, the full VAT is reimbursed for the export of permanent magnets. Thus, in the upper and middle parts of the supply chains, an economic competitive advantage of 13 % has been established in favour of the Chinese companies and an economic incentive for the value added in all stages when it comes to China.
- If a non-Chinese company produces rare earth element products that are to be sold to China, the following applies:
    - Mineral concentrates are exempt from VAT and import duties
    - Processed raw materials (carbonates, oxides, etc.) are subject to 5 % import duty, calculated on the basis of ‘cost-insurance and freight’ China prices, and 13 % VAT on this amount.
- When determining the product price, the basket price is calculated on the basis of the Mixed Rare Earth Compound (MREC), but generally no payment is made for the rare earth elements that are overproduced (e.g. cerium, lanthanum, samarium, yttrium and europium) or for niche products like e.g. holmium, erbium, thulium, ytterbium, and lutetium; it is also normal to deduct 20 % for the material loss during the processing phase (Kruemmer 2021a).

This means, amongst other things, that non-Chinese magnet producers can only become competitive if they can base their production on non-Chinese raw materials that can match Chinese prices for similar products, and also produce the product at prices that can match similar Chinese products. Mining companies are not likely to sell their mineral concentrates cheaper than the price they will be able to obtain from Chinese buyers as this will affect investors negatively. The Chinese tax and duty system has the added consequence that new mines in the west will not be able to achieve added value for the ore by processing the concentrates further and then exporting to China, as taxes and VAT will then have to be paid, so it is therefore necessary to sell at lower prices to be competitive in China. New western mines and producers in the supply chains for rare earth elements can therefore, under the current schemes, only be established if they produce targeting the domestic market where all the mine and value chain products can be sold. Overall, China's tax system means that China, without changes to the VAT refund schemes, will maintain its monopoly-like status on rare earth element value chains. China's tariffs for rare earth element products are shown in Table 11-5. It also follows that, to the extent that economic assessments of new non-Chinese REE projects are based on export prices from China, these prices include 13 % VAT; the assessments must therefore be adjusted to incorporate this amount.

The business concepts for a number of western exploration projects are reportedly based on mining the ore and sending mineral concentrates to China for processing and separation to subsequently sell these products to countries outside China. However, this model is not possible when, in 2016, China introduced a ban on undertakings where China only conducts partial processing of the raw materials.

China’s raw materials
China's current raw material taxes came into force on 1 September 2020 and are as follows:
Export: The tax is calculated based on the value of the ore/mineral concentrate

- LREE: 11.5 % (Shandong: 7.5 %; Sichuan: 9.5 %)
- MREE: 20 %
- HREE: 20 %

Imports: China has removed tariffs on imports of REC, RE carbonates and mineral concentrates for 2022 to make it more attractive for new projects to market their products to China (The Rare Earth Observer 2021e).

Table 11-5 *China's tariffs for REE products. Source: Kruemmer (2021a).*

Product	Told code (Harmonized System Code)	VAT (%)	VAT refund for export products (%)	General tariff (%)	National tariff (%)	Additional tariff on imports from USA (%)
REE raw material tariffs						
Ore with REE	2530 9020 00	13	0	0	0	0
Monazite (thorium ore and concentrates)	2612 2000 00	13	0	0	0	0
REO (excl. phosphorescence) > 30 % TREO	2846 9019	13	0	0	0	27.5
Other REE carbonates (> 30 % TREO)	2046 9048	13	0	30	5	25.0
Other REM combinations (> 30 % MHRE)	2846 9099	13	0	30	5	22.5
REE Tariffs						
Cerium oxide	2846 1010 00	13	0	30	5	22.5
Cerium carbonate	2846 1030 00	13	0	30	5	0
Yttrium oxide	2846 9011 00	13	0	30	5	27.5
Lanthanum oxide	2846 9012 00	13	0	30	5	22.5
Neodymium oxide	2846 9013 00	13	0	30	5	0
Europium oxide	2846 9014 00	13	0	30	5	0
Dysprosium oxide	2846 9015 00	13	0	30	5	0
Terbium oxide	2846 9016 00	13	0	30	5	0
Praseodymium oxide	2846 9017 00	13	0	30	5	27.5
Erbium oxide	2846 9019 20	13	0	30	5	27.5
Gadolinium oxide	2846 9019 30	13	0	30	5	27.5
Samarium oxide	2846 9019 40	13	0	30	5	27.5
Ytterbium oxide	2846 9019 70	13	0	30	5	27.5
Scandium oxide	2846 9019 80	13	0	30	5	27.5
Other REE oxides (incl. NdPr-oxide)	2846 9019 99	13	0	30	5	27.5
Neodymium chloride	2846 9024 00	13	0	30	5	0
Praseodymium chloride	2846 9025 00	13	0	30	5	0
Neodymium fluoride	2846 9034 00	13	0	30	5	0
Praseodymium fluoride	2846 9035 00	13	0	30	5	0
Other REE fluorides	2846 9039 00	13	0	30	5	0
Neodymium carbonate	2846 9044 00	13	0	30	5	0
Other REE carbonates (> 30 % TREO)	2846 9045 00	13	0	30	5	25.0
Other non-mixed REE carbonates	2846 9048 90	13	0	30	5	0
Lanthanum mixtures, others	2846 9091 00	13	0	30	5	7.5
Neodymium mixtures, others	2846 9092 00	13	0	30	5	7.5
Praseodymium mixtures, others	2846 9095 00	13	0	30	5	7.5
Phosphorescence (yttrium) for LED	2846 9096 01	13	0	30	5	27.5
Other REM with MHRE content (> 30 %)	2846 9099 10	13	0	30	5	22.5
Other REM (excl. LED and Ce products	2846 9099 90	13	0	30	5	22.5
REM Tariffs						
Lanthanum metal	2805 3014 00	13	0	30	5	7.5
Sc-Y alloy	2805 3029 00	13	0	30	5	27.5
Other REM	2805 3019 00	13	0	30	5	7.5
REE Magnet Tariffs						
Non-REE magnets	8505 1190 00	13	13	20	7	20
REE magnets	8505 1110 00	13	13	20	7	25

11.3 China’s trade with rare earth elements

Below is a historical overview of the development in China's exports of rare earth elements in the period 2016-2021. The overview, which is only indicative, is included to show trends during this period. Lack of information on what is actually included in exports and imports makes it impossible to establish a mass balance (MFA) for the raw materials. This is in part due to the customs declarations being designed for other purposes and therefore do not provide the relevant information in full. This is also the reason for the significant volume differences seen over identical periods below.

11.3.1 Export

China's exports of rare earth elements can be divided into three groups: (i) raw materials/mineral raw materials, (ii) components and (iii) finished products. Exports within the individual groups vary considerably from year to year, from month to month and between different inventories (Table 11-6, Table 11-7, Figure 11-3, and Figure 11-4). From 2016 to 2020, the total annual export of rare earth elements was relatively stable at around 46,000-53,000 tonnes TREO (Table 11-6). The stability is probably due to the fact that since the beginning of the year 2000, China has introduced economic measures that encourage the processing of all products in China, while at the same time the quota system has made it possible to reorganise primary productions so that they are compensated for the reduced productions, which were the result of a series of environmental measures (discussed in Chapter 7) that China introduced in 2010-2012, including the shutdown of production of many IA deposits. A Chinese study of exports of rare earth elements from 1995 to 2015 showed that the shutdown did not lead to a reduction in exports of raw materials and finished products (Pan et al. 2021). The Chinese strategy for exporting highly refined products with rare earth elements follows China's expansion plans that can be seen in the first half of 2021, where China exported 22,700 tonnes of NdFeB magnets, which in volume corresponded to 38 % more than the first half of 2020, and in terms of value, this is an increase of 59 %. The EU is the largest buyer of magnetic exports (35 %), followed by the United States (14 %), Korea (12 %), Vietnam (8 %), Thailand (5 %) and Japan (3 %) (Rare Earth Industry Association 2021).

Table 11-6 *China’s export of rare earth elements in tonnes in the period 2016-2021. Source: The Rare Earth Observer (2021a).*

	2016	2017	2018	2019	2020	2021
January	4,013	4,571	3,890	3,753	3,322	4,023
February	3,240	3,293	4,451	2,886	2,167	3,045
March	4,343	4,694	4,180	4,659	5,551	4,837
April	3,696	5,068	3,874	4,329	4,317	3,737
May	4,073	4,294	4,447	3,640	2,865	4,171
June	3,849	4,290	5,456	3,966	2,893	4,012
July	3,945	4,353	4,529	5,243	1,620	
August	4,170	4,185	4,314	4,352	1,642	
September	3,674	3,715	4,951	3,571	2,003	
October	3,432	3,467	3,100	3,639	2,288	
November	3,987	4,103	4,610	2,636	2,611	
December	4,805	5,156	5,421	3,657	4,168	
Total	**47,227**	**51,189**	**53,223**	**46,331**	**35,447**	

The Rare Earth Observer (2021c) believes that the low level of exports of rare earth elements from China in 2020 (Table 11-6) is a consequence of the Covid-19 pandemic, which has led to lower demand, but expects that exports in 2021 will reach approx. 47,000 tonnes TREO.

Table 11-7 *China's export of unspecified products with rare earth elements and the five largest buyer countries in 2019. Source: China Briefing (2021).*

	Export	**Japan**	**USA**	**South Korea**	**Netherlands**	**Italy**	**ROW***
2019	**tonne**	**tonne**	**tonne**	**tonne**	**tonne**	**tonne**	**tonne**
Lanthanum	19,397	3,256	11,030	639	2,484	368	1,620
Cerium	9,105	4,849	1,823	474	443	456	1,060
Praseodymium	72	42	15	0	2	-	13
Neodymium	835	561	15	10	75	15	159
Europium	13	2	2	-	8	-	2
Terbium	115	100	7	-	-	7	-
Dysprosium	156	91	-	51	-	-	14
Yttrium	3,153	1,427	762	247	71	419	227
Others	12,704	6,046	1,564	1,029	1,276	350	2,438
Total (tonnes)	**45,550**	**16,375**	**15,218**	**2,451**	**4,358**	**1,614**	**5,532**

* Rest of the World

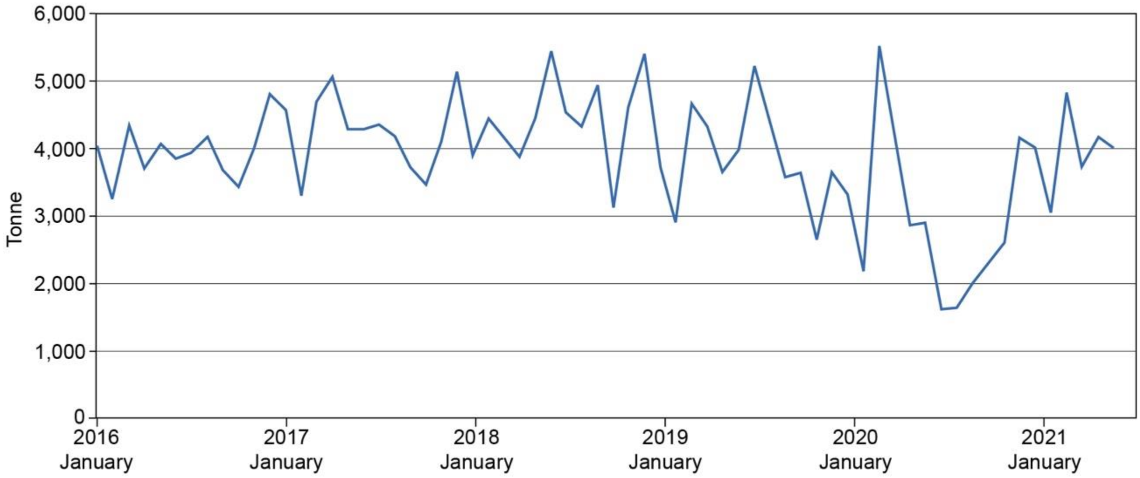


Figure 11-3 *China's exports of unspecified REE products on a monthly basis from January 2016 to March 2021. As can be seen, there are large monthly variations in the quantities exported. Source: The Rare Earths Observer (2021c).*

Lanthanum and cerium comprise by far the largest share of exports (Figure 11-5), whereas exports of niobium, praseodymium, terbium and dysprosium, which are important raw materials for the production of permanent magnets, account for only a very small share, which is in line with China's strategy.

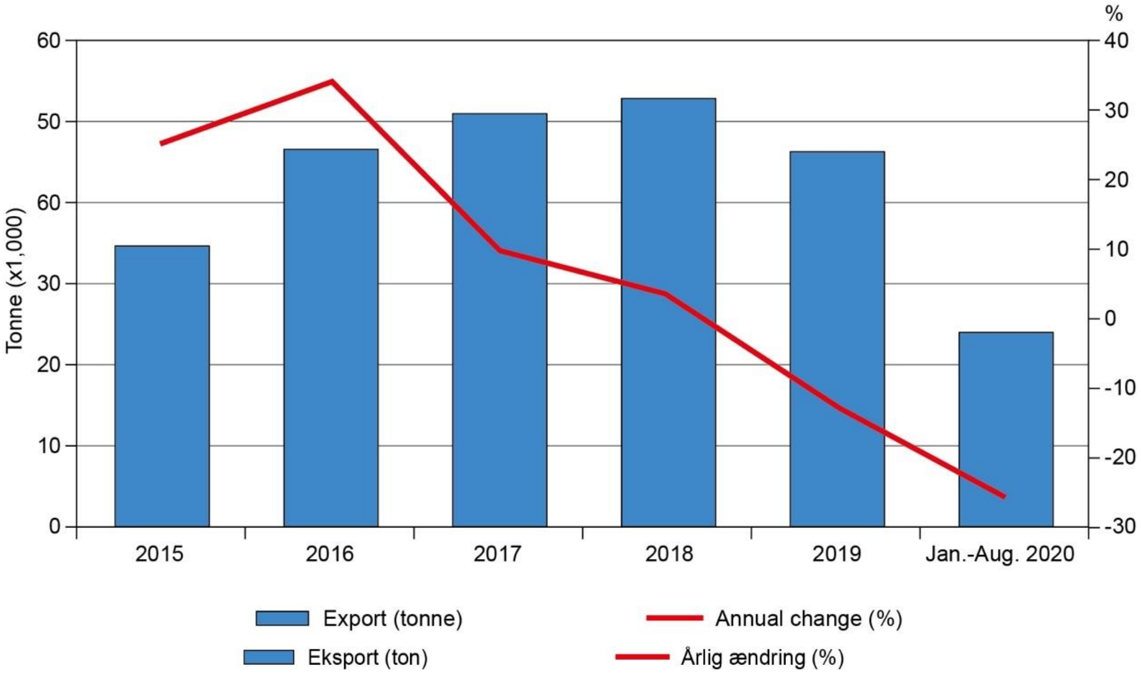


Figure 11-4 *Developments in China's exports of rare earth elements from 2015 to August 2020. Source: S&P Global (2020).*

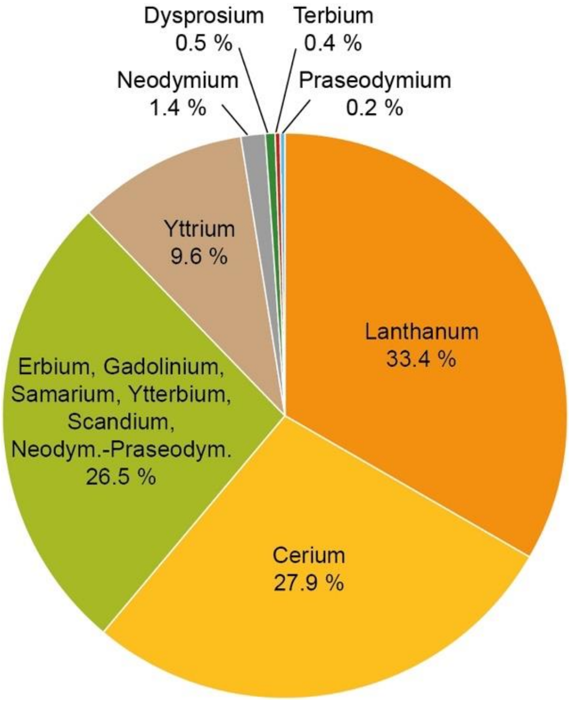


Figure 11-5 *China's exports (2019) of rare earth elements, listed in terms of quantities. Source: The Rare Earth Observer (2021a).*

11.3.2 Import

China imports REE mineral concentrates from all producing countries except Australia, Russia and India. Table 11-8 shows the rapid increase in imports of ‘rare earth elements’ – here put in quotation marks, as the tonnage must be assumed to include mineral concentrates, and the content of TREO will then constitute 30-40 % of the imported quantity. However, it has not been possible to identify quantitative and qualitative data for imports. The import figures indicate that China is increasingly supplementing its own production with imported raw materials. It is unclear whether the reason for the increase in imports is that China's own production is insufficient, or whether the imports are motivated by a desire to tie new producers to the Chinese value chains and thereby make it difficult to establish western supply chains (China's influence on western supply chains in Chapter 12).

Table 11-8 *China's imports of 'rare earth elements' (see text for explanation of quotation marks). Source: Ginger International Trade & Investment Pte., Ltd. (2021).*

Year	Tonnage	Difference %
2017	35,000	
2018	82,000	133
2019	105,000	29
2020	121,000	15
2021 (estimate)	167,000	38

12. China's Value Chains for Rare Earth Elements

China has developed a highly diversified infrastructure to produce rare earth element raw materials, processing, and raw material production, as well as the production of goods in which these products are included. Already in 2016, more than 400 companies, operating in 23 provinces, were involved in mining, processing, and trading of rare earth elements (Adamas Intelligence 2017). As part of China's efforts to halt illegal production, which had grown significantly since 2011, and to improve environmental conditions - especially around the mine sites - China established, in 2014, the majority of rare earth element value chains in a consortium consisting of six large groups of companies, often referred to as 'The Big Six' (see 11.2.1). This REE industry structure gave, amongst other things, the opportunity to ensure that the industries delivered on the planned targets set by the central government, which were to ensure consistency between supply and demand.

12.1 The Big Six – changed to the Big Four

In 2014, China's production of rare earth elements was, as mentioned above, organised into six large, vertically integrated business groups – The Big Six (Table 12-1) – that are all, to a certain extent, involved in the processing of the raw materials towards completed REE products. The geographical distribution of the companies is divided so that they represent different geological environments and therefore, different mineralogical compositions, which allows the central government in Beijing, using the production quota system, to regulate production so that it best meets the needs of industry. In November 2021, China decided to restructure The Big Six to The Big Four, and as a result, the China Aluminium Corporation (Chinalco), China Minmetals Rare Earth Corporation (Minmetals), and Ganzhou Rare Earth Group merged under the new name of 'China Rare Earth Group' based in Jiangxi Province in Southern China. China Rare Earth Group will become China's second largest producer of rare earth elements; the quotas of the three consortia will be transferred to the new company (Jingjing 2021; Zhai 2021) (see also Table 11-4).

An overview of some of the subsidiaries related to The Big Six is shown in Appendix V.

Table 12-1 *List of companies that were part of The Big Six and as of December 2021 are included in The Big Four.*

The Big Six	The Big Four (established December 2021)
China Xiyou Rare Earths Corp (China Aluminium, Chinalco) incl. China Steel Research Technology Group Co. Ltd	***China Rare Earth Group Co. Ltd***
China Southern Rare Earth Group Co. Ltd Incl. Jiangxi Copper participation in Sichuan	
Minmetals Rare Earth Group Co. Ltd	
China Northern Rare Earth (Group) High-Tech Co. Ltd	***China Northern Rare Earth (Group) High-Tech Co. Ltd***
Xiamen Tungsten Co. Ltd	***Xiamen Tungsten Co. Ltd***
Guangdong Rare Earth Industry Co. Ltd Incl. China Nonferrous Metals Construction Co. Ltd	***Guangdong Rare Earth Industry Co. Ltd*** Incl. China Nonferrous Metals Construction Co. Ltd

The organisation of China's rare earth element production in The Big Six provides a consolidation that allows China to exploit the vast resources of Bayan Obo in Inner Mongolia as well as the deposits of Sichuan Province in the west and Shandong Province in the east, which are dominated by light rare earth elements. The large contribution of heavy rare earth elements comes from the exploitation of the IA deposits in the southern provinces: Jiangxi, Ganzhou, Guangxi, Hunan, Fujian, Guangdong, and Yunnan. Overall, The Big Six controlled more than 74 % of Chinese rare earth element raw material production in the first half of 2016 (Liu 2016). This share has presumably increased as China has reduced the volume of illegal production in the country.

Chinese primary production takes place mainly in the three northern provinces: (i) Inner Mongolia with Bayan Obo as the dominant producer; (ii) Sichuan Province with China Southern Rare Earth Group/Jiangxi Coppers' expansion of the Maoniuping mine, Chinalco/Shenghes Resources' expansion of the Dalucao mine along with a number of new projects; and (iii) Shandong Province with Chinalco/CISRI's expansion of the Weishanhu Mine as well as expansion of production in the other mines within the province. This development is also linked to the allocation of production quotas to the provinces where Inner Mongolia and Sichuan are allocated 52 % and 31 % of the quotas respectively. In contrast, there is declining production in Southern China with mine closures in Jiangxi, Hunan, Guangdong, and Guangxi provinces, while illegal production from IA deposits has also been shut down; this has resulted in an overall decline in the production of heavy rare earth elements. In discussions with the World Trade Organization (WTO), China has argued that these much-needed environmental measures are the cause of cuts in production and thus in the export of semi-finished products (Section 4.3.3). The shutdown in production of many IA deposits has certainly resulted in China being challenged when it comes to primary supplies of heavy rare earth elements.

Figure 12-1 shows the main provinces of China and where The Big Six produces and processes rare earth elements. Deposit types are also shown, as well as whether the provinces are dominated by light or heavy rare earth elements. Figure 12-2 shows the distribution between the rare earth elements in Southern, Western and Northern China.

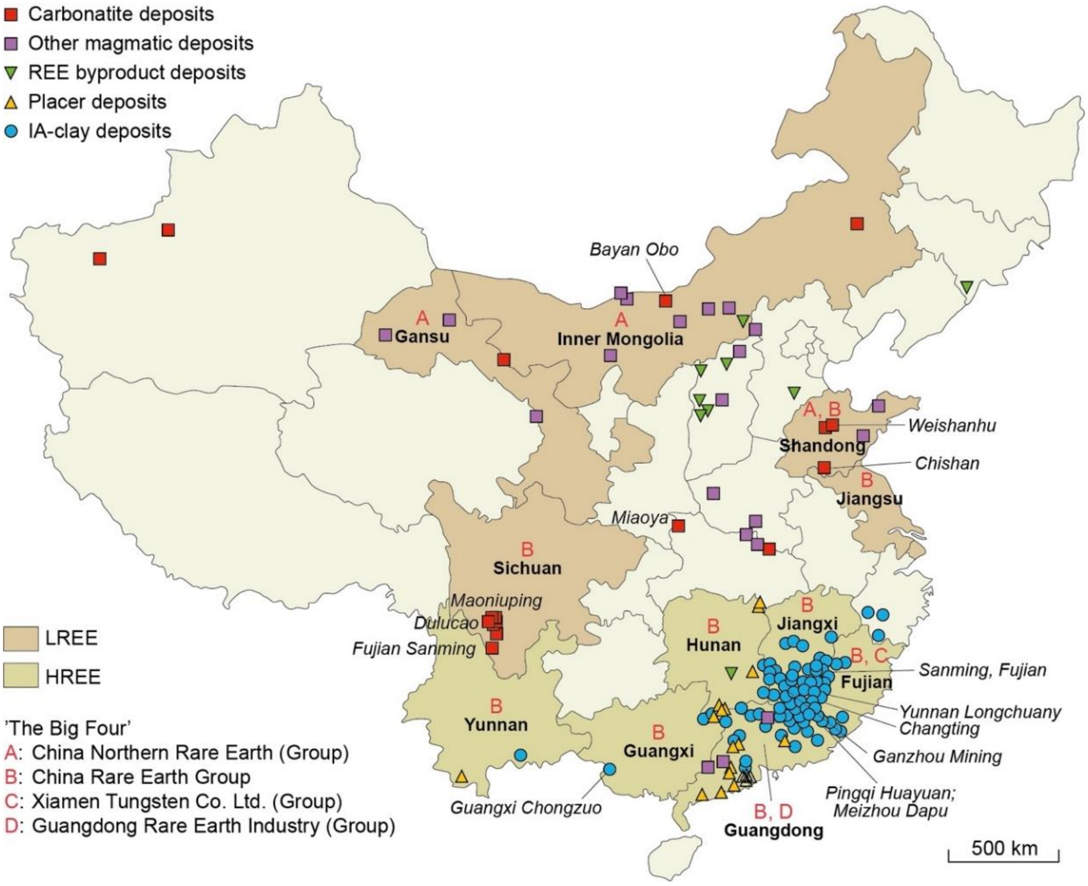


Figure 12-1 *The most important provinces in China, where rare earth elements are produced and processed. Based on Metal Events (2016).*

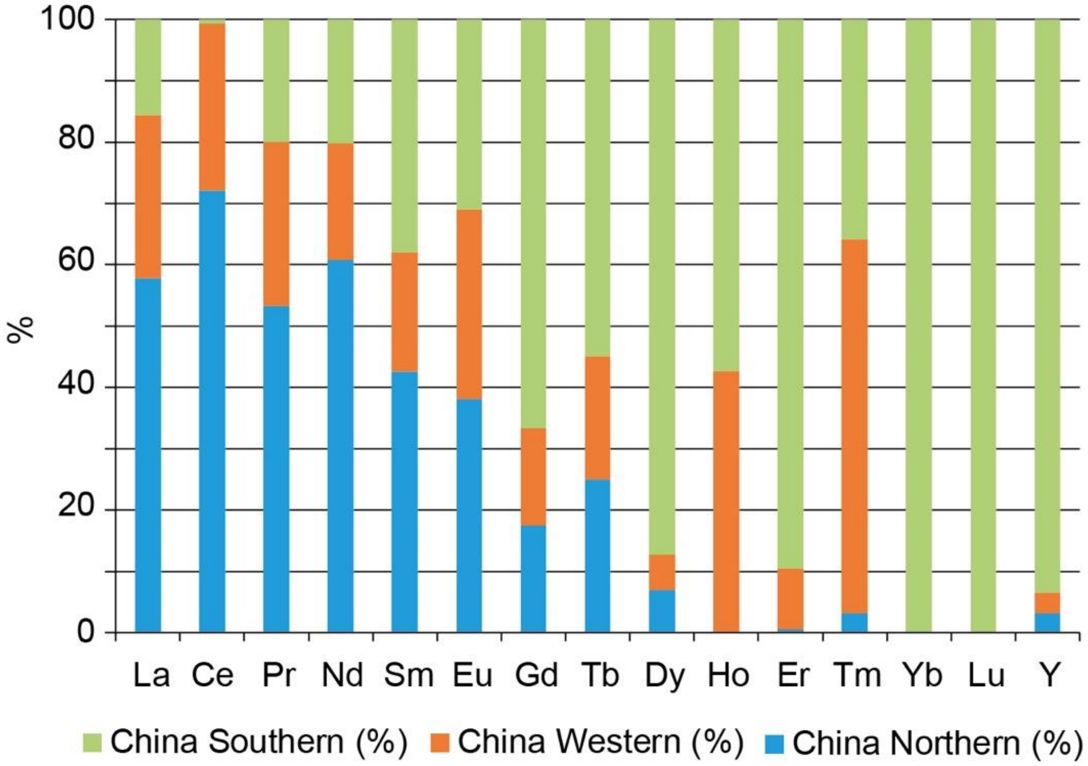


Figure 12-2 *Estimated distribution of rare earth elements in Southern, Western and Northern China. Prepared by MiMa based on data from Liu (2016) and official production quotas (Rao 2016).*

1. China Rare Earth Group

China Rare Earth Group Co. Ltd. (CREG) was established in December 2021, as a result of a merger between China Aluminium Corporation, China Minmetals and China Southern Rare Earth Group. CREG is owned by the following companies: Assets Supervision Commission (SA-SAC, Beijing) (31.21 %), China Aluminium Corp (20.3 %), China Minmetals Corp. (20.33 %), Ganshou Rare Earth Group Co. (20.33 %), China Iron & Steel Research Technology Group Co. Ltd. (3.90 %) (SASAC, Beijing) and Grinm Technology Group Co. Ltd. (3.90 %) (formerly named: Beijing General Research Institute of Nonferrous Metals, under SASAC Beijing). (The Rare Earth Observer, Jan. 4, 2022).

1.a China Aluminium Corporation (Chinalco)

Chinalco Rare Earth Corporation (CREC) is a subsidiary of the state-owned Aluminium Corporation of China (Figure 12-3).

Production in Guangxi is managed by the subsidiary Guangxi Nonferrous Rare Earth Development Co. Ltd.

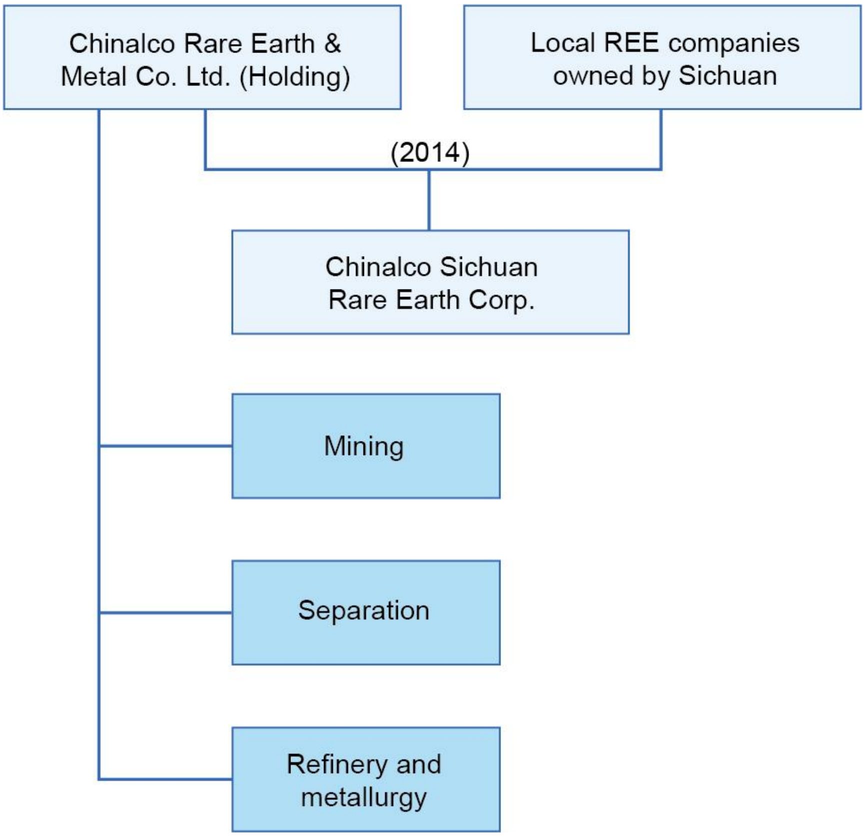


Figure 12-3 *The state-owned Aluminium Corporation of China – often referred to simply as Chinalco – has the majority of activities in separation, refining and metallurgical processes; mining is only a small part of these activities.*

1.b China Minmetals Rare Earth Corporation

China Minmetals Rare Earth Corporation is involved in mining (especially extraction from IA deposits), processing of these raw materials and separation of all rare earth elements into high purity oxide products and is also involved in research and development as well as consulting. Most of the raw materials are extracted from the Shenggongzhai mining area; the company also has exploitation permits for the Fetian mining area. No exploration has been carried out in recent years.

In 2019, China Minmetals Rare Earth Corporation's total production of rare earth elements was approx. 4,000 tonnes (SMM News 2020).

The subsidiaries Dingnan Dahua and Guangzhou Jianfeng produce and sell high quality products of rare earth element oxides. Production includes heavy rare earth species (HREE) in particular.

In 2011, China Minmetals established Minmetals Sande (Ganzhou) Rare Earth Materials in Jiangxi in a joint venture with Japanese Sand to produce NdFeB magnetic alloys and magnets.

1.c China Southern Rare Earth Group

China Southern Rare Earth Group (CSREG) was established in 2015 and included Ganzhou Rare Earth Group and 16 city government owned REE companies. Now owned by Ganzhou Rare Earth Group (60 %) (owned by the city council), Jiangxi Copper Group (35 %) and Jiangxi Rare Earth & Rare Metal Tungsten Group Comp. (5 %) (Figure 12-4 and Table 12-1). CSREG has been part of the China Rare Earth Group (CREG) since December 2021; however, Jiangxi Copper was not involved in the merger with CREG, and it is unclear to what extent the significant quota for Jiangxi Copper will be transferred to CREG.

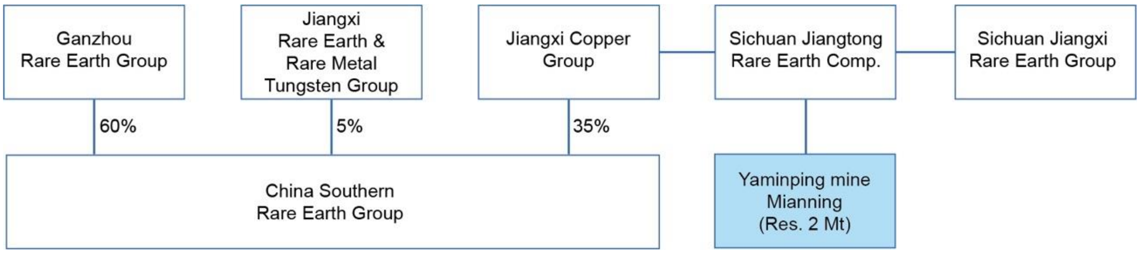


Figure 12-4 *China Southern Rare Earth Group consists of three companies with a number of subsidiaries.*

Table 12-2 *Overview of China Southern Rare Earth Group's parent company, subsidiaries, and shareholders/co-owners.*

Group	Parent company	Subsidiary	Shareholders
China Southern Rare Earth Group (CSREG)	Ganzhou Rare Earth Group	Minmetals Rare Earth	
		Guangsheng Group	
		Ganzhou Huahong Rare Earth New Materials Comp. Under construction: expected capacity 60,000 tonnes/year magnetic scrap and a production of approx. 20,000 tonnes/year (Nd, Pr, Tb, Dy).	Jiangsu Huahong Technology Co. (45 %) Ganzhou Zeyu Management Consulting Co. (28 %) Ganzhou Huayi Management Consulting Co. (17 %) (China Southern Rare Earth Group (10 %)???

The Ganzhou region of Jiangxi Province is the main area for IA deposits in China and hence for the production of the heavy rare earth elements; the mines in the area have, however, been closed since 2016, but will possibly be reopened if the environmental problems can be dealt with. Three of The Big Six operate in this area: Minmetals, Guangsheng Rising Nonferrous Metals and China Southern Rare Earth Group (CSREG). In addition, some of the major magnet manufacturers have established themselves in the area, such as Jin Li Permanent Magnet, which expects to increase its current capacity of 15,000 tonnes/year to 23,000 tonnes/year by 2023, and China Science Sanhuan is also expected to establish a plant in collaboration with CSREG.

Ganzhou Rare Earth Mining, which has 43 mining licenses in Jiangxi Province, includes companies Minmetals Rare Earth and Guangsheng Group.

2. Guangsheng Rising Nonferrous Metals

Guangsheng Rising Nonferrous Metals (GRNM) is a listed company under the Guangdong Rare Earth Group, which is involved in mining, processing and separation of rare earth elements and tungsten and the trading of these products. The company has three mines and four separation plants as well as a production unit to produce MREE and HREE metals. GRNM is also part of a consortium that manufactures NdFeB magnets. Production from the mines has been declining since 2018 as a result of restructuring and the closures of IA deposits in China. On the other hand, the other operations have been increasing (SMM News 2020).

3. Northern Rare Earth Group (often referred to as Baogang Group)

Northern Rare Earth Group (NREG) is the world's largest producer of light rare earth elements. The main shareholder in NREG is Baotou Iron & Steel Co., which is a subsidiary of Baogang (Group) Company (100 % state-owned); the license for mining and processing for the Bayan Obo mine was awarded to Baotou Iron & Steel Co. About half of NREG's production comes from the mining of the Bayan Obo mine, which has given NREG a significant role among the other members of The Big Six.

The group's production includes all parts of the processing chains, i.e. mining, processing of minerals, separation of the rare earth elements and refining for metal fabrication, and production of magnets (NdFeB), polishes, phosphorescence and materials for catalytic processes and NiMH batteries.

NREG is obliged to supply an agreed product volume internally in Baotou Iron & Steel Co., which in 2021 amounted to mineral concentrates equivalent to 100,000 tonnes TREO.

Baotou Rare Earth is a co-owner of Beijing Sanjili New Materials Magnet Alloying, a major magnet manufacturer.

4. Xiamen Tungsten Corp. Ltd

Xiamen Tungsten Corporation (XTC) is primarily involved in tungsten-molybdenum value chains and the production of rare earth elements, which have increased in the last 10 years. The largest shareholders in XTC are Fujian Rare Earth (Group) Co. Ltd (approx. 32 %), China Minmetals Nonferrous Metals Co. Ltd. (about 9 %) and A.L.M.T. Corp. (7 %). According to Orbis (2021), XTC is organised into 103 subsidiaries and is laterally integrated in the production and trade of tungsten and molybdenum products as well as rare earth element products covering all parts of the supply chains from extraction to finished products and consumables in all industrial areas that use rare earth elements. The mining activities are linked to the Shanghang Jiazhuang and Liancheng Huangfang mines; The Changting Yangmeikeng mine is under construction. The Xiamen

Group's subsidiaries are shown in Appendix V. It is expected that the primary production in the coming years will mainly come from Shanghang Jiazhuang Rare Earth Mine, Liancheng Huangfang Rare Earth Mine and the mining projects in Changting Yangmeikeng.

12.1.1 Internal competition between Chinese manufacturers

The fast-rising prices in 2011-2012 resulted in a significant increase in production in many companies and led to an overproduction of a number of the rare earth elements, including lanthanum and cerium in particular. The subsequent falling prices have contributed to significant competition between the Chinese companies involved in the upper parts of the supply chains for the rare earth elements. This is illustrated in Figure 12-5, which shows the development in revenue and profit for China Northern Rare Earth Group in the period 2007-2017; the group is the dominant producer of LREE (The Rare Earth Observer 2021a).

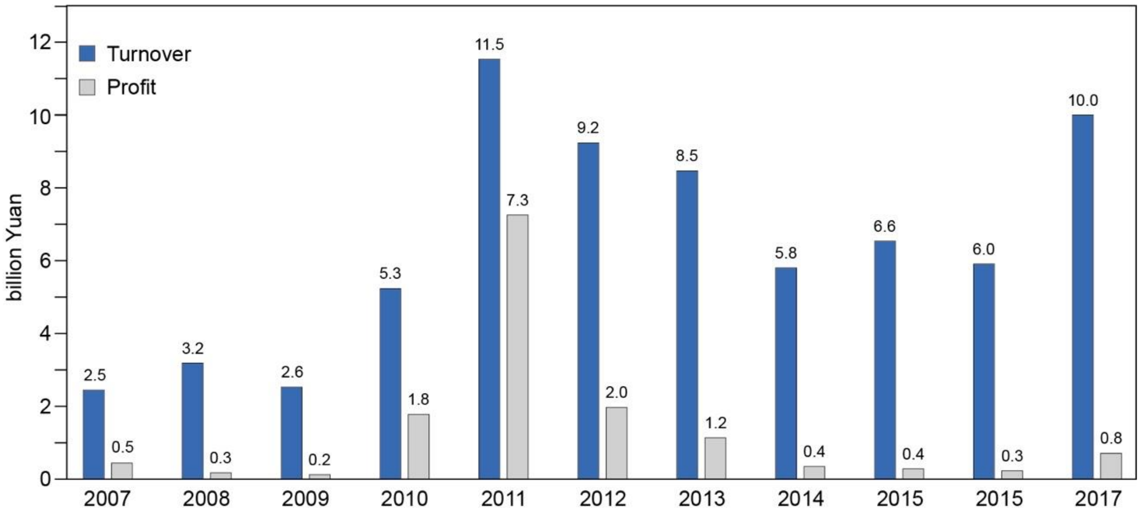


Figure 12-5 *The economic development of China Northern Rare Earth Group shows increasing revenue but declining earnings. Source: Rare Earth Observer (2021a).*

12.2 Other large Chinese manufacturers

Shenghe Resources Holding Co. Ltd.

Shenghe Resources Holding Co. Ltd. is a large, vertically integrated manufacturer of rare earth elements and zirconium titanium products. The company is involved in mining, breakdown/dissolution of minerals, separation (only of rare earth elements) and production of metals and alloys, as well as trade in products from these value chains. Shenghe is the primary producer of rare earth elements in China and the United States and is also involved in the processing of these raw materials in both Vietnam and China. (Chen 2020).

Shenghe Resources Holding Co. Ltd. was established in 2013 with headquarters in Hengdu Sichuan and is listed on the Shanghai Stock Exchange. Shenghe's relation to The Big Six and China's central government are unclear, but the owners include Chengdu Institute of Multipurpose Utilisation of Mineral Resources (IMUMR) (14 %) (Zeuthen personal communication 2021b), which is affiliated with the Ministry of Land and Resources and Sichuan Geological and Minerals Resources Company (which conducts mineral exploration in Laos and Mozambique amongst others). The state-owned Institute of Multipurpose Utilisation of Mineral Resources, which is a unit under the Geological Survey of China in Chengdu, is the largest shareholder in Shenghe, which also has headquarters in Chengdu. The former director of IMUMR, Mr. Wan Quangen, is the largest private shareholder in Shenghe Resources. The leadership of Shenghe and IMUMR coincide to a significant extent (Zeuthen personal communication 2021b).

Shenghe Resources have entered a formal partnership with Chinalco Sichuan Rare Earth Co. Ltd. establishing the company Mianning Minali Rare Earth Conc. Co. Ltd., which owns the processing plant, with the plan to work with mineral concentrates from the Yangfanggon Rare Earth mine, which is awaiting environmental approvals before it can begin (Figure 12-6).

In 2013, Shenghe Resources and Arafura entered an MoU on the development of the Nolan Bore project in Australia; whether the agreement has been extended is unknown. Two years later, in 2015, Shenghe entered into an agreement with Tantalus Resources to purchase 3,000 tonnes MREO annually from Tantalus' IA deposit in Northern Madagascar. Shenghe also entered into an agreement to finance 30 % of the project's development costs against security in production. This marketing agreement is the first a Chinese company has entered with a non-Chinese producer, and it must be assumed to have been approved by the Chinese central government.

In 2016, Shenghe Resources Holding Co. Ltd. and the Australian Greenland Minerals Ltd. (GM) made a co-operation agreement on the development of the project at Kvanefjeld/Kuannersuit in South Greenland; at the same time, Shenghe bought approx. 8 % of the shares in GM and was represented on the Board of Directors. Shenghe thus became the most important strategic partner, which in addition to knowledge of process technology, is the de facto guarantor of the potential sale of products from Kvanefjeld/Kuannersuit; it is unclear to what extent Shenghe has the right to buy the majority stake in GM.

Shenghe Rare Earth Co. Ltd. entered into an agreement in 2017 with the US company MP Materials Corp. (formerly Mountain Pass) on co-ownership and now owns approx. 9 % of the shares distributed on Shenghe Resources Holding Co. Ltd, Shenghe Resources (Singapore) Pte. Ltd., and Shenghe Resources (Singapore) International Trading Pte. Ltd. The ownership structure is shown in Figure 12-6; allegedly, Shenghe is not represented on the boards of either MP Mine Operation or MP Materials Corp. (MP Materials 2020).

MP Materials is one of the largest producers of REE mineral concentrates outside China (see Chapter 13) and plans to develop a lateral supply chain from minerals to magnets to supply the North American markets. The planned production from MP Materials' processing plant in California is 5,000 tonnes/year; the bulk of the ore concentrate will therefore still have to be shipped for processing in China.

Shenghe Resources was reorganised in 2019, establishing four production groups:

- Sichuan subgroup: Leshan Shenghe, Coburi and Geo Mining (formerly Dechang County Polymetal Ore Test Mining Plant) focusing on: mining, processing and metal production of LREE
- Jiangxi subgroup: Chenguang Rare Earth, Quannan New Resources and Bulai Terbium with main business areas in separation of MREE-HREE, extraction of rare earth elements from waste streams, and metal processing
- Hainan subgroup: Hainan Wensheng, Haituo Mining, Fujian Wnsheng, Fang-chenggang Wensheng focusing on the extraction and processing of heavy sand deposits
- The ‘Overseas’ subgroup with a particular focus on trading non-Chinese REE projects.

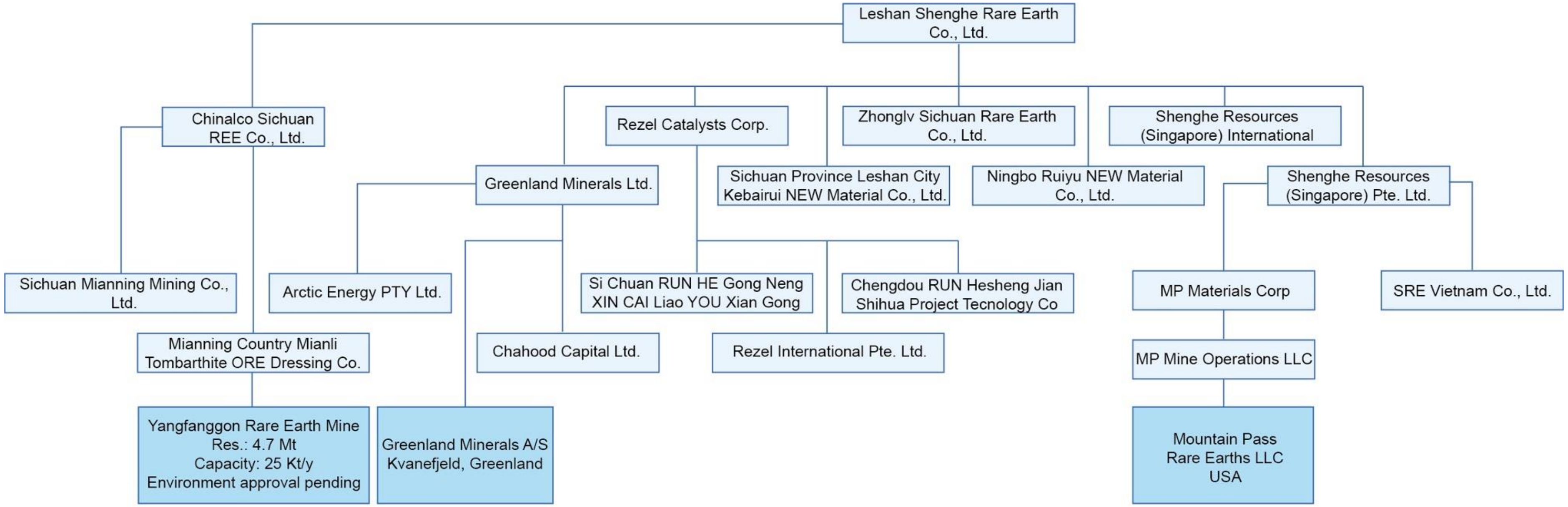


Figure 12-6 *(Leshan) Shenghes group structure. Source: Orbis (2021).*

An organisation chart of Leshan Shenghe and their relationships with the Big Six, as well as Mountain Pass (USA) and Greenland Minerals (Kvanefjeld/Kuannersuit, Greenland), is shown in Figure 12-6.

In 2019, Shenghe produced approx. 7,300 tonnes of praseodymium-neodymium as well as 48 tonnes of terbium and 375 tonnes of dysprosium (SMM News 2020).

In 2021, Leshan Shenghe Resources produced approx. 50,000 tonnes TREO, most of which comes from MP Materials, USA, as well as a separation capacity (Liannyun gang) of approx. 15,000 tonnes/year and a REE metal production (Chenguang) of approximately 12,000 tonnes/year (in 2019, NdPr metal amounted to approx. 7,300 tonnes, Tb approx. 48 tonnes and Dy approx. 375 tonnes (SMM News 2020)). Shenghe also has the capacity to process approx. 500,000 tonnes/year of heavy sand products.

(Leshan) Shenghe Resources apparently seeks to increase the company's supplies of primary raw materials and, in 2021, entered into a co-operation agreement with the Australian exploration company RareX to form a joint trading company for the purchase of mineral concentrates of rare earth elements from producers outside China and processing at Shenghe’s plant in China. The agreement also gives Leshan Shenghe Resources the right to purchase any production from RareX's Cummins Range (Roskill 2021b). In 2015, Shenghe entered into a marketing agreement with Tantalus to purchase 3,000 tonnes/year MREC (Mining Review Africa 2015).

China Nonferrous Metal Mining (Group) Co. Ltd.

China Nonferrous Metal Mining (Group) Co. Ltd. (CNMC) was established in 1983 and is a state-owned consortium dealing in the development of non-ferrous metals, engineering work and consulting and trade; the company was primarily formed to undertake tasks outside China. By 2021, the company is represented in more than 80 countries and has been involved in almost all types of non-ferrous metal projects, including rare earth elements.

CNMC is organised into several listed companies as well as 33 holding companies, including China Nonferrous Metal Industry Foreign Engineering and Construction Co. Ltd., which has been involved in a number of rare earth element projects in the west. For example, in 2009, CNMC tried to buy the Australian Lynas Corp., which owns the Mt. Weld project, but this trade was rejected by the Australian authorities. In the years 2014-2016, CNMC entered into a co-operation agreement with Greenland Minerals (GM) on the development of the Kvanefjeld project in Greenland (see Chapter 10); in 2016, for reasons unknown, CNMC was replaced by Shenghe Resources. The group structure of CNMC is shown in Table 12-3.

In 2019, CNMC entered into a non-binding agreement with Chinese ISR Capital (now Reenova Investment Holding Ltd.) to establish and operate Tantalus' project in Madagascar; at the same time, they were included in a purchase option of 3,000 tonnes/year of the ‘products’. Reenova Investment Holding is reportedly the real licensee.

Table 12-3 *Group overview for China Nonferrous Metal Industry Foreign Engineering and Construction Co. Ltd. Source: Orbis (2021).*

China Nonferrous Metal Industry Foreign Engineering and Construction Co. Ltd	CNFC Equipment Co. Ltd
	CNFC Kazakhstan (Kz)
	Chifeng NFC Zinc Co. Ltd
	Guangdong Zhujiang Rare Earths Co. Ltd
	Shenyang Jiacheng Industrial Co. Ltd
	Zhongse Int. Alumina Develop. Co. Ltd
	Beijing Zhongse Metal Resources Co. Ltd
	Monglia Industrial Construction Co Ltd (Mn)
	China-Australian Resources Holding Ltd (LA)
	NFC Rare Earth Co. Ltd
	NFC Shenyang Metallurgical Machinery Co. Ltd
	China-Australian Resources (Laos) Hong Kong Ltd.
	Xindu Cargo Co. Ltd (MN)
	Chifeng CNMC Baiyinnuoer Mining Industry Co. Ltd
	Acxap-Tay (KZ)
	Zhongse Meigong Mines Ltd. (LA)
	Zhnagse Southern Rare Earth (Zinfeng) Co. Ltd
	SNFS (Elos) (RU)
	NFC (Saudi Arabia Co. Ltd. (A)
	Kaifeng Resources Holdings Ltd. (VG)
	NFC Metal Pte. Ltd
	China Nonferrous Metals (Erenhot) Co. Ltd.
	NFC Development (DRC) Company Ltd. Sarl (CG)
	Baisheng fulcrum Company (Pty) Ltd (ZA)
	NFC Kyrgyzstan Co. Ltd (KG)
	Chifeng Hongye Investment Co. Ltd.
	NFC Russia Co. Ltd (RU)

12.3 Major Chinese magnet manufacturers

One of the results of the green transition, and electrification of the transport sector is a very sharp increase in the consumption of permanent magnets. A significant proportion of these magnets are of the NdFeB and SmCo types (see section 3.2.1), which has become the most economically important market for the four rare earth elements praseodymium, neodymium, terbium and dysprosium. The production of high-quality magnets is tied up in patents and knowhow, and occurs in a competitive market, which also presupposes that there is access to the correct raw materials. The aforementioned factors limit the potential for establishing new factories as the need arises. China is believed to have an annual production capacity of approx. 400,000 tonnes of magnets, which is larger than the current global demand, so China is currently the market leader.

Examples of some of the major Chinese magnet manufacturers are listed below.

Beijing Zhongke Sanhuan High Technology Co. Ltd.
Beijing Zhongke Sanhuan High Technology Co. Ltd. (Zhongke Sanhuan) is primarily involved in research & development and production and sales of materials for NdFeB magnets and is reportedly the second largest manufacturer in the world of this type of magnet. There are raw material

supply agreements with China Southern Rare Earth Group (CSREG) and Keli Rare Earth. The consortium includes, amongst others, subsidiary Ningbo Koningda Industrial Co. Ltd., which, in partnership with Dandong Rare Earth Group Co. Ltd., owns Ningbo Zoning Special Alloy Co. Ltd., which has entered into an agreement on raw material supplies with CSREG. The group has entered into a co-operation agreement with Tesla Motors Inc. (USA) and is a partner with Vacuumschmelze GmbH & Co. (Germany).

Galaxy Magnet
Galaxy Magnet was established in 1993 with business areas that focused mainly on research & development, production of magnetic materials and bonded NdFeB magnets (see section 3.2.1) as well as hot-pressed SmCo magnets.

Hengdian East Magnetic Field
Hengdian East Magnetic Field (HEMF) is a privately owned company that produces materials for magnets and energy-saving products. In addition, the group is involved in the manufacture of photovoltaic systems. The group is the largest of its kind in China and supplies Huawei, Tesla, Bosch, Samsung, Valeo and Panasonic to name just a few.

Jin Li Permanent Magnet
The focus of business of Jin Li Permanent Magnets (JL Mag) is primarily high-quality magnets for energy production and savings. Located in Ganzhou, Jiangxi Province, the company is located in one of the regions where large quantities of heavy rare earth elements are mined and the company has entered into a supply agreement with Ganzhou Rare Earth Group. JL Mag has been supplying magnets to Bosch Group for several years and, in 2019, entered into an agreement to supply magnets to Volkswagen Group MEB and American General Motors. In 2017, the annual production capacity was expanded from 6,000 tonnes to 10,000 tonnes of NdFeB magnets, and JL Mag was the largest magnet producer in 2020 with around 14.5 % of the market (The Rare Earth Observer, Jan. 4, 2022).

Ningbo Yun Sheng
Ningbo Yun Sheng specialises in high-quality NdFeB magnets based on its own research & development projects, specifically magnets targeted at vehicle manufacturers, and is one of China's largest manufacturers in the field. In 2019, they produced approx. 170,000 tonnes of sintered NdFeB magnets and approx. 7,900 tonnes of bonded magnets (SMM News 2020).

Yantai Zhenghai Magnetic Material
Yantai Zhanghai Magnetic Material specialises in the production of NdFeB magnets for areas of industry where special requirements are placed on the performance of the magnets. The company has a capacity of approx. 10,000 tonnes/year.

13. Supply chains outside China - examples

Many of the existing western companies that are part of the value chains for rare earth elements depend on the import and export of their raw materials and products, where China is without a doubt the hub of many of these activities. In order to gain a competitive advantage, a number of western companies have set up subsidiaries in China, and conversely, a number of companies registered in China have set up subsidiaries in the west, with the result that there is no clear distinction between the terms 'China' and 'West', and preferred market strategies are not clear either. This lack of transparency is a challenge to business policy initiatives that have been initiated in several countries to meet the western policy goals of establishing national, China-independent value chains, *e.g.* because companies align their ‘nationality’ with what is commercially most advantageous in a given situation. It should be noted that in the mining industry, it is more the exception than the rule that the raw materials are processed in the country where they are mined.

The Mountain Pass mine in the USA is an example of a company from the upper part of the value chains, in close co-operation with China. After a series of turbulent years from 2002 to 2015 when Molycorp filed for Chapter 11 bankruptcy, (see section 13.1.21). In 2017, MP Materials (a consortium consisting of MP Mining Operation LLC, QTT Financial, JHL Capital and the Singapore-listed company Resource International Trading (which is a subsidiary of Shenghe Resources)) won the public auction. The new consortium changed the Molycorp business model based on a complete REE-supply chain, to the sale of mineral concentrate for reprocessing and consumption in China. The United States thus became a major exporter of rare earth elements to China. With the combination of Chinese co-ownership, the sale of all production in China and relocation and registration in the US, MP Materials is a hybrid of a western/Chinese company.

Neo Magnequench is another example of an international company with an unclear national affiliation. Originally named Magnequench and owned by General Motors and one of the largest magnet networks in the United States that developed the first NdFeB magnets in the 80’s, Magnequench was acquired in 1995 by the American Sextant Group and the two Chinese companies China Non-Ferrous Metal Import & Export (CNNMC) and San Huan New Material. In 1997, Onfem Holding, a subsidiary of CNNMC, acquired the Chinese majority in the company and in 2000 transferred production and patents to China. This happened at the same time as the Mountain Pass mine closed at the request of the authorities (see section 4.3.1). Thus, the USA lost both raw material production, processing and know-how, which was both accepted and encouraged by the US government as part of minimizing the costs of e.g. wages. In 2005, Magnequench and the Canadian company AMR Technologies were merged, and the name was changed to Neo Materials Technologies, which in 2012 was acquired by Molycorp Inc.,who acquired the REE-separation Silmet plant in Estonia in 2011. Neo Magnequench, which is the company's latest name, is listed on the Toronto Stock Exchange with dealings in China in, amongst others, Beijing, Tianjin, Hejn, Zibo and Jiangyn. Magnequenchs has license agreements with Beijing Zhongke Sanhuan High Technology to produce REE magnets. Neo Magnequench belongs to the Neo Performance Materials group, set up in 2016 as a reconstruct of the rest of the Molycorp America; further details in 13.1.5.

Other western companies with joint ventures or co-ownership in midstream productions in China include: the collaboration between Sumikin Molycorp, Hitachi Metals and Advanced Materials Japan Corporation with magnet manufacturer Grirem Advanced Material; Hitachi Metals' licensing agreement with Beijing Zhongke Sanhuan High Technology for the production of REE magnets; Vacuumschmelze GmbH & Co.'s joint venture with Beijing Sanvac, which produces NdFeB magnets; and Beijing Zhongke Sanhuan High Technology's joint venture with Sagami Chemical Metal Co. Ltd. on magnetic production (NdFeB).

China is the only country that has complete value chains in rare earth elements with the capacity to ensure both its own supply and export of industrial products in which the rare earth elements are included. The value chains for rare earth elements in countries outside China are incomplete (Table 13-1). Below examples are listed of western companies that are part of the existing value chains, and companies that are working on projects that may eventually become part of these chains.

Table 13-1 *Overview of countries with supply chains for rare earth elements. The west's capacity for separation, processing (oxide for metal and for alloys) and magnetic production is small compared to that of China. Mixed compounds here indicate mixed REE products which are obtained by dissolving the mineral; most often it is MREC products.*

Country	Mining	Mixed compounds	Separation	Processing: oxide to metal	Processing: alloys	Magnet production
Australia	X	(X)				
Brazil	X					
Burundi	X					
Estonia			X			
France			X			
India	X	X	X			
Japan			X	X	X	X
Kazakhstan			(X)			
China	X	X	X	X	X	X
Madagascar	X					
Malaysia		X	X			
Myanmar	X					
Russia	X	X	X			
UK				X	X	
Thailand	X					
Germany					X	X
USA	X	(X)	(X)			(X)
Vietnam	X			X	X	X
Austria					X	X

13.1 Examples of potential new 'western' supply chains

This section provides examples of the partnerships that are part of some of the potential new 'western' rare earth element supply chains. The examples illustrate that the mineral industry and the related supply chains are international; very few supply chains can act as isolated national chains. It also appears that in some cases the exploration companies have accepted the condition that there are no buyers for their products in the west, which is why agreements have been entered into with Chinese partners to varying degrees.

The examples are arranged alphabetically in relation to the country in which the upper part of the chain is geographically located. Any other products of the projects, which do not consist of rare earth elements, are mentioned only on exception. The review of the examples should only help to provide a picture of where, how, what and who is involved in some of the potentially new supply chains, and no business assessment of the projects is made. An overview of the projects' location in the value chains and the companies that are part of each chain is shown in Table 13-1.

13.1.1 Angola

Pensana Rare Earth (Longonjo)

Pensana Rare Earth Plc announced in May 2021 that the company had begun establishing a 125 million USD separation plant at Saltend Chemical Park, Hull, England. The plant is stated to create 100 new jobs and deliver approx. 5 % of global demand for magnetic metal oxides (Figure 13-1).

Collaborators/Partners: China Great Wall/China EX-IM-bank is involved in financing the mining project (Pensana Annual Report 2020 (https://pensana.co.uk/wp-content/uploads/2020/09/Penana-Annual-Report_30-June-2020-FINAL.pdf))[4].

Stated annual production: approx. 12,500 tonnes TREO, of which 4,500 tonnes are of NdPr oxide. The ore holds as well 0.09 % thorium, which with the planned annual production is equivalent to 1,340 tonnes ThO_2 (The Rare Earth Observer May 19, 2021 (https://treo.substack.com/p/pensana-acknowledge-radioactive-materials)), which has to be disposed[5].

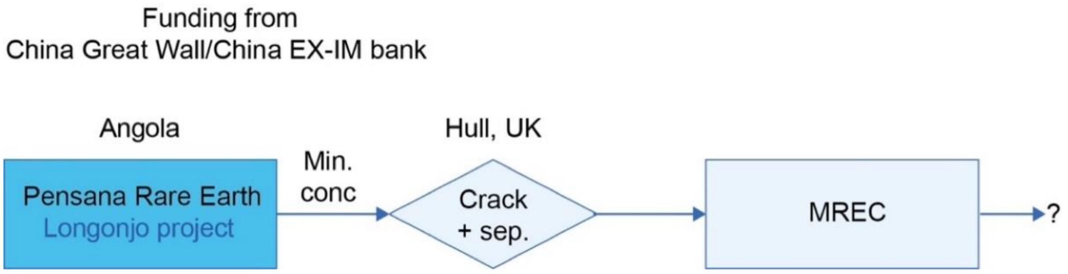


Figure 13-1 *Supply chain for ore from the Longonjo deposit in Angola, owned by Pensana Rare Earth.*

13.1.2 Australia

Alkane (Dubbo) – Vietnam Rare Earth JSC – South Korea Zircon Tech (South Korea)

Alkane, which is developing the Dubbo project, expects to process the ore in Australia and send the mineral concentrate for processing and separation at the Vietnam Rare Earth JSC (VRE JSC), which will carry out this work on commission (tolling) (Figure 13-2). Shenghe Resources (Singapore) Pte. Ltd. owns 90 % of VRE JSC; 10 % is owned by the Japanese company Chuo Denki Kogyo Co. Ltd. It is not stated which product will be forwarded to South Korea Zircon Tech or whether some of the products will be sold to a third party.

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[4] Pensana claims (e-mail correspondance, August 2022) this information is incorrect, but documentation supporting their allegations have not been forwarded.

[5] Pensana c claims (e-mail correspondance, August 2022) this information is incorrect, but documentation supporting their allegations have not been forwarded.

Stated annual production: 3,675 tonnes TREO.

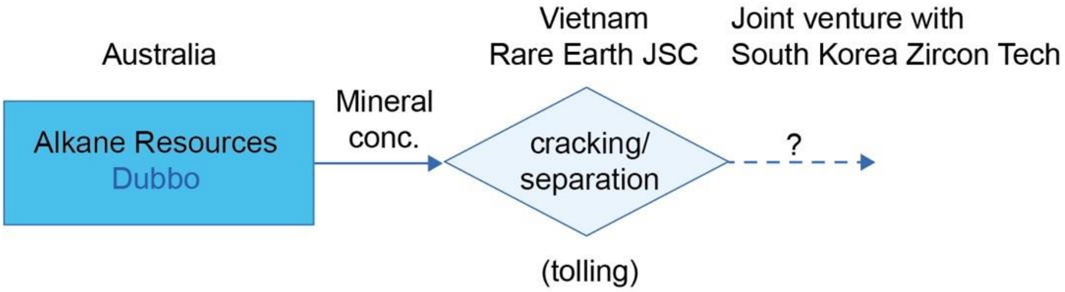

Figure 13-2 *Intended supply chain for ore from the Australian deposit Dubbo.*

Arafura Resources Ltd. (Nolans Bore) – Vietnam/Thailand

In 2013, Arafura Resources Ltd. agreed a MoU with China Nonferrous Metals Co. on the development of the Nolan's Bore deposit. It is unclear whether this agreement has been extended, but in 2019, Arafura entered into a MoU with Baotou Tianhe Magnets Technology Co. Ltd. with a view to a multi-year sales agreement of approx. 4,350 tonnes of NdPr oxide/year as raw material for Baotou Tianhe's NdFeB magnet production. An overview of the supply chains for ore from Nolans Bore can be seen in Figure 13-3.

In 2021, Arafura announced that sales agreements are being negotiated with companies in Europe, Japan, South Korea, the United States and China, corresponding to 120 % of the planned production from Nolan's Bore. The final decision on commissioning is expected to be decided in the second half of 2022 (Arafura Resources 2021).

Stated annual production: 14,000 tonnes TREO.

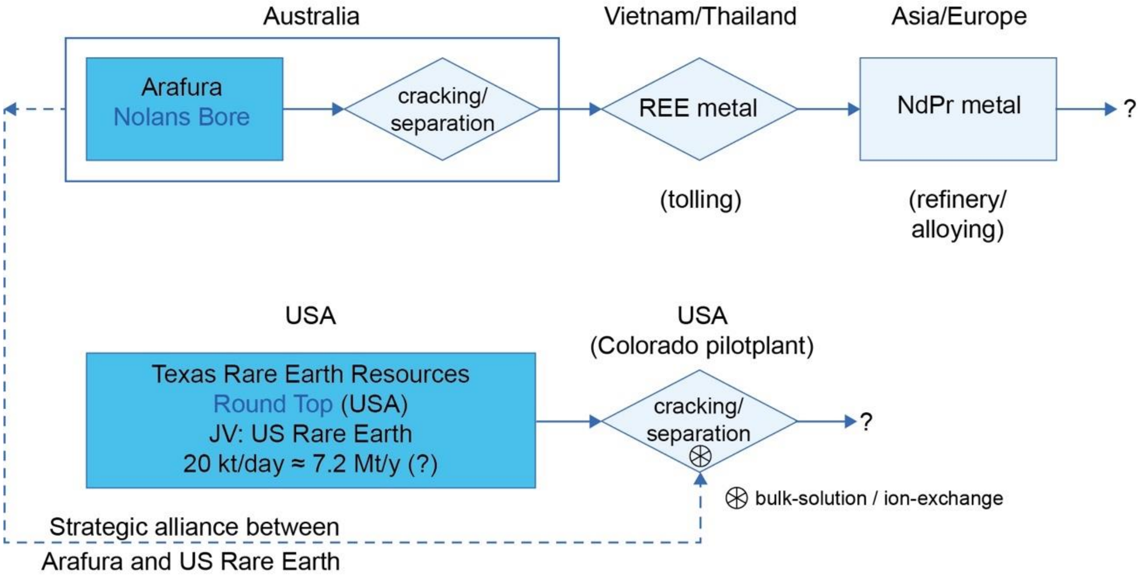

Figure 13-3 *Supply chains for ore from the Nolans Bore project in Australia. Mineral dissolution and separation in Australia, subsequent refining, and metallurgy in either Vietnam or Thailand. In addition, a strategic alliance has been entered into with US Rare Earth.*

Hastings Technology Metals (Yangibana) – China Northern and Thyssenkrupp Material Trading

Hastings Technology Metals, which is working to develop the Yangibana deposit at Onslow in Australia, has business relations with China Northern Rare Earth and, in 2017, entered into the following marketing agreements:

- Delivery of 2,500 tonnes/year MREC to Baotou Sky Rock Rare Earth New Material
- Delivery of 2,000 tonnes/year MREC to China Rare Earth Holding
- Delivery of 1,500 tonnes/year MREC to Ganzhou Qiandong Rare Earth Group which develops, produces, and sells RE raw materials; the agreement is for 3-years with the possibility of extension
- Delivery of 6,000 tonnes/year (uncertain information) to Thyssenkrupp Material Trading.

The ore from Yangibana is characterised by having a high content of neodymium and praseodymium. Construction of the mine and processing plant is expected to start in 2022 with expected production in 2024. The planned annual production is 15,000 tonnes MREC (containing approximately 23 % TREO). Parts of the planned progress from mine to Thyssenkrupp Material Trading can be seen in Figure 13-4.

Stated annual production: approx. 3,500 tonnes TREO.

Lynas Corp. Ltd.

Lynas Corp. Ltd., the largest western producer of rare earth elements, opened mines and processing plants at Mt. Weld in 2007, and commenced processing and separation at the Lynas Advanced Material Plant (LAMP) plant in Gebeng, Malaysia in 2013. The processing plant at Mt. Weld for the concentrating of monazite (etc.) can produce approx. 70,000 tonnes of mineral concentrate/year, corresponding to approx. 28,000 tonnes TREO. The LAMP system has a separation capacity of approx. 26,000 tonnes/year TREO, but the permits for production expire in 2023, and the company is challenged in terms of meeting the Malaysian authorities' environmental requirements for tailings.

Japan is Lynas' largest market and has, since 2011, contributed loan financing for establishment and expansion. Lynas Rare Earths Ltd. announced in August 2021 that the company had received 10.9 million USD from the Australian State for the development of ‘the world’s largest production facility outside China’; the company plans to establish the facility near Kalgoorlie, Australia (The Rare Earth Observer 2021d). Lynas expects to invest around 400 million USD in the plant, which will produce REC of the ore from Mt. Weld for export (presumably for the LAMP plant in Malaysia); it must be assumed that the plant at Kalgoorlie will eventually be expanded to replace LAMP.

See also Lynas Rare Earth's activities in section 13.1.21.

Northern Minerals (Browns Range) – Conglin Baoyuan – Thyssenkrupp Material Trading

Northern Minerals, under the common name Browns Range, develops the deposits Wolverine, Gambit West, Gambit, Area 5, Cyclops, Banshee and Dazzler in Northern Western Australia. A pilot plant opened in 2018, which was built in collaboration with Sinosteel that provides technical and financial support for the project. Northern Minerals has entered into an agreement with Thyssenkrupp Material Trading for the treatment of 114 tonnes of mineral concentrate from the Brown Range project's pilot production (Figure 13-4).

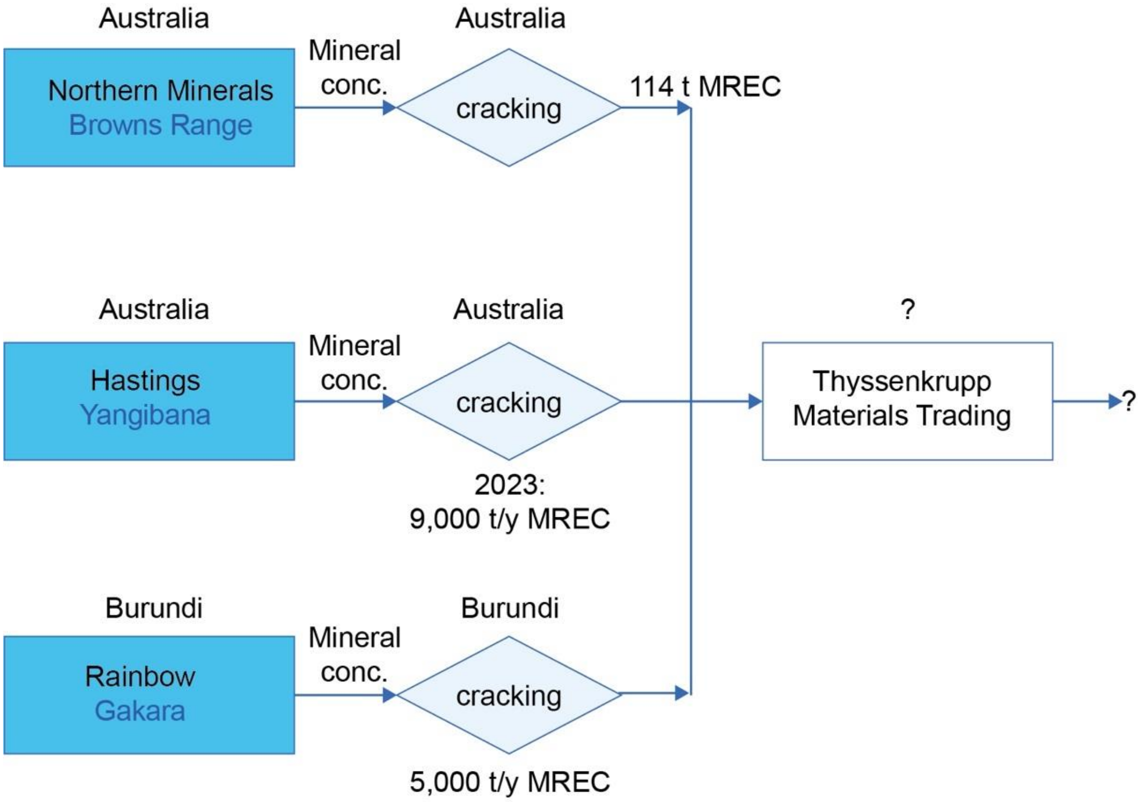

Figure 13-4 Supply chain of raw materials for processing/separation at Thyssenkrupp Materials.

In 2012, Northern Minerals applied to the Australian authorities for permission to enter into an investment partnership with China Northern Rare Earth Group and Baotou Steel (Baogang) for a Chinese investment of 20 million AUD for the development of the Browns Range project; the authorities did not approve this co-operation. Northern Minerals subsequently entered into a sales agreement with an unnamed Japanese company. A small portion (< 5 %) of Northern Minerals shares are owned by Conglin Baoyuan Int. Investment Group, controlled by Chinese investors.

Stated annual production: Undisclosed

RareX (Cummins Range Project) – Shenghe Resources
In February 2021, RareX entered into a non-binding co-operation agreement with Shenghe Resources on the development of RareX's Cummins Range project, the establishment of a joint trading company for the purchase of TREO raw materials from areas outside China and the establishment of a jointly owned refinery outside China. The joint venture, Rare Earths Trading Company (RET Co.), is 51 % owned by Shenghe and 49 % by RareX.

Stated annual production from Cummins Range: Undisclosed.
Trading. Comments on Rainbow's production are listed in section 13.1.3 Burundi.

13.1.3 Burundi

Rainbow Rare Earth (Gakara), Bujumbura, Burundi) – Thyssenkrupp Material Trading
Rainbow Rare Earth Ltd. was licensed in 2015 to exploit high-grade ore from several smaller deposits near Bujumbura (Gakara) in Burundi for 25 years; trial production was initiated in Gakara

in 2019 with ongoing mineral exploration being undertaken concurrently. The business concept is based on the export of mineral concentrate (bastnäsite, monazite) with an expected annual production of approx. 5,000 tonnes of mineral concentrate, increasing to approx. 10,000 tonnes/year with a stated content of approx. 50 % TREO (Figure 13-3). The ore has a relatively high content of light rare earth elements.

Trial quarrying and processing is ongoing but was suspended in July 2021 following an order from the government, which wants the license agreement renegotiated. A sales agreement has been entered into with Thyssenkrupp Material Trading for 5,000 tonnes/year of mineral concentrate and shipping via Mombasa, Kenya.

Stated annual production from Gakara: Undisclosed – but estimated to be approx. 5,000 tonne/year TREO.

13.1.4 Belgium

Solvay Rare Earth Systems

Solvay is a global company with approx. 23,000 employees and projects/offices in more than 60 countries focusing on composite materials and chemicals; rare earth elements are included in the product portfolio.

In 2011, the Belgian group Solvay acquired the French chemical group Rodia and their separation plant in La Rochelle, France. The plant has an installed production capacity of 9,000 tonnes/year TREO. There have reportedly been environmental problems due to the content of radioactive substances in the liquids that are treated at the plant, and production has apparently moved to China. Solvay has subsequently offered to carry out separation for new mining companies, provided that the materials that are to be treated can meet the technical requirements in place at the plant (for example, must not contain uranium, thorium, iron, aluminium, and fluorine), as well as the French environmental standards for radioactive content.

13.1.5 Canada

Avalon/Vital Metals/Cheetah Resources (Nechalacho) – Search Minerals – REEtec

Avalon and Vital Metals have joint ownership of NWT Rare Earth Ltd. (NWTREL) with Vital Metals' subsidiary Cheetah Resources as the operator. The government of Saskatchewan has provided financial support (approximately CAD 31 million) for the establishment of a separation plant (Menezes 2021). The concept in this supply chain is based on Cheetah mining the minerals containing REE in the T-zone of the Nechalacho deposit and is also responsible for building and operating a plant that processes the minerals and produces a mixed carbonate product containing all the rare earth elements. The processing is based on a patent (Direct Extraction Process), which is owned by Search Minerals. The carbonate product is subsequently exported to REEtec's separation plant at Porsgrunn in Norway, which will produce RE oxide products with 99-99.999 % purity (Avalon 2020). The agreement covers the delivery of 2,000 tonnes/year TREO with a content of 750 tonnes of NdPr oxide with a maximum of 25 % cerium oxide. No information is available on the subsequent processing route.

Stated annual production from Nechelacho: Undisclosed, but Vital Metals has a five-year contract for the delivery of 1,000 tonnes/year MREC (excluding cerium) to REEtec, and work is underway on a ten-year contract of 2,000 tonnes/year MREC as well as a supply agreement for Ucore Rare Metals’ Alaska 2023 project.

Defense Metals Corp. (Wicheeda) – Sinosteel
In August 2021, Defense Metals Corp. (DMC) entered into a technical and economic co-operation agreement with Sinosteel Equipment & Engineering Co. Ltd. (a subsidiary of Sinosteel Corp.) with a view to establishing pilot plants for mineral processing and separation of the individual rare earth elements to be used for the development of DMC's Wicheeda deposit in British Columbia, Canada. The business model is stated to be the production of mineral concentrate with a minimum of 48 % rare earth elements with a focus on raw materials for military industrial applications (Bird et al. 2019).

Stated annual production from Wecheeda: Undisclosed.

Medallion Resource Ltd.
Medallion Resource Ltd.’s business concept is based on the purchase of monazite concentrates, which must be processed at its own plant using its own patented method. There is no information on where the plant will be constructed and who will subsequently separate and refine the products.

Neo Performance Materials
Neo Performance Materials (NPM) was established in 2012, as part of the reconstruction of Molycorp (which owned and was a producer at Mountain Pass, USA). Subsequently, NPM is divided into Neo Magnaquench, Neo Chemicals & Oxides, Neo Rare Metals and Neo Water Treatment (Ecclestone 2019) (Figure 13-5).

Neo Performance Materials has a total of three rare earth element separation plants; the Silmet plant in Estonia (see section 13.1.6 Estonia) has a capacity of approx. 2,500 tonnes/year, while two plants in China, Zibo and Jiangxi, have a total capacity of approx. 10,000 tonnes/year (Figure 13-5).

13.1.6 Estonia

Neo Performance Materials (Silmet)
In 2015, Molycorp acquired the separation plant Silmet in Estonia, and subsequently following Molycorp’s bankruptcy the plant was taken over by the new company, Neo Performance Materials (NPM), of which Neo Magnequench is a division. The plant has a capacity of approx. 2,500 tonnes/year and has been primarily used to process ore from the Russian deposits of the Kola Peninsula. Given the geographical location of the plant, it is widely regarded as part of the 'western' value chains, which are to liberate the supply chains of rare earth elements from China's dominance. The extent to which Chinese relations will affect Neo Performance Materials' activities is unknown.

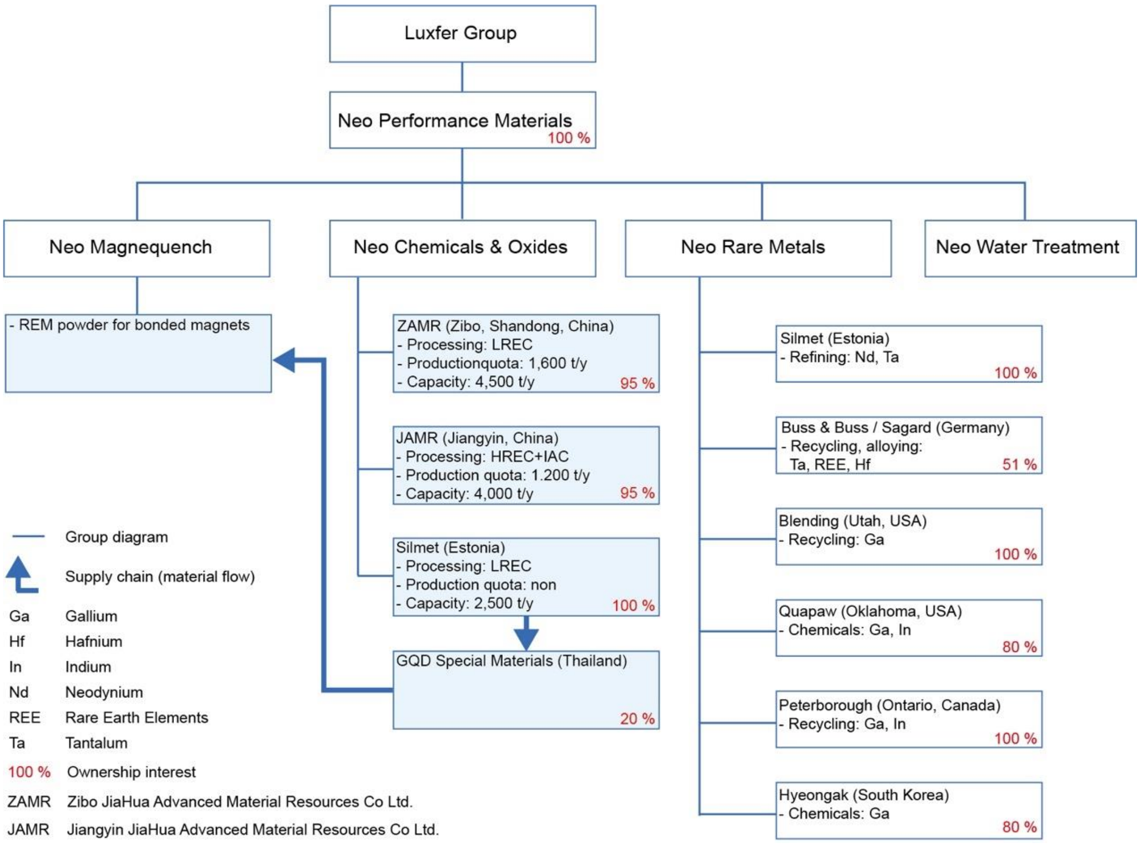

Figure 13-5 *Neo Performance Materials' organisational breakdown. Source: Neo Performance Materials (2020).*

13.1.7 Greenland

Greenland Minerals (Kvanefjeld/Kuannersuit) – Shenghe Resources
Greenland Minerals' project Kvanefjeld is based on the extraction of the mineral steenstrupin from an open pit mine. The project is in the final approval phase with an ongoing EIA process, which is happening at the same time that a new law has been introduced that does not allow mineral exploration and mining of ore with an average concentration of more than 100 ppm uranium; the future of the project is thus uncertain. In 2016, Greenland Minerals entered into a co-operation agreement with Shenghe Resources, which is also a minority shareholder (see also sections 10.3.2.4 and 12.2). The work has two overall business concepts; (i) preparation of a mineral concentrate of steenstrupin, which is exported for reprocessing at one of Shenghe's plants; and that (ii) the ore is mined and processed in Greenland, and an LRE carbonate and an HRE carbonate are produced, which are also exported to one of Shenghe's separation plants. In model (i), the content of uranium and thorium in steenstrupin will be exported; in model (ii) it is envisaged to produce an export product of uranium and deposition of thorium.

Stated annual production from Kvanefjeld: approx. 30,000 tonnes TREO (the project is currently on hold December 2021).

Tanbreez (Kringlerne/Killavaat Alannguat)
The privately owned company Tanbreez has an exploitation permit for the extraction of rare earth elements and other metals (including Zr, Nb, Ta) from the eudialyte ore from Kringlerne in South

Greenland. The deposit contains an estimated tonnage of ore of approx. 4.3 billion tonnes, one of the largest in the world. Production is planned based on constructing an open mine near the coast, and the production of a mineral concentrate from eudialyte, which is then shipped. No plans have been published for where and under what framework the extraction of rare earth elements will take place, nor is there any information on partners. Tanbreez's owner has often signalled that the project should not be linked to Chinese customers and has also announced that the project will be able to start up in 2023 with full production in 2025.

Stated annual production from Kringlerne: approx. 5,000 tonnes TREO in the start-up phase with a long-term goal of 10,000-15,000 tonnes TREO.

13.1.8 India

Indian Rare Earths Ltd
Indian Rare Earths Ltd (IREL) produces monazite concentrates as a by-product of heavy sand extraction. In addition, IREL has a processing plant in Odisha, India, for the treatment of monazite, which can produce a mixture of rare earth elements; the plant has a capacity of 11,200 tonnes/year, but this capacity was not utilised in 2016 (Gambogi 2019).

13.1.9 Japan

Chuden Rare Earth
Chuden Rare Earth produces magnetic alloys in both Japan and China (including Langfang Gans Magnetic Material) and Vietnam (Vietnam Rare Earth).

Hitachi Metals Ltd.
Hitachi Metals Ltd. produces various types of REE magnets and magnetic alloys. In 1982, Hitachi Metals manufactured the strongest NdFeB magnet, which was patented and marketed for Neo-Max Magnet, which kick-started the widespread use of these magnets.

Santoku
Santoku manufactures REE magnets and battery alloys from plants in Phoenix, Arizona, USA. Originally the company was owned by Rhône-Poulenc, but in 1988, it was taken over by Santoku Metal Industry Co. Ltd. (Kobe, Japan). In 2010, they established China Minmetals Santoku (Gnazhou). Rare Earth Material Co. Ltd. Santoku was acquired in 2018 by Hitachi Metals.

13.1.10 Madagascar

Tantalus Rare Earth Malagasy Resources – ISR Capital Ltd – Leshan Shenghe Resources – China Nonferrous Metal Industry Foreign Engineering and Construction Co. Ltd.
In 2015, Leshan Shenghe Resources (LSR) and Tantalus Rare Earth Resources (Tantaus) entered into a 3,000 tonnes TREO sales agreement from Tantalus' IA deposit on the Ampasindava Peninsula in North-western Madagascar. It was also agreed that LSR would finance 30 % of the project's development costs. The project, which was in trouble, was subsequently sold to ISR Capital Ltd. (Singapore), which in June 2019 entered into an agreement with China Nonferrous Metal Industry Foreign Engineering and Construction Co., on the development of the deposit and the sale of 3,000 tonnes of TREO/year. The status of the project is unknown.

13.1.11 Malawi

Mkango Resources/Talaxis (Songwe Hill) – Chinalco Guangxi
A joint venture group controlled by Mkango Resources and investor group Noble Group Holding Ltd.'s subsidiary Talaxis conducted an FS study in 2021 of the Songwe Hill project in Malawi. Mkango oversaw the exploration and Talaxis was responsible for financing and commercial activities. Mkango plans to export a mixed product of rare earth element carbonate and a mineral concentrate shipped from Beira in Mozambique.

In December 2019, Talaxis entered into an agreement with Chinalco Guangxi for the supply of 42,000 tonnes/year of rare earth mineral concentrates and oxides (Noble Group Holding Ltd. 2019). It is unclear whether this large supply is to be produced by Mkango alone, or whether the contract allows concentrate from other deposits. In August 2021, Mkango Talaxis took over its share of the project in exchange for Noble Group Holding receiving 23 % of Mkango Resources. It is therefore assumed that the sales agreement with Chinalco Guangxi, as well as the agreement on technical and financial support for the start-up of the Songwe Hill project, have been maintained. Company construction and collaboration are shown in Figure 13-6.

Mkango Resources has also established a subsidiary in Poland (Mkango Polska), which through Grupa Azoty Zaklady Azotow Pulawy will build and operate a separation plant in Poland with an expected capacity of approx. 2,000 tonnes/year NdPr oxide (Figure 13-6).

Stated annual production from Songwe Hill: not clearly stated.

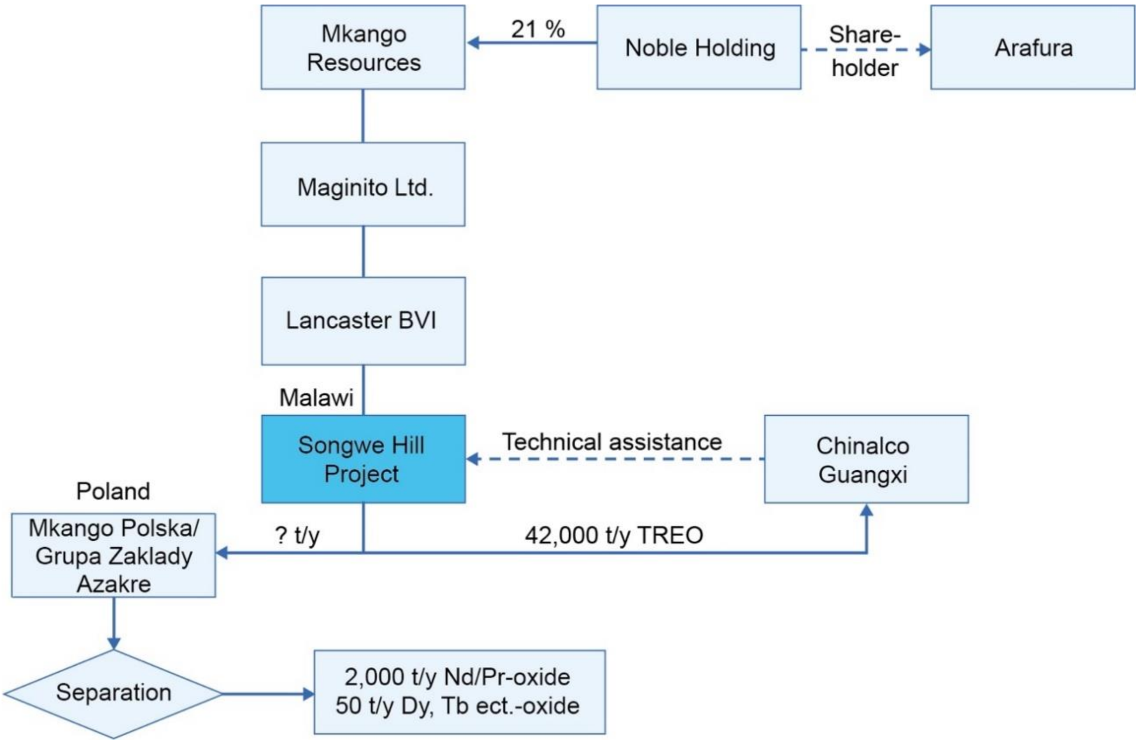

Figure 13-6 *Corporate organisation of the Songwe Hill project in Malawi.*

13.1.12 Norway

Yara – REEtec – Less Common Metals – Vacuumschmelze Gmbh & Co.
REEtec is owned by Scatec Innovation in Norway and is a partner in the EU-Horizon 2020 project SecREEts (https://secret-project.eu/) with a total research grant of 12.5 million EUR. The project involves, amongst others, Less Common Metals (LCM) from England and Vacuumschmelze Gmbh & Co. (VAC) from Germany. Based on 650,000 tonnes of phosphate ore (apatite) from Yara's plant in Porsgrunn (Norway), the project has initiated a supply chain where REEtec will extract, separate and refine rare earth elements and produce high-quality REO products (up to 3N), which will subsequently be refined and alloyed by LCM in a quality that can be used to make NdFeB magnets at VAC (Figure 13-7). VAC is linked to the Chinese magnet industry through its ownership of Beijing Sanvac.

In addition to the agreement with Yara, REEtec has a co-operation agreement with Vital Metals, to process up to 1,000 tonnes/year from the Nechalacho deposit in Canada. The first test shipments were transported in September 2021.

Stated annual production from Yara phosphate ore: 2,000-6,500 tonnes TREO, which is estimated to be composed thus: 400-1,200 tonnes La, 800-2,400 tonnes Ce, 400-1,200 tonnes Nd, 200-600 Pr, and 100-325 tonnes Dy (Messecar 2020).

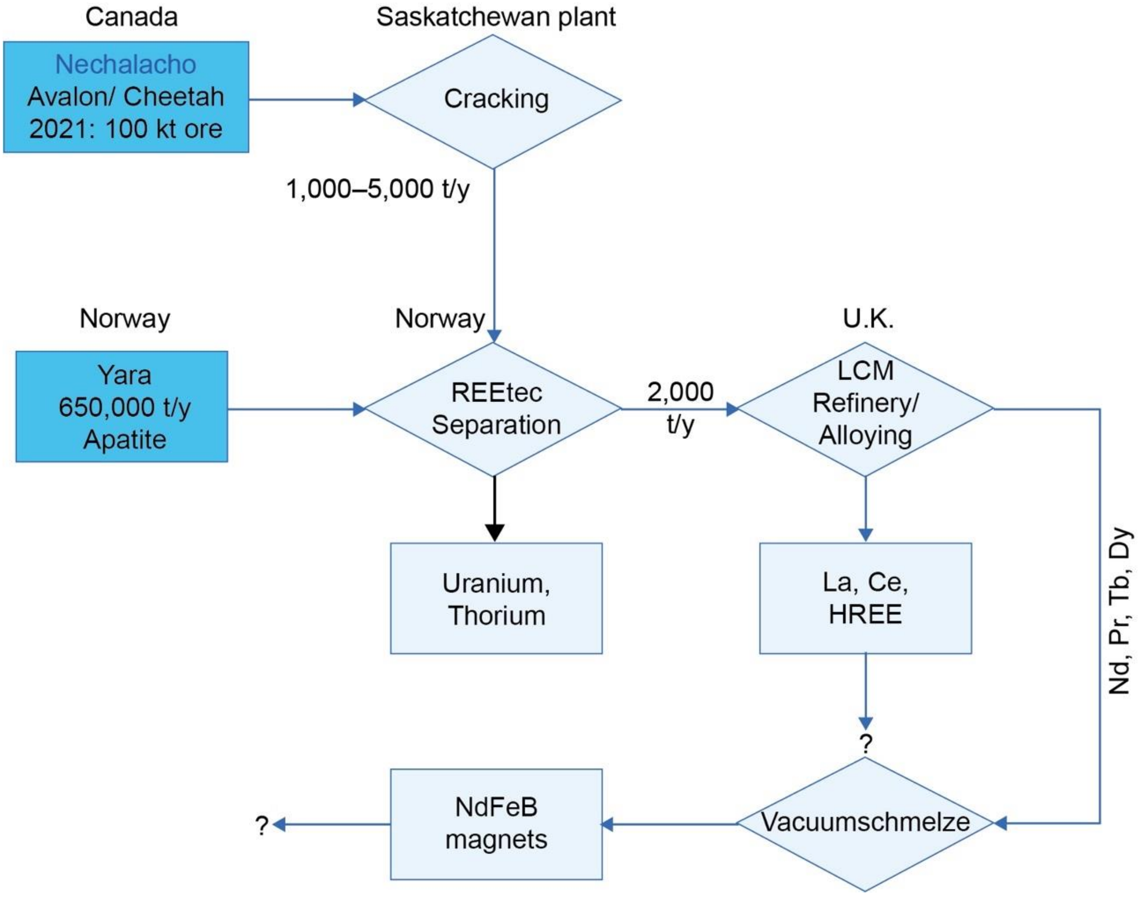

Figure 13-7 *The 'European' supply chain which is in part a result of the EU-Horizon 2020 project. Sources: from company websites.*

13.1.13 Poland

Mkango Resources/Grupa Azoty Zaklady Azotow Pulawy S.A

Mkango Resources/Grupa Azoty Zaklady Azotow Pulawy is working on setting up a separation plant in Poland for processing TREC from the Songwe Hill deposit in Malawi, which is owned by Mkango Resources.

13.1.14 Russia

JSC Solikamsk Magnesium Works

JSC Solikamsk Magnesium Works in Perm Krai, Western Russia produces various mixed products of rare earth elements based on loparite from the Lovozero mine (operated by Lovozersky GOK); the plant has a capacity of approx. 13,000 tonnes/year loparite. There is no information on where these products are subsequently separated and refined.

Stated annual production from Lovozersky: in 2016 approx. 3,000 tonnes TREO (Gambogi 2019).

ThreeArc Mining LCC (Tomtor)

ThreeArc Mining LCC has conducted an exploration of the Tomtor deposit in the Olenyoksky district of Northern Russia for the production of rare earth elements. It is unclear whether the pilot trials have been conducted. The business model is based on the establishment of a processing plant at Krasnokamensk in South-eastern Siberia, close to the border with China. This location has apparently been chosen to facilitate the export of the raw material to China. The plant, which has a planned capacity of 160,000 tonnes/year of ore, will produce MREC, which will be separated 'on account' (tolling); there is no information on who will do it.

ThreeArc Mining LCC has entered into an agreement with Rosatom for the treatment of 82,000 tonnes of monazite concentrate, a residual product from Rosatom's processes, for the extraction of rare earth elements.

ThreeArc Mining LCC is a subsidiary of Polymetal International Plc., which owns silver and gold mines in Russia, Armenia, and Kazakhstan; it is registered in the Jersey Islands and listed in London.

Stated annual production from Tomtor: 11,500 tonnes TREO.
Stated annual production from Rosatom monazite: approx. 33,000 tonnes TREO.

13.1.15 United Kingdom

Less Common Metals Ltd.

Less Common Metals Ltd. (LCM) produces alloy metals, based on rare earth elements, with an emphasis on the production of raw materials for SmCo and NdFeB magnets; the capacity is approx. 2,000 tonnes/year. Less Common Metals in Cheshire in the north of England is owned by the Great Western Minerals Group and Lang Ltd. (which in 2015 was taken over by Indian Ocean Rare Metals Ptd. Ltd.). The relationship with the Great Western Minerals Group means that LCM also now has relationships with a number of the potential new producers of MREC, such as Steenkampskraal (South Africa) and Hoidas Lake (Canada). LCM is the only company in Europe that refines and manufactures alloys of rare earth elements on an industrial scale and is therefore an important part of a European value chain. Most of LCM's raw materials are imported from

China with higher raw material prices than the Chinese competitors, as VAT is not activated, but to which transport costs must be added.

13.1.16 Sweden

Leading Edge Materials Ltd. (Norra Kärr)
The Norra Kärr project is owned by Greenna Mineral AB, which is owned by Leading Edge Materials Ltd. (Canada) and its subsidiary Tasman Metals Ltd. (Canada). The Norra Kärr project was (provisionally) shutdown in 2018 after a negative EIA report and conflict over Natura 2000 requirements, which is why the permit for mining from 2014 was withdrawn. Leading Edge Materials is working on relaunching the project with a changed business concept and has appealed the withdrawal of the license. In the new concept, the ore must be treated by leaching at an unspecified location in Northern Sweden. The new concept also includes a higher degree of industrial use of the minerals that do not contain rare earth elements, thereby reducing the volume of tailings. Production is thought to be based on the mining of 1.15 million tonnes of ore/year with an expected lifespan of 26 years. There is no information on sales agreements or downstream project partners.

Stated annual production from Norra Kärr: 5,350 tonnes TREO, which is expected to contain 578 tonnes of Nd oxide, 143 tonnes of Pr oxide, 248 tonnes of Dy oxide and 36 tonnes of Tb oxide.

13.1.17 South Africa

Great Western Minerals Group (Steenkampskraal) – Less Common Metals Ltd. – Ganzhou Qiangong Rare Earth Group
The Steenkampskraal project includes a small but high-quality monazite deposit in the Western Cape province of South Africa, where Anglo American produced monazite back in the 1960s. Great Western Minerals Group, which owns 28 % of Steenkampskraal Monazite Mine (Pty) Ltd., entered into an agreement with Ganzhou Qiangong Rare Earth Group (GQR) in 2012 to establish a joint venture, Great Western GQD Rare Earth Materials Propriotary Ltd., with a 25 % ownership interest in GQR, which will also ensure the establishment and operation of a separation plant. The company construction is shown in Figure 13-8 and it is stated that the products will be sold to Great Western Group's subsidiary Less Common Metals as well as to other unnamed customers (Proactive 2020). The project has apparently not developed significantly since 2012.

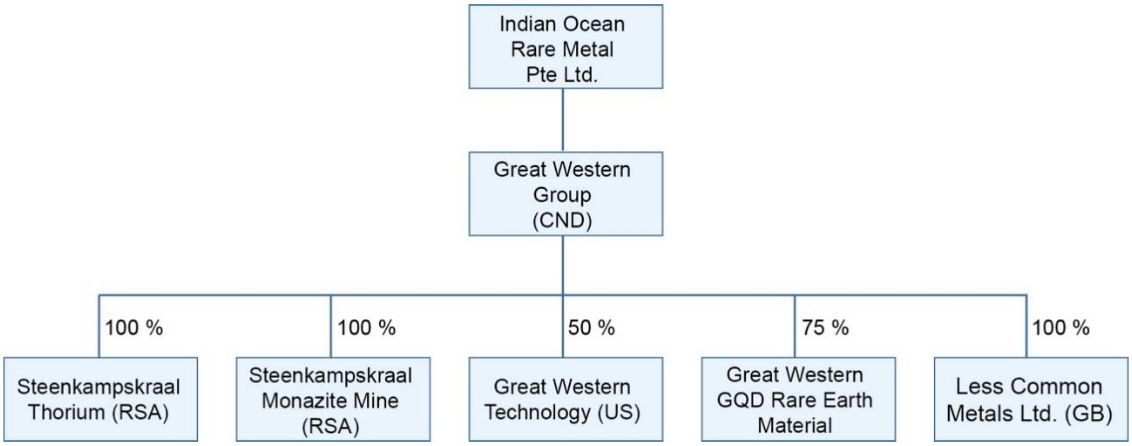

Figure 13-8 *Concern structure of Great Western Minerals Group.*

13.1.18 Tanzania

Peak Resources Ltd. (Ngualla Hill)

The Australian company Peak Resources Ltd. plans to start production of the Ngualla Hill deposit, Songwe Region, Tanzania, in 2022; the license was issued to PR NG Minerals Ltd., which is 100 % owned by Peak Resources. There are negotiations with the authorities about the terms of the license. The mineral concentrate is planned to be shipped to Peak's planned processing and separation plant in Teesside in northern England. According to the plan, Teesside Refinery will produce NdPr oxide for use in magnets for electric vehicles, which requires grades that reach at least > 3N.

Regulatory approvals for Peak Resources' Teesside processing and separation facilities were issued in April 2021. No information is available on the planned technology, capacity, partnerships, or schedules.

Expected production: 32,700 tonnes mineral concentrate (equivalent to 10-12,000 tonnes TREO).

13.1.19 Germany

Vacuumschmelze Gmbh & Co.

Vacuumschmelze (VAC), with headquarters in Germany, is owned through a number of holding companies by NEW VAC Intermediate Holding B.V. Production. VAC owns the Finnish NdFeB magnet factory Neorem Magnets Oy, and is also a co-owner of Beijing Sanvac along with Chinese NdFeB magnet manufacturer Beijing Zhong Ke San Huan Hi-Tech, which is a minority shareholder in China Southern Rare Earth Group (CSREG). VAC has been producing REE cobalt magnets since 1973 and NdFeB magnets since 1985. VAC’s research focuses on the development of non-dysprosium NdFeB magnets for use in induction motors. The development work is undertaken by four subsidiaries registered in Germany, the United Kingdom and Slovakia. VAC is one of the world's largest NdFeB magnet producers, and capacity is expected to double to around 40,000 tonnes/year from 2023 to 2025 (The Rare Earth Observer 2021b).

13.1.20 Uganda

Ionic Rare Earth (Makuutu, Uganda) – Sino Platinum Metals Co. – Chinalco

Ion adsorption project Makuutu approx. 100 km east of Kampala is owned by Ionic Rare Earth (51 %), Kunming Sino-Platinum Metals Co. Ltd. (SPMC) (24 %) and, amongst others, Rwenzori Rare Metals. The final feasibility study is expected to be completed in 2023, and production is expected to begin in 2024. An MoU has been entered into with China Rare Earths Jiangsu (subsidiary of Chinalco) on the development of the mining project and technical assistance agreements with Chinalco (Figure 13-9). SPMC must be responsible for production. In the long term, Ionic Rare Earth is considering establishing its own separation and refining plant with a capacity of 4,000 tonnes/year TREO.

Stated annual production from Makuutu: 3,200 tonnes MREC, which in phase 3 must be increased to approx. 6,000 tonnes MREC. The expected annual products are shown in Table 13-2.

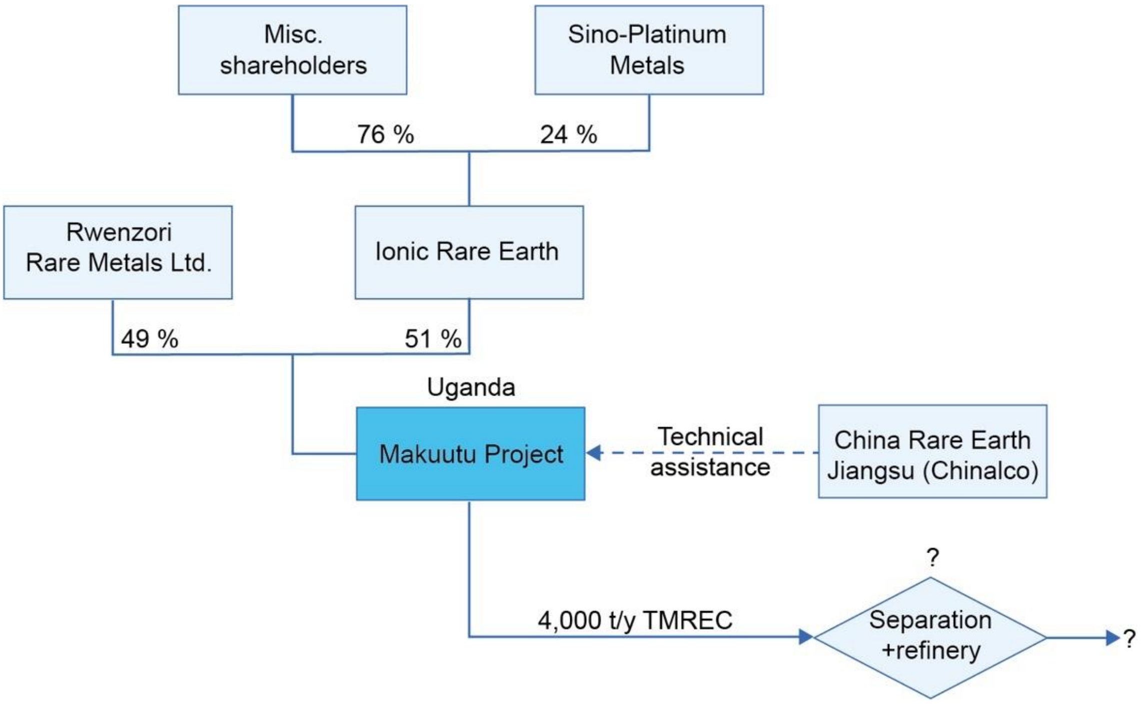

Figure 13-9 *Project ownership for the Makuutu project in Uganda, based on various internet sources.*

Table 13-2 *Expected production from a separation plant such as the one Ionic Rare Earth has under consideration. Source: ASX Release (2021).*

	REO tonnes/year
La	580
Ce	550
Pr	220
Nd	1.000
Sm	180

	REO tonnes/year
Eu	35
Gd	170
Tb	25
Dy	140
Ho	30

	REO tonnes/year
Er	75
Tm	11
Yb	65
Lu	10
Y	1,000

13.1.21 USA

American Resources Corporation

American Resources Corporation is working to establish a production facility for the separation and refining of rare earth elements as well as other critical metals in Noblesville, Indiana, USA. The plant has been developed for the use of scrap metals as a raw material.

Chemours (Georgia monazite heavy sand) – Energy Fuels – Neo Performance Materials Ltd. (Silmet)

The business model for exploiting monazite deposits in Georgia, USA, is based on: (i) Chemours supplies monazite concentrate to Energy Fuels' plant in Utah, USA; (ii) Energy Fuel is establishing a new processing plant in the United States, which is expected to be operational in 2024, and which will extract uranium (and thorium) and rare earth elements (MREC) from the monazite concentrate; and (c) Energy Fuels allocates the rare earth elements to Neo Performance Materials

(NPM), which will carry out the separation of the rare earth elements at their plant in Estonia (Hui 2021a). A sample shipment of about 30 tonnes was shipped to NPM in early July 2021 (Hui 2021b; Neo Performance Materials Ltd. 2021). The competitive advantage of this concept is allegedly that it is a by-product of monazite, which is recovered with extraction of uranium as the main product, whereby the raw material can be obtained cheaply and without further large investments for extraction. The stated business model is based on the sale of rare earth elements to the European battery market. The challenge for this concept is, among other things, that there are no refining and alloying plants or magnetic plants in Europe of the necessary scope, and that there is no plan for the other rare earth elements that will be separated. It is therefore reasonable to assume that any production from Silmet in Estonia will be exported to Neo Performance Materials alloy and magnet factories in Korat, Thailand.

Energy Fuels' pilot plant, White Mesa Mill, developed by Carester SAS, is established in a processing plant that, in 2006-2012, was used to process monazite for the extraction of uranium. Energy Fuels is considering moving the plant closer to Chemour's mining area in the long term but will also treat monazite from other mines at their new plant. The plant processes approx. 2,500 tonnes of monazite/year, and the target is a production of 15-30,000 tonnes/year, which should be possible as the capacity is significantly larger (Chalmers 2021). A small production of TREC is in progress and is being separated at Silmet's plant in Estonia, but in the long term the establishment of its own separation plant is being considered. Both uranium and thorium oxides are indicated as to be commercial products.

Chemours also extracts monazite from two heavy sand deposits in China in a joint venture with a Chinese company. The Canadian Neo Performance Materials has a total of three rare earth element separation plants, Silmet in Estonia and Zibo and Jiangxi in China (Figure 13-10).

Stated annual production from Georgia monazite heavy sand: based on 2,500 tonnes of monazite, they can produce approx. 1,000 tonnes of TREO; 15,000 tonnes of monazite will produce approx. 6,000 tonnes of TREO.

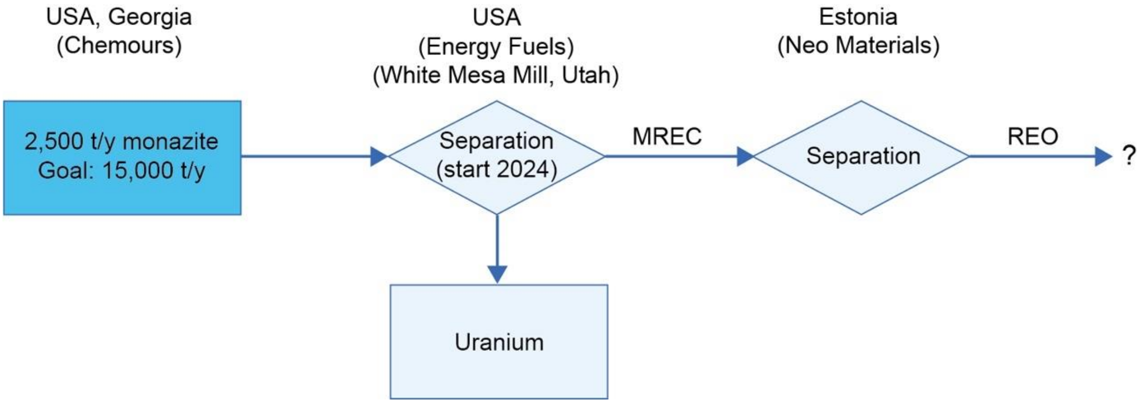

Figure 13-10 *Planned supply chain for extraction of rare earth elements from monazite in Georgia, USA.*

Lynas Corp. Ltd. (unidentified resource) – Blue Line Corp. – ?

The Australian mining company Lynas Corp. Ltd. and the American chemical company Blue Line Corp. have formed a joint venture (with Lynas as principal owner) with a view to establishing a separation plant in Honda, Texas, USA, for heavy rare earth elements (incl. terbium and dysprosium) and subsequent expansion of the plant for separation of light rare earth elements (incl.

praseodymium and lanthanum) (Figure 13-11). This development work is supported with 30 million USD from the US Department of Defense (Menezes 2021; Hui 2021a). It is unclear where the REE minerals for this project will come from, and thus the composition is unknown; in addition, partners for subsequent refining/alloying are undisclosed.

Stated annual production from Lynas Corp./Blue Line Corp.: approx. 5,000 tonnes TREO.

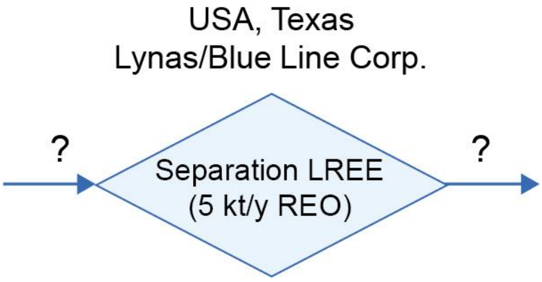

Figure 13-11 *Overview of Lynas' American project. There is no information on the supply chains for the project that Lynas will oversee.*

MP Materials (Mountain Pass) – Shenghe Resources

MP Materials produces mineral concentrates from the Mountain Pass mine in California, USA. The mine has played a major role in the global supply of rare earth elements. A historical overview of the mine's owner(s) and activity is shown in Table 11-1, while the current ownership's relationship with main shareholders can be seen in Figure 13-12.

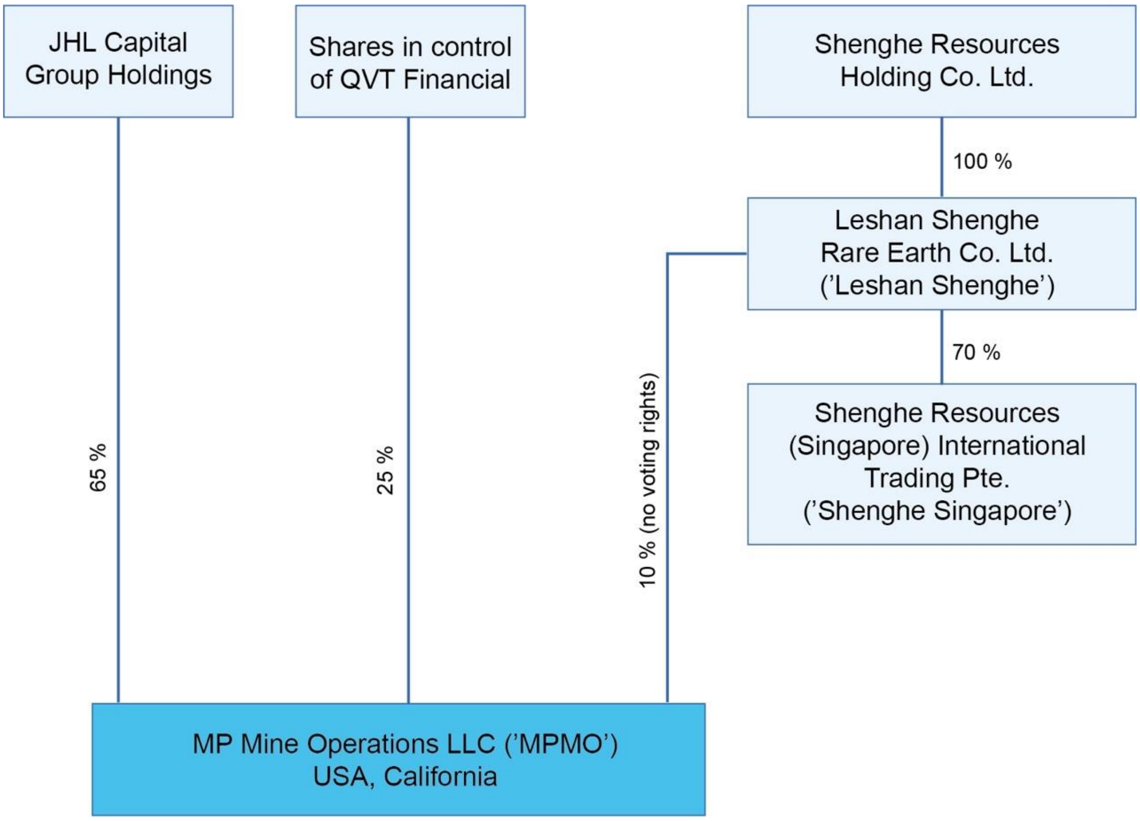

Figure 13-12 *Major shareholders in MP Materials Mountain Pass mine. Source: MP Materials (2020).*

In November 2020, Fortress Value Acquisition Corp. acquired MP Materials and established MP Materials Corp. In this transaction, MP Materials received 545 million USD, which is supposed to be used to establish a complete supply chain for rare earth elements, which is to be divided into the following two phases (Menezes 2021):

- Establishment of separation plant with a focus on Nd-Pr, which is expected to be ready in 2022 (in November 2020, the US Defense Production Act provided 9.6 million USD for this development)
- Establishment of a complete NdFeB magnet production in 2025.

The production of minerals (bastnäsite) from the Mountain Pass mine is sent for processing in China (in 2020 the production was about 30,000 tonnes TREO). The plans to establish a single supply chain in the United States will, if China considers MP Materials as a non-Chinese company, mean that all products must be sold outside China in order to avoid the Chinese tax systems (see section 11.2). The composition of rare earth elements in the ore from the Mountain Pass mine will be a challenge for a business concept that includes a complete supply chain.

US Rare Earth/Texas Minerals Resources Corp. (Round Top) – Search Minerals – GeoMega Resources

In April 2020, US Rare Earth LLC (URE) entered into a partnership with Texas Mineral Resources Corp. (TMR) and in May 2021, URE acquired 80 % of the TMR shares and initiated a final profitability study, incl. a pilot processing plant for exploitation of the Round Top deposit in Hudspeth County, Texas, USA. The Round Top deposit is a polymetallic deposit, which also contains rare earth elements. Project design includes an open pit and heap leaching followed by separation of the rare earth elements (using a combination of the techniques ion exchange and chromatography) and is expected to have a yield of 85 %. The estimates are based on a 20-year production period.

URE's business model is based on a fully integrated supply chain with production of raw materials for NdFeB magnets. As part of this plan, URE entered into an agreement with Search Minerals in November 2020 on the use of their ‘direct extraction process’ patent and can thus, in principle, produce a mixed product of rare earth elements. In April 2020, URE and TMR acquired Hitachi Metals America's plant to produce NdFeB magnets and plans, through its subsidiary US Rare Earth Magnets, to manufacture NdFeB magnets in Wheat Ridge, Colorado, USA. In addition, in July 2020, URE entered into an agreement with GeoMega Resources with a view to integrating recycling into production. There is also an agreement between Texas Rare Earth Resources and Arafura (Australia) to process and separate ore concentrate from Nolan's Bore at URE's facilities in Texas (see Figure 13-3).

Ucore Rare Metals (Bokan Hill) – Alaska Strategic Metals Complex

In April 2020, Ucore acquired Innovation Metals Corp. (IMC), which has proprietary technology for the separation of rare earth elements (Rapid SXTM). They want to establish a supply chain from primary REE minerals from their own project Bokan Mountain, Alaska, USA and up to an unspecified separated product. With financial support, (2 million USD) and financial guarantees of 145 million USD, it is working to establish the Alaska Strategic Metals Complex in Ketchikan; IMC's facility is located in Kingston, Ontario, Canada (Menezes 2021).

Urban Mining Comp.

In July 2020, the US Department of Energy allocated 28.8 million USD to Urban Mining Corp. to implement their patent ‘magnet-to-magnet’ (Menezes 2021).

13.1.22 Vietnam

Vietnam Rare Earth Co. Ltd. – Shenghe Resources – Chou Denki Kogyo
In 2019, Shenghe Resources Singapore Pte. Ltd. and Chou Denki Kogyo Co. Ltd. (Japan) acquired Vietnam Rare Earth (VRE) with respective ownership interests of 90 % and 10 %. VRE's production facility in Thuan Thanh, Bac Ninh Province in Vietnam performs processing and separation on ad hoc contracts. The plant has a capacity of approx. 4,000 tonnes/year; the capacity of the electrolytic plant is approx. 700 tonnes/year.

Lavreco (Dong Pao) – Toyota Tsusho – Sojitz
In 2011, Vietnam's state-owned mining company Lavreco, Japanese Toyota Tsusho and Sojitz entered into a joint venture agreement to exploit the Dong Pao deposit in Vietnam with a view to marketing the products on the Japanese market. Extraction was started with a planned production of 3,000 tonnes/year in 2013 (Adamas Intelligence 2014), but according to the USGS (2000-2020), production has not exceeded 1,300 tonnes/year, with peak production in 2019.

13.2 Conclusions regarding the West’s potential supply chains

The preceding compilation includes examples of western companies that are part of the existing value chains, and companies that are working on projects that may eventually become part of western supply chains.

Table 13-3 provides an overview of the relationships in the potential supply chains for selected projects outside China. The table illustrates that the West's supply chains are incomplete and, in addition include significant Chinese collaboration. The review in section 13.1 also shows that the processing capacities are very modest. It must therefore be noted that even if all the potential projects are realised, there is still a long way to go before the west is independent of Chinese supply chains; in particular, major challenges can be expected if the west is to be self-sufficient in the production of metal/alloy of the rare earth elements, just as there are few companies that can produce the in-demand NdFeB magnets.

13.3 Examples of policy initiatives to support the development of 'Western' value chains

In the western world, politicians and organisations are seeking to implement economic measures to establish value chains independant on China.

For example, in April 2021, the United States introduced the Reclaiming American Rare Earths Act, a law to reduce taxes on production of critical raw materials. In addition to this law, the United States is working to introduce financial support measures for the development of national value chains for rare earth elements, the Rare Earth Magnet Manufacturing Production Tax Credit Act. The proposal includes a tax credit of USD 20/kg for NdFeB magnets produced in the USA, increasing to USD 30/kg if raw materials produced in the USA are used (Hui 2021c). If implemented, this Act could, for instance, provide a tax credit of 40-60 million USD to US Rare Earth, which is working to establish an NdFeB magnet production of approx. 2,000 tonnes/year using ore from the company's Round Top project.

Table 13-3 *Overview of the relationships in the potential supply chains for selected projects under development outside China. The companies that form the first part of the chains are mentioned in the text above. The value chains go from left to right, i.e. from Exploration → Mining and mineral concentrate → Trade → Leaching of REE → Separation of REE → Metal/alloy REE → NdFeB magnets. Each colour change marks a new supply chain.*

Companies	**Exploration**	**Mine and mineral concentrate**	**Trade**	**Leaching of REE**	**Separation of REE**	**Metal/alloy REE**	**NdFeB-magnets**
Pensana	Longonjo (Angola)	Longonjo (Angola)		England (Hull)	England (Hull)		
Alkane	Dubbo (AUS)	Dubbo (AUS)					
Vietnam Rare Earth JSC (Shenghe)				Vietnam			
South Korea Zirkon Tech					South Korea		
Arafura Resources	Noilans Bore (AUS)						
Hastings Technology Metals	Yangibana (AUS)						
Thyssenkrupp							
Lynas Corp.		Mt. Weld (AUS)		LAMP Malaysia			
Northern Minerals	Browns Range (AUS)	Browns Range (AUS)					
Thyssenkrupp							
China Northern REE				China			
RareX	Cummins Range (AUS)	Cummins Range (AUS)					
RET Co.							
Shenghe				China	China		
Rainbow Rare Earth	Gakara (Burundi)	Gakara (Burundi)					
Thyssenkrupp							
Avalon/Vita Metals/Cheetah Resources	Nechalacho (Canada)	Nechalacho (Canada)					
REEtec				Norway	Norway		
Ucore Rare Metals				Alaska	Alaska		
Defense Metals Corp.	Wicheeda (Canada)	Wicheeda (Canada)					
Greenland Minerals	Kvanefjeld (Greenland)	Kvanefjeld (Greenland)		Greenland			

Companies	**Exploration**	**Mine and mineral concentrate**	**Trade**	**Leaching of REE**	**Separation of REE**	**Metal/alloy REE**	**NdFeB-magnets**
Shenghe Resources				China	China		
Tanbreez	Kringlerne (Greenland)	Kringlerne (Greenland)					
Mkango Resources/Talaxis	Songwe Hill (Malawi)	Songwe Hill (Malawi)					
Chinalco Guangxi				China	China		
Mkango Polska					Poland		
Yara			Norway				
REEtec				Norway	Norway		
Less Common Metals						England	
Vacuumschmelze							?
Lovozero GOK		Lovozero (Russia)		?	?		
JSC Solikamsk Magnesium Works						Russia	
ThreeArc Mining LCC	Tomtor (Russia)	Tomtor (Russia)					
Rosatom				Russia	Russia		
Steenkampskraal Monazite Mine (PTY) Ltd.	Steenkampskraal (South Africa)	Steenkampskraal (South Africa)					
Ganzhou Qiangong Rare Earth Group				South Africa	South Africa		
Less Common Metals						England	
Peak Resources Ltd.	Ngualla Hill (Tanzania)	Ngualla Hill (Tanzania)		England	England		
Ionic Rare Earth	Makuutu (Uganda)	Makuutu (Uganda)					
Kunming Sino Platinum Metals				China	China		
Chemours		Georgia (USA)					
Energy Fuels				USA			
Neo Performance Materials (Silmet)					Estonia	?	?
Lynas Corp./Blue Line Corp.				USA			
MP Materials		Mountain Pass (USA)		USA		USA	USA

Companies	**Exploration**	**Mine and mineral concentrate**	**Trade**	**Leaching of REE**	**Separation of REE**	**Metal/alloy REE**	**NdFeB-magnets**
Shenghe Resources				China	China		
US Rare Earth/Texas Minerals resources	Round Top (USA)	Round Top (USA)		USA	USA	USA	USA
Ucore Rare Earth Metals	Bokan Hill (USA)	Bokan Hill (USA)					
Alaska Strategic Metals Complex				Canada	Canada		
Vietnam Rare Earth Co. Ltd.	Vietnam	Vietnam					
Shenge Resources				Vietnam	Vietnam		
Lavreco (Vietnam)/ Toyota Tsusho/Sojitz (Japan)	Dong Pao (Vietnam)	Dong Pao (Vietnam)					
Solvay Rare Earth Systems					France		
Medallion Resources Ltd.				?			
Indian Rare Earth Ltd. (IREL)				India	India		

At the federal level, the United States also provides financial support for industrial development projects to build complete U.S. value chains for rare earth elements from extraction to finished products. Hence, in April 2021, the US Department of Energy supported 13 projects with a total amount of 19 million USD; in addition, the US Department of Defense has granted 30.4 million USD to Lynas to establish a U.S. separation plant in Texas to separate LREE (Fixler & Gilbertson 2021); provided that Lynas invests a similar amount. In December 2020, the U.S. Department of Defense supported MP Materials with 9.6 million USD as part of the US Defense Production Act. The money will contribute to the establishment of a 200 million USD plant to reprocess light rare earth elements for use in the US market; the plant is expected to be set to production in 2022 (Magnuson 2021). It should be noted that US production of rare earth elements from the Mountain Pass mine in California is approx. 30,000 tonnes/year TREO, and that small quantities of products containing monazite are exported unprocessed to China. Taken together, this quantity could potentially cover US consumption for the manufacture of permanent magnets.

In the EU, rare earth elements have been on the political agenda since 2010, when the critical raw materials in the EU were mapped for the first time (European Commission 2010). Subsequently, many EU and nationally supported research projects have focused on different parts of the value chains for rare earth elements. Summaries of the value chain challenges in the EU are included in Kooroshy et al. (2014) and Machacek & Kalvig (2017). According to these analyses the challenges are primarily due to the lack of industrial infrastructure in Europe, which is a consequence of China's strengths in technical know-how, IP rights, complete value chains and diverse products.

Japan
In 2019, Japan introduced the Foreign Exchange and Foreign Trade Act (FEFTA) with the aim of protecting selected industrial sectors of vital interest to Japan against unwanted foreign acquisitions. The scheme means that foreign investments in excess of 1 % of the share capital in 12 key industry sectors need prior approval. In addition, extensive efforts have been made to increase IP rights in vulnerable areas; for example, in 2019, Japan was the western country with the highest number of IP rights (13,929) for the treatment and processing of rare earth elements, ahead of the United States (9,810) and the EU (7,280); by comparison, China has 25,911 patents (Ng 2019), and overall, Japan's dependence on China in relation to rare earth elements over the past 10 years has been reduced from approx. 80 % dependence to approx. 60 %. This is, in part, a result of Japan's strategic decision to invest in Lynas' development of the Mt. Weld mine in Australia and the processing plant in Malaysia.

13.3.1 The European Raw Materials Alliance

The European Raw Materials Alliance (ERMA, https://erma.eu) was an initiative established in 2021 by the European Commission, as a follow-up activity to the latest analyses of critical raw materials in the EU from 2020. The purpose of the alliance is to support and develop raw material supplies for the 'green' and 'digital' development of Europe, with a specific focus on developing and strengthening the supply lines for rare earth element magnets and electric motors. ERMA, which is partly funded by the EU, is administratively organised under EIT RawMaterials (www.eitrawmaterials.eu). The activities are divided into two tracks; (i) value chain-specific activities to identify supply challenges and put forward industrial and regulatory solutions; and (ii) investment activities in primary and secondary raw material projects for the 'supply of EU industrial ecosystems'; this must in part be realised through the establishment of a ‘Raw Material Investment Platform’ and through investments, also in projects outside the EU.

In September 2021, there were about 400 members (Appendix VII) (https://erma.eu/network/) distributed among primary/secondary raw material producers (242), producers of advanced materials and 'intermediates' (131), companies involved in final products (83), companies involved in recycling (126), industry associations (67), research & development institutions and universities (63), national raw materials authorities (17), financial institutions (4), NGOs (4) and trade organisations (1). The membership represents companies registered in the EU, the rest of Europe, North and South America as well as several countries in Africa and Asia. No members have indicated Russia or China as their nationality. However, several members have close relationships with Chinese companies, either directly or through related companies (*e.g.* JL Mag, Neo Performance Materials, Greenland Minerals, Hastings, Mkango and Ionic Rare Earth). Moreover, a significant part of the core services of the membership does not seem to include ERMA's one focus area of developing and strengthening the EU's supply lines for rare earth element magnets and electric motors, thereby ensuring the EU's green and digital transition.

In September 2021, ERMA launched the action plan ‘Rare Earth Magnets and Motors: A European Call for Action’, focusing on how the EU can ensure sufficient supplies of rare earth elements to carry out the green transition (EIT RawMaterials 2021). The plan includes (i) policy initiatives for financial support schemes to ensure production at competitive prices relative to China; (ii) an obligation for companies to buy an agreed, significant quantity of their raw materials from European producers; (iii) recycling of a large proportion of scrap materials including rare earth elements in the EU; and (iv) national funding schemes for projects to contribute to the development of rare earth element value chains in the EU. The plan does not include any measures to increase Sino-European co-operation.

13.3.2 Rare Earth Industry Association

The Rare Earth Industry Association (REIA) (https://www.global-reia.org/) was originally established as an EU-funded research project (GloREIA), which mapped the value chains for rare earth elements in the EU with the goal of contributing to the development of western supply chains, independent of China. REIA is presently an international interest organisation uniting companies and institutions involved in the value chains for rare earth elements with the aim of disseminating knowledge about and improving the life cycle of rare earth element products. REIA had, as of December 15, 2021, 39 members, ranging from research & development, mineral exploration, mining, magnet production and companies that utilize the magnets. The members come from several of European countries as well as Australia, Canada, the USA and China (Appendix VI). The research companies all (via websites) express a desire to break the Chinese dominance in the market, and several emphasise their independence from China, but as stated in section 13.1, several members work in close co-operation with Chinese companies. In addition, the membership includes two Chinese magnet manufacturers.

13.4 Challenges for the establishment of independent value chains in the West

Many of the exploration projects, which now announce that they will be ready for the production of rare earth elements within a few years, were initiated 10-15 years ago, typically based on deposits identified by geological mapping many years earlier. But only two out of several hundred western projects have come into production: Mt. Weld in Australia, which began mining in 2007 and the separation plant in Malaysia in 2013 (see section 13.1.2), as well as the Mountain Pass mine in the USA, which has a longer history with several closures and openings (see sections 11.1 and 13.1.2). In addition, there is only minor western by-production from heavy sand. The existing raw material processing industries are mainly made up of a series of companies with decades of experience, which in the early 2000s established co-operations with Chinese producers. Despite regional, national, and private initiatives supporting the establishment of independent processing industries, there are only a few cases where western facilities have been established, with Lynas' plant in Malaysia being one example of a larger plant; Lynas has a production capacity of approx. 22,000 tonnes/year TREO, of which approx. 75 % is utilised. From this author's point of view (see Chapters 11 and 12) this is due to China's political focus on the industrial importance of the rare earth elements over recent decades, its large investments in research & development, and the vertically integrated industry organised with the 'Big Six' consortia (Section 12.1).

Among western manufacturers involved in the REE value chains, it is also the assessment that under the current conditions, it is difficult to break China's control. For example, Less Common Metals (LCM), England, on behalf of the English government, has carried out an analysis of the potential for establishing independent magnet factories in England (Less Common Metals 2021). LCM points out that establishing independent complete mine-to-magnet supply chains requires that each part of the supply chain is competitive with Chinese products on social and environmental issues as well as on price. LCM concludes that due to China's tax system that ensures that value addition takes place in China, this will only be possible if the raw materials in the west can be obtained at very low prices, e.g. as by-products from heavy sand, fertiliser raw materials and iron ore. LCM also points out that several potential 'western' mining projects with capital investments of 300-1,000 million USD, are economically challenged due to low prices for mineral concentrates and uncertain market conditions. The projects are also technically challenged when it comes to the handling of radioactive elements, which are concentrated during production, as well as by the companies' insufficient know-how about all production stages. Finally, LCM considers that the UK magnet market is insufficient to warrant setting up a magnet factory in the UK.

14. Assessment of Supply Challenges for the Green Transition

Rare earth elements are crucial raw materials in the green energy transition with increased consumption as a result (Chapter 3), of which markets related to the production of NdFeB magnets for electric and hybrid vehicles, wind turbines, air conditioning systems, economically are key areas. The International Energy Agency expects this consumption to increase sevenfold by 2040 (International Energy Agency 2021). The question is, therefore, whether there is a balance between the probable raw material supplies and the expected demand for the rare earth elements.

To try to answer this question, an analysis has been prepared based on the rare earth elements praseodymium (Pr), neodymium (Nd) and dysprosium (Dy), which are key raw materials in magnets of the type neodymium-iron-boron (NdFeB), which are used in e.g. electric vehicles and wind turbines (see also section 3.2.1), and because the prices for these metals dominate the ore value of both existing and future mines. Production in the mines will therefore be organised in relation to the opportunities of maximising the sales of these three raw materials; the other rare earth elements of the ore will economically be reduced to by-products, which will be produced in quantities based on the composition of the ore, and the planned production of the magnet elements. As the demand for magnet elements is currently growing faster than for the other markets, it is likely that, in the long run, there will be an overproduction of some of the rare earth elements consumed by other sectors. Estimates of the balance between supply and demand for rare earth elements up to 2030 can therefore be reduced to a problem of supply and demand for the raw materials used for magnets. Consequently, the analysis only includes estimates of expected supply from the mines and expected demand for the three most important rare earth elements for NdFeB magnets in 2025 and 2030. Any challenges to capacity in the down-stream value chains that process the ore into magnet raw materials are not included in these scenarios.

The available is inadequate for to undertake detailed statistical supply- and demand analyses. Moreover, estimates for the period beyond 2030 are deemed unreliable and thus not included. To overcome these shortages the assessments of the balance between supply and demand of the magnet elements are performed as four scenarios based on combinations of ‘low’ and ‘high’ estimates for supply and demand (Table 14-1) and estimation as are undertaken for 2025 and 2030 respectively.

Table 14-1 *Principles of four scenarios for the balance between supply and demand.*

Scenario number	Combination	Scenario number	Combination
1	Low demand/ Low supply	2	High demand/ Low supply
3	Low demand/ High supply	4	High demand/ High supply

14.1 Estimates of demand towards 2030

The estimates of demand up to 2030 have been prepared on the following basis:

- The total consumption of rare earth elements is divided into 10 industrial sectors, based on Merriman (2021).
- The relative distribution of the rare earth elements in the individual sectors is based on Binnemans (2013); however, the distribution for the magnet sector is based on Merriman (2021).
- The demand for magnet elements praseodymium, neodymium, and dysprosium in 2025 and 2030 respectively has been estimated from three datasets: King (2021), Adamas Intelligence (2021) and Merriman (2021), all of which set expectations for the consumption of rare earth elements for NdFeB magnets. These three analyses of the magnet market indicate the consumption of NdPr oxide (King 2021), NdFeB magnets (Merriman 2021) and are divided into praseodymium oxide (Pr-oxide), neodymium oxide (Nd-oxide) and dysprosium oxide (Dy-oxide) (Adamas Intelligence 2021) (Table 14-2).

Table 14-2 *The expectations for the consumption of a variety of products for use in the manufacture of NdFeB magnets in 2025 and 2030. Data forms the basis for the demand scenarios in this chapter.*

	Unit	2020	2025	2030
King (2021)	tonnes NdPr-oxide*	1,000	18,000	48,000
Merriman (2021)	tonnes NdFeB total	105,000	150,000	195,000
Adamas Intelligence (2021)	tonnes TREO	4,000	8,000	20,000

* neodymium-praseodymium-oxide

The estimates for the development of the magnet markets have been converted to the expected needs for praseodymium, neodymium, and dysprosium (Table 14-2). China expects that its need for NdPr oxide in 2025 will be around 125,000 tonnes, which largely constitutes global demand and puts them on the high level of these three estimates. It should be noted that this data is only included as a basis for the estimates below; the author is responsible for the context and method in which the data is included.

The following assumptions have been used to assess demand up to 2030:

- The magnet market for NdFeB magnets is divided into two types:
  (i) Permanent Magnet Synchronous Motors (PMSM) with a typical composition of 12 % Pr oxide, 75 % Nd oxide and 7 % Dy oxide.
  (ii) Other magnets with an average composition of 12 % Pr oxide, 70 % Nd oxide and 2 % Dy oxide.
- The relative distribution of demand for 2025 and 2030 from the magnet sector and the other sectors that consume Pr, Nd and Dy according to Merriman (2021).
- There will be a significant processing loss from raw ore to finished magnet powder; this loss is estimated at 40 %, which is presumably optimistic. This loss is included in demand.
- Manufacture of magnets for specific purposes results in 15-30 % material waste due to shape adjustment. Such losses are not recognised, as it is unclear to what extent this material is included in subsequent production.

The distribution key used for material for magnets for electric vehicles, material for other magnets and consumption in other sectors in 2025 and 2030 is shown in Table 14-3.

Table 14-3 *Distribution key used for the scenarios for the total raw material consumption for the magnet elements Pr, Nd and Dy in 2025 and 2030. The figures indicate the percentage distribution that each of the three elements constitutes. Sources: King (2021); Merriman (2021) and Adamas Intelligence (2021).*

	Percentage (%) of		
	Pr oxide	**Nd oxide**	**Dy oxide**
Materials for magnets for electric vehicles (drivetrains)			
2025	12	17	34
2030	16	21	44
Materials for other magnets			
2025	32	38	37
2030	36	41	27
Compensation for material loss from mine to magnet powder (40 %)			
2025	21	25	29
2030	21	25	29
Use in other sectors			
2025	35	20	-
2030	27	13	-
Total 2025	**100**	**100**	**100**
Total 2030	**100**	**100**	**100**

The estimated needs for the three magnet elements praseodymium, neodymium, and dysprosium in 2025 and 2030 are shown in Table 14-4 and Figure 14-1, with the year 2020 for comparison. It appears that the estimates from Merriman (2021) and Adamas Intelligence (2021) are very similar, while the estimates based on King (2021) are significantly higher for all three magnet elements.

Table 14-4 *Estimated consumption of the three magnet elements praseodymium, neodymium and dysprosium in 2025 and 2030. Red numbers are included in the four scenarios, cf. Table 14-1.*

Total usage	**Year**	**Pr oxide tonnes**	**Nd oxide tonnes**	**Dy oxide tonnes**
King (2021)	2025	23,000	70,000	4,000
	2030	43,000	143,000	8,000
Merriman (2021)	2025	11,000	50,000	2,000
	2030	14,000	64,000	3,000
Adamas Intelligence (2021)	2025	13,000	37,000	1,000
	2030	14,000	67,000	2,000

By comparison, Morgan Stanley Research (2021) expects that the demand for NdPr oxide in 2025 and 2030 will be 66,000 tonnes and 83,000 tonnes, respectively. To this, the quantity used in other sectors should be added on, as well as the quantity to compensate for the processing loss (40 %); the total need for 2025 and 2030 will thus amount to around 123,000 tonnes and 150,000 tonnes of NdPr oxide and is thus on a par with the estimates from King (2021). In an article by Watari et al. (2020), the expected total consumption of Nd oxide in 2030 varies between 39,000 tonnes and 220,000 tonnes with an average of approx. 90,000 tonnes, which corresponds to the level in this study (Table 14-1); Watari et al. (2020) does not include praseodymium oxide. For dysprosium oxide consumption, Watari et al. (2021) refers to eight estimations of dysprosium oxide consumption in 2030, which estimates an average level of approx. 7,000 tonnes; this level also corresponds to the estimates in this study but is nevertheless at the higher end. China's estimate for the expected consumption of NdPr oxide in 2025 is 120,000 (The Rare Earth Observer 2022) and is thus within the ranges found in this study.

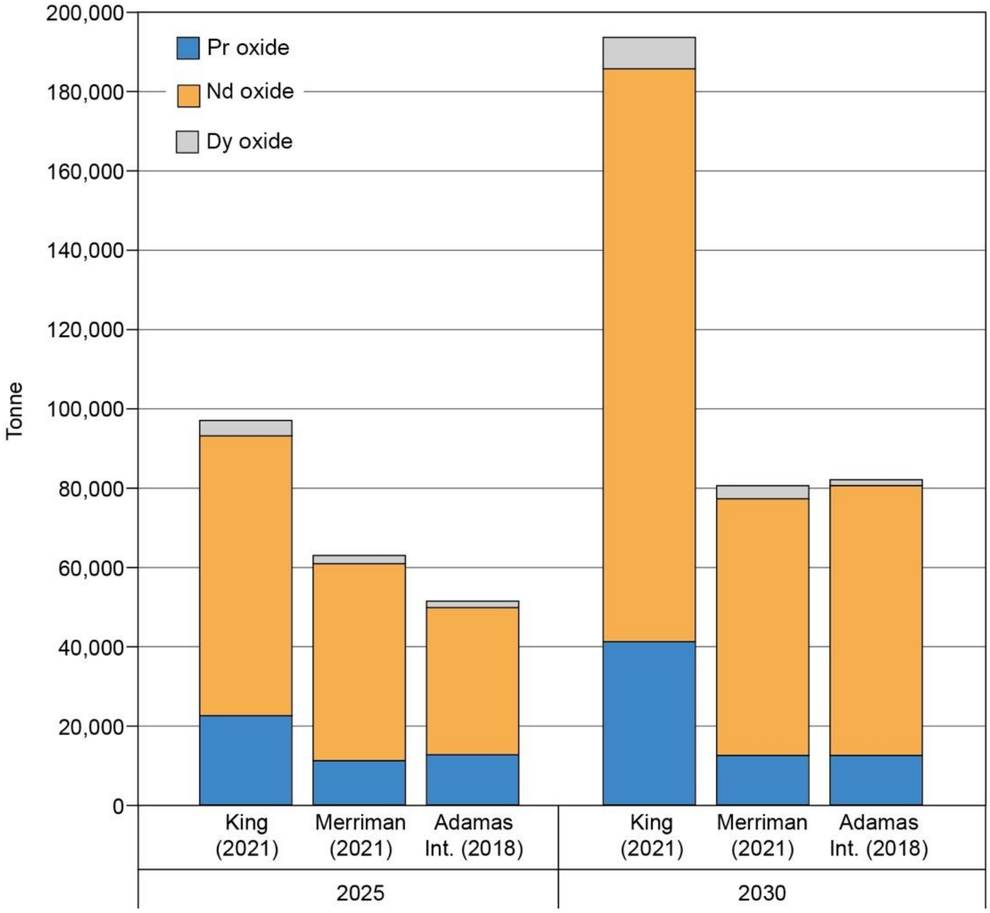

Figure 14-1 *Estimated needs for praseodymium, neodymium and dysprosium for electric vehicles by 2030. Data from King (2021), Merriman (2021) and Adamas Intelligence (2021) has been used in scenarios concerning the need for rare earth elements.*

The prognoses for demand may be affected in a downward direction if the automotive industry introduces new types of magnets that completely, or partially, phase out the use of rare earth elements. This is not an unrealistic scenario, as development work is underway on increasing the substitution of cerium with NdPr oxide, which is found in larger quantities and is significantly cheaper. In addition, several large, western vehicle manufacturers have changed the motor drive technology in electric vehicles from the current system, where electric motors contain NdFeB batteries and so powered by battery power, to induction motors, where battery power is instead used to create a magnetic field that drives the motor; this technology uses significantly smaller amounts of rare earth elements.

Demand for the magnet elements praseodymium, neodymium and dysprosium may be affected in an upwards direction compared to forecasts if land transport electrification takes place at a faster pace than expected in countries with large populations and growing economies, such as India, Malaysia, Indonesia, and Nigeria amongst others.

14.2 Assessments of supplies up to 2030

Estimates of the production of primary raw materials, used in the following estimates for supply capacity, are based on the existing active mines, as well as on a number of advanced exploration projects that are considered likely to be in production by 2025 and 2030 respectively (Table 14-5), with the exception of two projects, the capacity is based on the companies' own information. Estimated productions for high and low scenarios in 2025 and 2030 are shown in Table 14-6 and Table 14-7).

Table 14-5 *Overview of exploration projects, which are included in the four supply scenarios.*

Country	2025 High	2025 Low	2030 High	2030 Low
Angola			Longonjo	
Australia			Browns Range (Wolverine)	Browns Range (Wolverine)
			Charley Creek	Charley Creek
			Cummins Range	Cummins Range
	Dubbo	Dubbo	Dubbo	Dubbo
	Eneabba		Eneabba	
	Nolans Bore		Nolans Bore	
	Yangibana North	Yangibana North	Yangibana North	Yangibana North
Brazil			Araxa	Araxa
Burundi	Gakara (Karonge)	Gakara (Karonge)	Gakara (Karonge)	Gakara (Karonge)
Canada			Ashram (Total resource)	
			Eco Ridge	
			Foxtrot (=Port Hope Simpson)	Foxtrot (Port Hope Simpson)
			Niobec	Niobec
	Nechalacho Upper	Nechalacho Upper	Nechalacho Upper	Nechalacho Upper
	Strange Lake	Strange Lake	Strange Lake	Strange Lake
Greenland	Kringlerne	Kringlerne	Kringlerne	Kringlerne
	Kvanefjeld (main)		Kvanefjeld (main)	
Kyrgyzstan	Kutesay II	Kutesay II	Kutesay II	Kutesay II
Malawi			Songwe Hills	Songwe Hills
Namibia			Lofdal	Lofdal
Sweden			Norra Kärr	
South Africa			Glenover	
			Kangankunde	Kangankunde
			Steenkampskral	Steenkampskral
			Zandkopdrift Mineral Ressource	
Tanzania	Ngualla Hill	Ngualla Hill	Ngualla Hill	Ngualla Hill
USA			Bokan Mountain	Bokan Mountain
	Georgia	Georgia	Georgia	Georgia
			Round Top	Round Top

Below, the assumptions and data that are included in estimates of raw material supply up to 2025 and 2030 are reviewed.

Table 14-6 *Estimated supplies, from mining, of the three magnet elements praseodymium, neodymium, and dysprosium, which are expected to be in production in 2025 and 2030. Estimates are respectively conservative and optimistic.*

	2025 Low	2030 Low	2025 Low	2030 Low	2025 Low	2030 Low
	Pr oxide Tonnes	**Pr oxide tonnes**	**Nd oxide tonnes**	**Nd oxide tonnes**	**Dy oxide tonnes**	**Dy oxide tonnes**
Angola	-	-	-	-	-	-
Australia	900	1,200	3.800	4.600	100	300
Brazil	-	100	-	400	-	-
Burundi	100	100	500	500	-	-
Canada	800	1,000	2.900	3.900	600	700
Greenland	200	200	600	600	100	100
Kyrgyzstan	200	200	400	400	300	300
Malawi	-	300	-	1.000	-	-
Namibia	-	-	-	100	-	100
South Africa	-	100	-	500	-	-
Sweden	-	-	-	-	-	-
Tanzania	300	300	1.100	1.100	-	-
USA	300	400	1.100	1.500	-	300
	3,000	**4,000**	**10,000**	**14,000**	**1,000**	**2,000**

	2025 High	2030 High	2025 High	2030 High	2025 High	2030 High
	Pr oxide tonnes	**Pr oxide tonnes**	**Nd oxide tonnes**	**Nd oxide tonnes**	**Dy oxide tonnes**	**Dy oxide Tonnes**
Angola	-	600	-	2,100	-	100
Australia	2,700	2,900	10,100	10,900	200	400
Brazil	-	100	-	400	-	-
Burundi	100	100	500	500	-	-
Canada	800	2,100	2,900	7,400	600	800
Greenland	1,500	1,500	4600	4,600	400	400
Kyrgyzstan	200	200	400	400	300	300
Malawi	-	300	-	1,000	-	-
Namibia	-	-	-	100	-	100
South Africa	-	1,500	-	5,200	-	200
Sweden	-	100	-	600	-	200
Tanzania	300	300	1,100	1,100	-	-
USA	300	400	1,100	1,500	-	300
	6,000	**10,000**	**21,000**	**36,000**	**2,000**	**3,000**

The estimates include the supplies of rare earth elements from both existing and potential future mines. These are selected by using the following criteria:

- Production from the existing mines has been carried out by distributing data from the USGS (2020) for the total global production to global tonnages for the individual rare earth elements (cf. Table 8-2).

- Data for potential future mines, which undertake the most advanced exploration projects; the projects are subjectively selected by the author (Table 14-5). In this choice, importance is attached if the projects have stated the expected, annual production volume.
- High and low scenarios are similarly based on the author's assessment of which projects are most likely to be in production in 2025 and 2030 respectively. Projects that are not included in one or more scenarios are indicated by an empty field in Table 14-5.

Supplies up to 2030 will include production from both existing and new mines. The production from the existing facilities is estimated based on Table 8-2 and is corrected by +20 % and +40 % for the high scenarios in 2025 and 2030 respectively, and with +10 % and +20 % for the low scenarios in 2025 and 2030 respectively (Table 14-7).

Table 14-7 *Estimated production of praseodymium, neodymium, and dysprosium from existing and new mines, assessed in high and low scenarios for 2025 and 2030.*

		Pr oxide tonnes	**Nd oxide tonnes**	**Dy oxide tonnes**
2025 – high	Existing +20 %	18,000	53,000	7.000
	New mines (list 25H)	6,000	21,000	2.000
	Total	**24,000**	**74,000**	**9.000**
2025 – low	Existing +10 %	17,000	49,000	6,000
	New mines (list 25L)	3,000	10,000	1,000
	Total	**20,000**	**59,000**	**7,000**
2030 – high	Existing +40 %	21,000	62,000	8,000
	New mines (list 30H)	10,000	36,000	3,000
	Total	**31,000**	**98,000**	**11,000**
2030 – low	Existing +20 %	18,000	53,000	7,000
	New mines (list 30L)	4,000	14,000	2,000
	Total	**22,000**	**67,000**	**9,000**

The estimates for the global supplies of praseodymium, neodymium, and dysprosium in 2025 and 2030, as seen in Table 14-7, show that new mines in both 2025 and 2030 can be expected to contribute 20-50 % of the amount of magnet elements produced by the existing mines. It is the author's assessment that for new mines the low scenarios are the most likely supply scenarios, as experience has shown that most projects exceed their own schedules by several years and some advanced projects are shut down for technical, economic, or regulatory reasons.

Some of the large existing mines will probably be able to increase capacity significantly; this applies, for example, to both the Mt. Weld Mine in Australia, the Mountain Pass Mine in California in the United States and the major mines in China, including Bayan Obo. Additionally, by 2030, there will be significant by-product contributions from, for example, heavy sand deposits, iron ore mines and IOCG deposits.

On the supply side, recycling will probably become increasingly important in line with the expansion of technical facilities for scrap processing, and as the amount of NdFeB magnets to be scrapped increases.

14.3 Assessment of the raw material balance up to 2030

The balance of raw material supply and demand is shown in Table 14-8 and illustrated in Figure 14-2, from which it appears that for those scenarios where consumption is not expected to grow significantly, demand will be met in line with the estimates on the supply side. However, low growth scenarios are not to be expected with the major political focus on green energy transition, and the rapid global transformation of the transport sector and rapidly growing wind turbine production, both of which depend on supplies of processed rare earth elements.

For the more probable scenarios where growth in demand has been applied, there are significant negative balances. For 2025, a shortage of around 3,000 tonnes of Pr oxide and 11,000 tonnes of Nd oxide is estimated, corresponding to, respectively, a 13 % and 16 % deficit in relation to the expected demand, assuming a high demand and low supply rate. For 2030, a balance deficit will occur for both Pr oxide and Nd oxide of 12,000 tonnes (28 %) and 45,000 tonnes (31 %) respectively, assuming both demand and supply are high. In the scenario for 2030 with high demand and low supply, the imbalance grows to a deficit of approx. 21,000 tonnes of Pr oxide (49 %) and 76,000 tonnes of Nd oxide (53 %). The results are shown in Figure 14-2. For comparison, Adamas Intelligence (2021) estimates that in 2025 and 2030 there will be a total deficit of Pr oxide and Nd oxide of 15,000 tonnes and 8,000 tonnes respectively. The scenarios indicate a positive balance for dysprosium, but it should be noted that there is great uncertainty associated with assessments of dysprosium, as these are relatively small tonnages, which are mostly in demand for special magnets, and dysprosium also makes up only a small proportion of the ore. Therefore, even small changes in the utilisation rate can have a major impact on the total volume available to the market.

The challenges on the supply side are not only related to the production from the mines, but - in the west - also to the infrastructure for processing the minerals into the raw materials that the industry demands, such as separation and refining plants (see also Chapter 5). China is believed to have an existing separation capacity of approx. 300,000 tonnes/year TREO NdFeB magnets, while capacity in the west by comparison is about 20,000 tonnes/year TREO, which is significantly less than the amount of rare earth elements consumed in the west. It is also expected that China will increase the production capacity of NdFeB magnets to approx. 480,000 tonnes in 2025, which is greater than the need (Kruemmer personal communication 2021b); additionally, the capacity that is expected to be established in the west may still be reached.

The introduction of new technologies in the high-consumption industries, such as the electric vehicle and wind turbine industries, can upset the balance between supply and demand for rare earth elements. This also opens the risk that the criticality problem (see Chapter 1) moves from the rare earth elements to one or more other elements.

Table 14-8 *Comparison of the scenario assessments for the supply and demand of Pr oxide, Nd oxide and Dy oxide in 2025 and 2030. Red numbers indicate negative balance.*

			Demand			Supply			Balance			
	Scenario		Pr-oxide	Nd-oxide	Dy-oxide	Pr-oxide	Nd-oxide	Dy-oxide	Pr-oxide	Nd-oxide	Dy-oxide	Probability
Year	Demand	Supply	tonne	tonne	tonne	Tonne	tonne	tonne	tonne	tonne	tonne	
2025	**High**	**High**	23,000	70,000	4,000	24,000	74,000	9,000	1,000	4,000	5,000	Low
2025	**High**	**Low**	23,000	70,000	4,000	20,000	59,000	7,000	-3,000	-11,000	3,000	High
2025	**Low**	**High**	11,000	37,000	2,000	24,000	74,000	9,000	13,000	37,000	7,000	Low
2025	**Low**	**Low**	11,000	37,000	2,000	20,000	59,000	7,000	9,000	22,000	5,000	Low
2030	**High**	**High**	43,000	143,000	8,000	31,000	98,000	11,000	-12,000	-45,000	3,000	High
2030	**High**	**Low**	43,000	143,000	8,000	22,000	67,000	9,000	-21,000	-76,000	1,000	High
2030	**Low**	**High**	14,000	64,000	2,000	31,000	98,000	11,000	17,000	34,000	9,000	Low
2030	**Low**	**Low**	14,000	64,000	2,000	22,000	67,000	9,000	8,000	3,000	7,000	Low

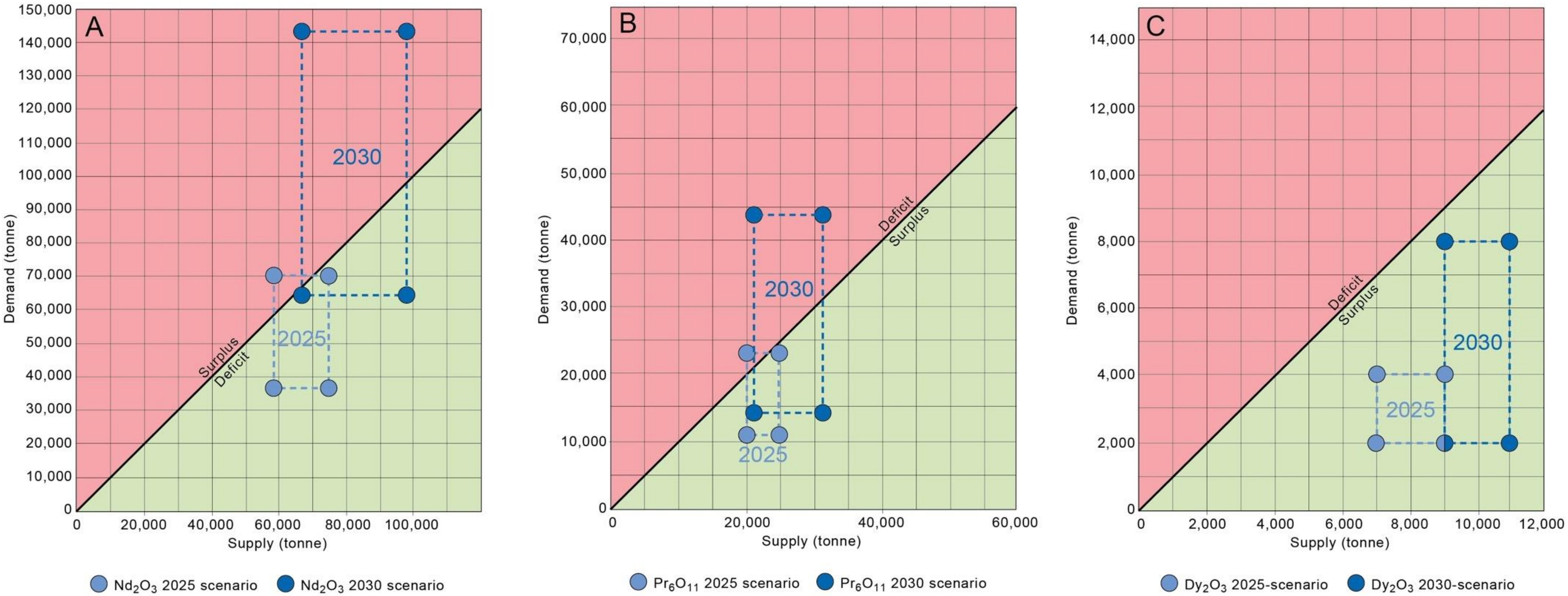

Figure 14-2 *Illustration of the raw material balance for neodymium (A), praseodymium (B) and dysprosium (C) using combinations of high and low scenarios for 2025 and 2030.*

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Appendix I

REE occurrences, deposits, exploration projects, and mines

Overview of REE occurrences, green- and brown-field exploration projects, and mines, providing details on country, geological type, REE-minerals, exploration status, and license holders.

Mineral abbreviations in Appendix II.

Locality/project	Country	REE type	REE mineral	Status	License holder
512 Xenotime Mine	China	Heavy mineral sand	xen, mon	Deposit – no data	
Ablah	Saudi Arabia	Alkaline		Deposit – no data	
Abu Tatar	Egypt	Phosphorite		Deposit – no data	
Abukalakskoe	Kazakhstan	No info	No info	Advanced explo.	No info
Adebo	China	Heavy mineral sand	mon, zir	Deposit – no data	
Adiondj	Mali	Carbonatite		Deposit – no data	
Adnew Lake	Canada	Uranium deposit		Deposit – no data	
Agate Mountain	Namibia	Carbonatite		Deposit – no data	
Agiut	Mongolia	No info		Exploration	
Agnes Waters	Australia	Heavy mineral sand, shore deposits		Deposit – no data	
Aiyang	China	Heavy mineral sand	xen, mon, zir	Production	
Akitskii	Russia	Alkaline		Deposit – no data	
Aksu Diamas	Turkey	Heavy mineral sand	apa, mon, all, bri	Exploration	AMR Mineral Metals Inc.
Aktyuz	Kirgizstan	No info		Exploration	
Alces Lake	Canada	No info	mon	Exploration	Appia Rare Earths & Uranium Corp
Alcobaca	Brazil	Heavy mineral sand, shore deposits	mon	Prospect	
Aley	Canada	Carbonatite		Deposit	
Alice Springs	Australia	No info		Advanced explo. – on hold	n.a.
Alnö	Sweden	Carbonatite		Deposit	
Alto Ligonha	Mozambique	Other/unknown		Deposit – no data	
Alway	India	Heavy mineral sand, shore deposits		Deposit – no data	
Amabtofinandrahana	Madagascar	Alkaline	bas	Exploration	Minbos Resources
Amba Dongar	India	Carbonatite	bas, mon	Production	
Ambadungar	India	No info		Advanced explo.	
Amis Complex	Namibia	Alkaline		Deposit – no data	
Amity	Australia	Heavy mineral sand, shore deposits	mon	Advanced explo. – former by-product	
Ampasindava	Madagascar	Alkaline		Deposit – no data	
Anchieta	Brazil	Heavy mineral sand, shore deposits	mon	Advanced explo. – former by-product	
Anexrouf	Mali	Carbonatite		Deposit – no data	
Anico dos Dias	Brazil	Carbonatite (with residual enrichment)		Deposit – no data	
Anitapolis	Brazil	Carbonatite (with residual enrichment)	apa	Advanced explo. – by-product	
Anomalnoe	Russia	Metamorphic		Deposit – no data	
Anxi	China	IA deposit		Deposit	
Apulia	Italy	Laterite	bas	Deposit – no data	
Aracruz	Brazil	Heavy mineral sand, shore deposits	mon	Advanced explo. – former by-product	
Aran	Ukraine	Hydrothermal			
Araxa	Brazil	Carbonatite	mon, gor, goy, apa	Exploration	Companhia Brazileira de metalurgia e Mineracao (CBMM) / Itafos

Locality/project	Country	REE type	REE mineral	Status	License holder
Archie Lake	Canada	Heavy mineral sand, fossil		Exploration	
Arenopolis	Brazil	Alkaline		Deposit – no data	
Argo James Bay	Canada	Carbonatite		Deposit – no data	
Arimoor	Nigeria	Heavy mineral sand, shore deposits		Advanced explo. – former by-product	
Arran	UK	Granit & pegmatite	all, fer, gad, mon	Deposit	
Ashram (Total Resource)	Canada	Carbonatite	mon, bas	Advanced explo.	Commerce Resources Corp
Atlantida	Uruguay	Heavy mineral sand, river deposits		Deposit – no data	
Atlin-Ruffner	Canada	Other- magmatic		Deposit – no data	
Auas Dulce	Uruguay	Heavy mineral sand, shore deposits		Deposit – no data	
Auer	Australia	Carbonatite/Laterite	mon	Advanced explo.	Hastings
Australind	Australia	Heavy mineral sand, shore deposits		Deposit – no data	
Avdrant	Mongolia	No info		Deposit	
Avonbank	Australia	Heavy mineral sand	mon	Advanced explo.	WIM Ressource Pty
Ayer Kuning	Malaysia	Heavy mineral sand, shore deposits	mon	Production – by-product	
Azov Sea Coast Dikes	Ukraine	Alkaline		Deposit – no data	
Azovske	Ukraine	Alkaline	all	Advanced explo. (on hold)	No info
Bachi	China	IA deposit		Deposit	
Badarmokam	Bangladesh	Heavy mineral sand, shore deposits		Deposit – no data	
Baerzhe	China	Alkaline	hin, pyr, syn, mon	Exploration	
Bahuis Mountains	Surinam	Alkaline		Deposit – no data	
Baima	China	Other/ unknown		Deposit – no data	
Baja Guainia	Columbia	Heavy mineral sand, fossil		Deposit – no data	
Bakony	Hungary	Laterite	bas	Deposit – no data	
Bald Hill	Australia	Carbonatite/Laterite	mon	Advanced explo.	Hastings
Bald Mountain	US	Heavy mineral sand, fossil		Advanced explo. – on hold	
Ban Yun	Thailand	Heavy mineral sand, river deposits		Deposit – no data	
Bancroft Haliburton	Canada	Alkaline	all	Deposit – no data	
Banda Aceh	Indonesia	Heavy mineral sand, shore deposits		Deposit – no data	
Bang Lin	Thailand	Heavy mineral sand, river deposits		Deposit – no data	
Banka Island	Indonesia	Heavy mineral sand, shore deposits		Deposit – no data	
Barghoriapara	Bangladesh	Heavy mineral sand, shore deposits		Deposit – no data	
Barra do Itapirapua	Brazil	Alkaline		Deposit – no data	
Barrytown	New Zealand	Heavy mineral sand, shore deposits	mon	Exploration	
Baska-Eldorado	Canada	No info		Prospect	Canoe Mining Ventures Corp
Bastnäs	Sweden	Hydrothermal	all, bas	Exploration	
Basto	Canada	No info		Prospect	Spectre Investments Incl.
Batang Berguntai	Malaysia	Heavy mineral sand, river deposits		Deposit – no data	
Batang Padang	Malaysia	Heavy mineral sand, river deposits	mon, xen	Production – by-product	
Bates Hole Area	US	Heavy mineral sand, river deposits		Deposit – no data	
Batu Gajah	Malaysia	Heavy mineral sand, shore deposits	mon, xen	Production – by-product	

Locality/project	Country	REE type	REE mineral	Status	License holder
Baude Lake	Canada	Carbonatite (pegmatite)	all	Exploration	Fancamp Exploration
Bayan Obo (East)	China	Carbonatite	bas, mon, eas	Production	China Northern Rare Earth Group/Baotou Steel
Bayan Obo (Main and West)	China	Carbonatite	bas, mon, eas, xen	Production	China Northern Rare Earth Group/Baotou Steel
Bayan Obo (surrounding)	China	Carbonatite	bas, mon, sur	Advanced explo.	China Northern Rare Earth Group/Baotou Steel
Bayan Obo (West)	China	Carbonatite	bas, mon,	Advanced explo.	China Northern Rare Earth Group/Baotou Steel
Bayside	Australia	Heavy mineral sand, shore deposits	bas, mon, bay	Deposit – no data	
Bear Lodge	US	Carbonatite	bur, par, syn	Exploration	Rare Element Resources
Bear Valley	US	Heavy mineral sand, river deposits	mon, lop, xen	Advanced explo. – on hold	
Bearpaw	US	Carbonatite	bes, mon, bea	Deposit – no data	
Beenup	Australia	Heavy mineral sand, shore deposits	bes, mon, bee	Advanced explo. – former by-product	
Behemoth	Australia	No info	n.a.	Prospect	Strategic Elements Ltd
Beihei	China	Heavy mineral sand, shore deposits	No info	Production	Local Government
Beilitung (biliton)	Indonesia	Heavy mineral sand, shore deposits	mon, cen, all	Advanced explo. – former by-product	
Belaya Zima	Russia	No info		Deposit – no data	
Benjamin River	Canada	No info	bes, mon, riv	Exploration	Fundy Minerals Ltd.
Berhala Island	Indonesia	Heavy mineral sand, shore deposits	bes, mon, isl	Deposit – no data	
Beruwalaq	Sri Lanka	Heavy mineral sand, shore deposits	bes, mon, ber	Deposit – no data	
Bidor Malaya Mine	Malaysia	Heavy mineral sand, river deposits	mon	Production – by-product	
Big Creek	US	Heavy mineral sand, river deposits	mon, eux	Advanced explo. – on hold	
Big Spruce Lake	Canada	Carbonatite	bis, mon, lak	Deposit – no data	
Biggejarvi	Norway	Hydrothermal	dav, lov, xen, syn	Exploration	
Bihor	Romania	Laterite	bas	Deposit – no data	
Bilugyun Beach	Myanmar	Heavy mineral sand, shore deposits	bis, mon, bea	Deposit – no data	
Bilundo	Angola	Carbonatite	bis, mon, bil	Deposit – no data	
Bingo (Bingu)	DRC	Carbonatite (with residual enrichment)	bis, mon, bin	Deposit – no data	
Birchfield	New Zealand	Heavy mineral sand, shore deposits	bis, mon, bir	Deposit – no data	
Birthday gift	Australia	Heavy mineral sand, shore deposits	bis, mon, bir	Exploration	
Blackfoot Bridge	US	Phosphorite	bls, mon, bri	Advanced explo. – on hold	
Blötberget	Sweden	Iron-oxide-apatite	apa, all, mon, xen	Prospect	
Bofal-Laoubboira	Mauritania	Phosphorite	bos, mon, lao	Deposit – no data	
Bokan Mountain	US	Alkaline/ hydro thermal?/Alkaline?	syn, apa, bas, mon, fer	Mine development	Ucore Rare Metals
Bomin-Khara	Mongolia	Alkaline	bos, mon, kha	Deposit – no data	
Bonga	Angola	Carbonatite	bos, mon, bon	Deposit – no data	
Boorama	Somalia	Other/ unknown	bos, mon, boo	Deposit – no data	
Bordvedaga	Norway	Metamorphic	bos, mon, bor	Deposit – no data	
Bosina	Slovakia	No info	bos, mon, bos	Prospect	Empire Metals Corp
Bou Naga	Mauritania	Carbonatite	bos, mon, nag	Prospect – on hold	
Boulia South	Australia	No info	bos, mon, sou	Exploration	Top Tung Ltd
Boulougne	US	Heavy mineral sand, shore deposits	bos, mon, bou	Advanced explo. – former by-product	

Locality/project	Country	REE type	REE mineral	Status	License holder
Bowen (Abbot Point)	Australia	Heavy mineral sand, shore deposits	bos, mon, abb	Deposit – no data	
Brandberg	Namibia	Alkaline	brs, mon, bra	Deposit – no data	
Brejo grande	Brazil	Heavy mineral sand, shore deposits	brs, mon, bre	Deposit – no data	
Bridge Hill Ridge	Australia	Heavy mineral sand, shore deposits	brs, mon, rid	Deposit – no data	
Brockmans	Australia	Alkaline	bas, cen, Y-niobate; sam	Advanced explo.	Hastings Technology Metals
Broughton Creek	Australia	No info	brs, mon, cre	Exploration	Broughton Minerals Metals Ltd
Bruce Bay	New Zealand	Heavy mineral sand, shore deposits	brs, mon, bay	Deposit – no data	
Brunswick-Altamaha	US	Heavy mineral sand, shore deposits	brs, mon, alt	Advanced explo.	
Buckton	Canada	Carbonatite	bus, mon, buc	Prospect	DNI Metals Inc. (?)
Bueme	Benin	Other/ unknown	bus, mon, bue	Deposit – no data	
Buena Norte	Brazil	Heavy mineral sand, shore deposits	mon	Production	Serra Verde
Buffalo Fluorspar	South Africa	Other – fluor deposit	bus, mon, flu	Deposit – no data	
Bukit Duabelas	Indonesia	Heavy mineral sand, shore deposits	bus, mon, dua	Deposit – no data	
Bukusu	Uganda	Carbonatite (with residual enrichment)	bus, mon, buk	Advanced explo. – former by-product	
Bunbury	Australia	Heavy mineral sand, shore deposits	mon, xen	Advanced explo. – former by-product	
Bunduk	Armenia	Alkaline	bus, mon, bun	Deposit – no data	
Bungalally	Australia	Heavy mineral sand	mon	Advanced explo.	WIM Resource Pty
Burpalinskii (Burpala)	Russia	Alkaline	bus, mon, bur	Deposit – no data	
Buru	Kenya	Carbonatite (with residual enrichment)	bus, mon, bur	Deposit – no data	
Busselton East	Australia	Heavy mineral sand, shore deposits	bus, mon, eas	Deposit – no data	
Byfield	Australia	Heavy mineral sand, shore deposits	bys, mon, byf	Deposit – no data	
Caballo Mountains	US	Alkaline	cas, mon, mou	Deposit – no data	
Cabin Bluff	US	Heavy mineral sand, shore deposits	cas, mon, blu	Deposit – no data	
Cable Sands	Australia	Heavy mineral sand, shore deposits	mon, xen	Advanced explo. – former by-product	
Caiapo	Brazil	Carbonatite (with residual enrichment)	cas, mon, cai	Deposit – no data	
Caldwell Canyon	US	Phosphorite	cas, mon, can	Advanced explo.	
Cam Hoa	Vietnam	Heavy mineral sand, shore deposits	cas, mon, hoa	Deposit – no data	
Cam Nhuong	Vietnam	Heavy mineral sand, shore deposits	cas, mon, nhu	Deposit – no data	
Campania	Italy	Laterite	bas	Deposit – no data	
Camratub	Brazil	Heavy mineral sand, shore deposits	cas, mon, cam	Deposit – no data	
Canakli I	Turkey	Heavy mineral sand		Prospect	AMR Mineral Metals Inc.
Cap	Canada	No info	cas, mon, cap	Exploration	Arctic Star Exploration Corp.
Cape Foulwind	New Zealand	Heavy mineral sand, shore deposits	wes, mon, wes	Deposit – no data	Westland Mineral Sands Ltd
Capel	Australia	Heavy mineral sand, shore deposits	cas, mon, cap	Advanced explo. – former by-product	
Capel North	Australia	Heavy mineral sand	cas, mon, nor	Deposit – no data	
Capuia	Angola	Carbonatite	cas, mon, cap	Deposit – no data	
Carb Lake	Canada	Carbonatite	cas, mon, lak	Deposit – no data	
Cargill	Canada	Carbonatite (with residual enrichment)	cas, mon, car	Exploration	
Caronlina monazite belt	US	Heavy mineral sand, river deposits	cas, mon, car	Deposit – no data	

Locality/project	Country	REE type	REE mineral	Status	License holder
Cat Khanh	Vietnam	Heavy mineral sand, shore deposits	mon, xen	Production – by-product	
Cataby	Australia	Heavy mineral sand, shore deposits	mon	Advanced explo. – former by-product	
Catalao I	Brazil	Carbonatite (with residual enrichment)	pyr, gor,	Advanced explo. – by-product	
Cerro Bamba	Bolivia	Alkaline	ces, mon, bam	Deposit – no data	
Cerro Impacto	Venezuela	Carbonatite (with residual enrichment)	bas, flo, mon	Exploration	
Cerro Manomo	Bolivia	Carbonatite	ces, mon, man	Deposit – no data	
Chambe Basin	Malawi	No info	chs, mon, bas	Exploration	
Chamberlin District	US	Heavy mineral sand, river deposits	chs, mon, dis	Deposit – no data	
Champ	US	Phosphorite	chs, mon, cha	Deposit – no data	
Changan	China	Heavy mineral sand, shore deposits	mon	Exploration	
Changit	Russia	Carbonatite	chs, mon, cha	Deposit – no data	
Changling	China	IA deposit	chs, mon, cha	Exploration	Xiamen Tungsten Industry Co. Ltd
Chao Fa Mine	Thailand	Heavy mineral sand, river deposits	chs, mon, min	Deposit – no data	
Charley Creek	Australia	Heavy mineral sand	mon, xen	Advanced explo.	Enova Mining Ltd; Crossland Strategic Metals; EMMCO Mining Sdn Bhd
Charlton County (GA)	US	Heavy mineral sand (TiO_2)	chs, mon, ga)	Prospect	Southern Ionics Minerals Inc. (ejer: Chemours)
Chatrapur	India	Heavy mineral sand, shore deposits	mon	Production – by-product	
Chavara	India	Heavy mineral sand, shore deposits	mon	Production – by-product	Indian Rare Earth Ltd (IREL)
Chenxian	China	IA deposit	chs, mon, che	Production	
Chernigovskii	Ukraine	Carbonatite	chs, mon, che	Deposit – no data	
Cheyne Bay	Australia	Heavy mineral sand, shore deposits	mon	Advanced explo. – former by-product	
Chiembwe (Petauke)	Zambia	Alkaline	chs, mon, pet	Deposit – no data	
Chilwa Island	Malawi	Carbonatite (with residual enrichment)	chs, mon, isl	Deposit – no data	
Chingshankangchow	Taiwan	Heavy mineral sand, shore deposits	chs, mon, chi	Deposit – no data	
Chiriguelo	Paraguay	Carbonatite	chs, mon, chi	Deposit – no data	
Chishan	China	Carbonatite		Deposit – no data	
Chongxianaobei	China	IA deposit			
Chongzou	China	IA deposit	chs, mon, cho	Deposit – no data	
Chuchinka	Canada	No info	chs, mon, chu	Prospect	International Montoro Resources Inc.
Chuktukun	Russia	No info		Prospect	
Chumphon	Thailand	Heavy mineral sand, river deposits	mon	Production – by-product	
Churata	Venezuela	Alkaline	chs, mon, chu	Deposit – no data	
Cida	China	Alkaline	fer	Exploration	
Cinder Lake	Canada	No info	cis, mon, lak	Exploration	
Circle	US	Heavy mineral sand, river deposits	cis, mon, cir	Deposit – no data	
Clay-Howells	Canada	Alkaline	cls, mon, how	Advanced explo.	
Clayton Vallye	US	No info		Exploration	Cypress Development Corp
Coldwell	Canada	Alkaline	cos, mon, col	Exploration	Canada Rare Earths Corporation
Coleroon-Sirkazhi	India	Heavy mineral sand, shore deposits	cos, mon, sir	Deposit – no data	
Con Negosa	Mozambique	Carbonatite (with residual enrichment)	cos, mon, neg	Deposit – no data	

Locality/project	Country	REE type	REE mineral	Status	License holder
Congolone	Mozambique	Heavy mineral sand, shore deposits	mon	Production – by-product	
Coogloegong	Australia	Other- magmatic	ytan, gad	Advanced explo. – former by-product	
Coojarloo	Australia	Heavy mineral sand, shore deposits	mon	Advanced explo. – former by-product	
Coola	Angola	Carbonatite	cos, mon, coo	Deposit – no data	
Cooloola	Australia	Heavy mineral sand, shore deposits	cos, mon, coo	Advanced explo. – former by-product	
Cornudas Mountains	US	Alkaline	cos, mon, mou	Deposit – no data	
Coromandel Peninsula	New Zealand	Heavy mineral sand, shore deposits	cos, mon, pen	Deposit – no data	
Cowalinya	Australia	Laterite	cos, mon, cow	Prospect	eMetals Ltd
Cox's Bazaar	Bangladesh	Heavy mineral sand, shore deposits	cos, mon, baz	Exploration	
Crater Lake	Canada	Alkaline	crs, mon, lak	Prospect	Imperial Mining Group
Crescent Peak	US	Other- magmatic	crs, mon, pea	Deposit – no data	
Cueva del Chacho	Argentina	No info	cus, mon, cha	Exploration	Pacific Bay Minerals
Cumberland Island	US	Heavy mineral sand, shore deposits	cus, mon, isl	Deposit – no data	
Cummins Range	Australia	Carbonatite	apa, mon, bas cra	Advanced, explo.	RareX Ltd
Cumuruxatiba	Brazil	Heavy mineral sand, shore deposits	mon	Production – by-product	
Curtis Island	Australia	Heavy mineral sand, shore deposits	cus, mon, isl	Deposit – no data	
Curumbin	Australia	Heavy mineral sand, shore deposits	cus, mon, cur	Advanced explo. – former by-product	
Dahuzhi	China	Heavy mineral sand	mon, U, Th	Advanced explo.	
Dajti	Albania	Laterite	bas	Deposit – no data	
Dalkainie	Somalia	Carbonatite	das, mon, dal	Deposit – no data	
Dalucao	China	Carbonatite	das, mon, dal	Production	Dechang Houdi Rare Earth Mining Co. Ltd
Daluhala	China	Carbonatite		Prospect	
Daluxiang (Dalucao)	China	Carbonatite	bas, mon, pyr	Production	
Dara-Pioz	Tajikistan	Alkaline	das, mon, pio	Exploration	
Dardanup	Australia	Heavy mineral sand, shore deposits	mon	Exploration	
Datang	China	IA deposit		Deposit	
Dechang	China	Carbonatite	No info	Mine development	No info
Deep Creek	US	Carbonatite	des, mon, cre	Deposit – no data	
Deep Sands	US	No info	des, mon, san	Prospect – on hold	Titan Mining Group
Denegama	Sri Lanka	Other- magmatic	des, mon, den	Deposit – no data	
Denison	Canada	Other – uranium deposits	des, mon, den	Deposit – no data	
Diamond Creek	US	Other- magmatic	mon, xen	Exploration	US Rare Earths Inc
Dianbai	China	Heavy mineral sand, shore deposits	mon	Production – by-product	
Dingnan	China	IA deposit	dis, mon, din	Production	
Ditau	Botswana	No info	dis, mon, dit	Prospect	Kavango Resources, Power Metal Resources
Ditrau	Romania	Alkaline	all, ba, syn, mon, xen	Prospect	Kanango Resources, Power Metal Resources
Dnieprodzerzhinsk	Ukraine	Phosphorite	dns, mon, dni	Deposit – no data	
Donald	Australia	Heavy mineral sand	mon	Advanced explo.	Astron Ltd
Dong Pao	Vietnam	Carbonatite	bas, par	Mine development	Dong Pao Rare Earth Develop. (JV partner Lai chau Rare Earth Co (Vimeco)

Locality/project	**Country**	**REE type**	**REE mineral**	**Status**	**License holder**
Dong Xuan	Vietnam	Heavy mineral sand, shore deposits	dos, mon, xua	Deposit – no data	
Dongara	Australia	Heavy mineral sand, shore deposits	dos, mon, don	Exploration	
Dongging	China	Other/ unknown	dos, mon, don	Deposit – no data	
Dora Bay	US	Alkaline	dos, mon, bay	Exploration	
Dory Pond	Canada	No info	dos, mon, pon	Prospect	Canada Rare Earths Corporation
Dubbo	Australia	Alkaline	eud, pyr, mon, bas	Advanced explo.	Alkane Resources/Australian Strategic Metals Ltd
Dubbo (Toongi)	Australia	Alkaline	dus, mon, too	Exploration	
Durness	Australia	Heavy mineral sand, shore deposits	mon	Advanced explo. – former by-product	
Eagle Creek	US	Andet – uranium deposits	eas, mon, cre	Deposit – no data	
Eco Ridge	Canada	Carbonatite (with residual enrichment)	mon	Exploration	Pele Mountain Resources Incl
Eden Lake	Canada	Alkaline	eds, mon, lak	Deposit – no data	
El Cabrito	Chile	IA deposit (hydrothermal)	mon, xen	Exploration	Minera BioLantanidos
El Dorado Creek Area	US	Heavy mineral sand, river deposits	els, mon, are	Deposit – no data	
Eldor	Canada	Carbonatite	mon	Exploration	Commerce Resources Corp/Sunrise Resources Ltd
Elet'ozerskii	Russia	Carbonatite	els, mon, ele	Deposit – no data	
Elisenvaara	Russia	Alkaline	els, mon, eli	Production	
Eljozero	Russia	Alkaline	els, mon, elj	Deposit – no data	
Elk Creek	US	Carbonatite	els, mon, cre	Advanced explo.	Nio-Corp Development Ltd.
Elk Creek	US	Carbonatite	eis, mon, cre	Deposit – no data	
Elliott Lake Teasdale	Canada	Heavy mineral sand (conglomerate)	mon, xen, bran	Advanced explo.	Appia Rare Earths & Uranium Corp
Emilie	Canada	No info	ems, mon, emi	Prospect	Services Miniers Mecanex
Encantada-Beuna Vista	Mexico	Other – F deposits	ens, mon, vis	Deposit – no data	
Eneabba	Australia	Heavy mineral sand	mon, xen	Production	Iluka Resources
Eorae San	South Korea	No info	eos, mon, san	Deposit – no data	
Erdenesant	Mongolia	No info	ers, mon, erd	Prospect	GTSO Resources; Rare Earth Exporters of Mongolia
Etanero	Namibia	Carbonatite		Deposit	
Eureka	Namibia	Carbonatite	mon	Prospect	E-Tech Resources/Mila Resources PLC
Evans Head Yuraygir	Australia	Heavy mineral sand, shore deposits	evs, mon, yur	Deposit – no data	
Fakiraghona	Bangladesh	Heavy mineral sand, shore deposits	fas, mon, fak	Deposit – no data	
Fanshan	China	Alkaline	fas, mon, fan	Advanced explo. – by-product	
Fatima	Mexico	Other – F deposits	fas, mon, fat	Deposit – no data	
Fen	Norway	Carbonatite	bas, mon, all	Exploration	REE Minerals AS
Fingerboards	Australia	Heavy mineral sand	mon, zir	Advanced explo.	Kalbar Resources Ltds
Flemington	Australia	Heavy mineral sand/Laterite	goethite	Exploration	Australia Mines Ltd
Flora	Australia	No info	fls, mon, flo	Prospect	Consolidated Global Investments Ltd
Florida	Namibia	No info	fls, mon, flo	Prospect	Namibia Rare Earth Inc.
Flowers Bay	Canada	Alkaline	fls, mon, bay	Deposit – no data	
Folkston	US	Heavy mineral sand, shore deposits	mon	Advanced explo. – former by-product	

Locality/project	Country	REE type	REE mineral	Status	License holder
Foreshore Beach	Bangladesh	Heavy mineral sand, shore deposits	fos, mon, bea	Deposit – no data	
Fort Dauphine	Madagascar	Heavy mineral sand, shore deposits	mon	Production	QIT Madagascar Minerals (Rio Tinto plc 80 %+ Government of Madagascar 20 %)
Fortymile	US	Heavy mineral sand, river deposits	fos, mon, for	Deposit – no data	
Foulun	Taiwan	Heavy mineral sand, shore deposits	fos, mon, fou	Deposit – no data	
Foxtrot (=Port Hope Simpson)	Canada	Alkaline	all, fer, bas, mon	Exploration	Search Minerals Inc
Francon Quarry	Canada	Carbonatite	frs, mon, qua	Deposit – no data	
Fraser	Australia	Carbonatite / Laterite	mon	Advanced explo.	Hastings
Fraser Island	Australia	Heavy mineral sand, shore deposits	mon	Advanced explo. – former by-product	
Fremont Butte	US	Other/ unknown	frs, mon, but	Deposit – no data	
Fujian Jinlong	China	IA deposit	fus, mon, jin	Mine development	Fujian Changting Jinlong Rare Earth Co. Ltd.
Fukeng	China	IA deposit		Deposit – no data	
Fullerton	Australia	Heavy mineral sand, shore deposits	mon	Advanced explo. – former by-product	
Gakara (Karonge)	Burundi	Carbonatite (with residual enrichment)	bas, mon	Mine development	Rainbow Rare Earth
Galineiro	Spain	Alkaline	ala, bas, par	Exploration	Vendors of Rare Earth Int. Ltd
Gallinas Mountains	US	Alkaline	gas, mon, mou	Deposit – no data	Strategic Resources Inc.
Gambang area	Malaysia	Heavy mineral sand, (river deposits) river deposits	xen, mon	Production – by-product	
Gambit West (Browns Range)	Australia	No info		Advanced explo.	Northern Minerals Ltd
Gangkou	China	Other/ unknown	gas, mon, gan	Deposit – no data	
Gangxia	China	IA deposit		Deposit – no data	
Gannan Mine	China	IA deposit	gas, mon, min	Deposit – no data	
Ganshahenao	China	Hydrothermal	zir, ilm	Deposit	
Ganzhou	China	IA deposit	gas, mon, gan	Production	Ganzhou Mining Group
Gardiner Complex	Greenland	Alkaline	pri, lop, apa	Deposit	
Gatineau	Canada	Carbonatite	gas, mon, gat	Deposit – no data	Critical Elements Corp
Gay and South Forty	US	Phosphorite	gas, mon, for	Deposit – no data	
Gem Park	US	Carbonatite	ges, mon, par	Deposit – no data	
Geoland	Canada	No info	ges, mon, geo	Prospect	Canada Strategic Metals Inc.
Georgia	US	Heavy mineral sand	mon	Advanced explo. – by-product	Chemours
Geotai	Thailand	No info	ges, mon, geo	Prospect	Geotai Exploration and Mining Company Ltd
Geoudini	South Africa	Carbonatite	ges, mon, geo	Deposit – no data	
Getengzui	China	IA deposit		Deposit	
Ghurayyah	Saudi Arabia	Alkaline	ghs, mon, ghu	Deposit – no data	
Gifford Creek	Australia	Carbonatite	gis, mon, cre	Prospect	Hastings Technology Metals
Ginger M	US	No info		Prospect	Strategic Resources Inc.
Gingin	Australia	Heavy mineral sand, shore deposits	gis, mon, gin	Deposit – no data	
Gladstone Mainland	Australia	Heavy mineral sand, shore deposits	gls, mon, mai	Deposit – no data	
Glenaladale	Australia	Heavy mineral sand	mon(?); xen(?)	Prospect	Fingerbords

Locality/project	Country	REE type	REE mineral	Status	License holder
Glenover	South Africa	Carbonatite	apa, hem	Exploration	Glenover Pty JV /Galileo Resources
Glogova Clesnestisti	Romania	Heavy mineral sand, shore deposits	gls, mon, sis	Advanced explo.	
Goias	Brazil	Carbonatite (with residual enrichment)	gos, mon, goi	Deposit – no data	
Gold Coast	Australia	Heavy mineral sand, shore deposits	gos, mon, coa	Deposit – no data	
Gomoe Ozero	Russia	Carbonatite	gos, mon, oze	Deposit – no data	
Gonghe	China	IA deposit		Deposit – no data	
Gordon	Australia	Heavy mineral sand, shore deposits	gos, mon, gor	Deposit – no data	
Goshen	Australia	Heavy mineral sand	mon	Advanced explo.	WHM Ltd
Gouin East	Canada	No info	gos, mon, eas	Prospect	Fancamp Exploration
Grande-Vallee	Canada	IA deposit	grs, mon, val	Advanced explo.	Orbite Aluminae Inc.
Grass Creek area	US	Heavy mineral sand, fossils	grs, mon, cre	Deposit – no data	
Grebnik	Kosovo	Laterite	bas	Deposit – no data	
Green Cove Springs	US	Heavy mineral sand	mon	Production – by-production ceased	
Greenvill	Canada	Other/ unknown	grs, mon, gre	Deposit – no data	
Gremyakha-Vrymes	Russia	Alkaline	grs, mon, vry	Deposit – no data	
Grängesberg	Sweden	Iron-oxide-apatite-Iron-oxide-apatite	apa, mon, xen, all	Production – ceased	
Grønnedal – Ika	Greenland	Carbonatite	bas	Prospect – inactive	
Guandong	China	IA deposit	gus, mon, gua	Production	Guandong Rising NF
Guangshui	China	Metamorphic	gus, mon, gua	Deposit – no data	
Guarapari	Brazil	Heavy mineral sand, shore deposits	mon	Production – by-product	
Guelb Zeilaga	Mauritania	Alkaline	gus, mon, zei	Deposit – no data	
Guidong	China	IA deposit	gus, mon, gui	Deposit – no data	
Guilherme Group	Mozambique	Other- magmatic	gus, mon, gro	Deposit – no data	
Guposhan	China	Other- magmatic	gus, mon, gup	Deposit – no data	
Gupsehan	China	IA Deposit	jis, mon, jia	Production	China Minmetals Corp.
Gympie	Australia	Heavy mineral sand, shore deposits	mon	Advanced explo. – former by-product	
Gzarta-Hudag	Mongolia	Alkaline	gzs, mon, hud	Deposit – no data	
Haifengtao	Taiwan	Heavy mineral sand, shore deposits	has, mon, hai	Deposit – no data	
Haikang	China	Heavy mineral sand, shore deposits	has, mon, hai	Production – by-product	
Hall Mountain Group	US	Other- magmatic	has, mon, gro	Deposit – no data	
Halpanen	Finland	Carbonatite		Deposit	
Ham Tan	Vietnam	Heavy mineral sand, shore deposits	has, mon, tan	Deposit – no data	
Hambantota	Sri Lanka	Heavy mineral sand, shore deposits	has, mon, ham	Deposit – no data	
Harrington	Australia	Heavy mineral sand, shore deposits	mon	Advanced explo. – former by-product	
Hastings	Australia	Alkaline	has, mon, has	Advanced explo.	Hastings Rare Metals Ltd
Hawks Nest	Australia	Heavy mineral sand, shore deposits	has, mon, nes	Deposit – no data	
Hedi	China	No info	No info	Production	Shenghe Resources Holding Co. Ltd
Heling	China	IA deposit		Deposit	
Henly Harbour	Canada	No info	hes, mon, har	Prospect	Search Minerals Inc
Henry	US	Phosphorite	hes, mon, hen	Deposit – no data	
Hérault	France	Laterite	bas	Prospect	

Locality/project	Country	REE type	REE mineral	Status	License holder
Hezhou Jinguang	China	No info	No info	Production	Guangxi Hezhou Jinguang Rare Earth Con
Hiashangchow	Taiwan	Heavy mineral sand, shore deposits	his, mon, hia	Deposit – no data	
Hicks Dome	US	Carbonatite	xen, bas, chu	Exploration	
Higgins	Australia	Heavy mineral sand, shore deposits	his, mon, hig	Deposit – no data	
Hilton Head Island	US	Heavy mineral sand, shore deposits	his, mon, isl	Exploration	
Hiren	Canada	No info	his, mon, hir	Prospect	Zimtu Capital Corps
Hnilcik	Slovakia	No info	hns, mon, hni	Prospect	Empire Metals Corp
Hoanak	Bangladesh	Heavy mineral sand, shore deposits	hos, mon, hoa	Deposit – no data	
Hoarusib	Namibia	No info	hos, mon, hoa	Prospect	AVZ Minerals Ltd
Hoidas Lake (Nisikkatch)	Canada	Hydrothermal	apa; all	Advanced explo.	Great Western Minerals Group (bancrupt?
Hokitika	New Zealand	Heavy mineral sand, shore deposits	hos, mon, hok	Deposit – no data	
Honeybugle	Australia	No info	hos, mon, hon	Exploration	Scandium International Mining Corp.
Horse Creek	US	Heavy mineral sand, river deposits	mon, xen	Advanced explo.	
Hot Springs	US	Heavy mineral sand, river deposits	hos, mon, spr	Deposit – no data	
Houyang Mine	China	Heavy mineral sand	xen, mon, zir	Production	
Huangshi	China	No info	No info	Production	Rising Nonferrous Metals Share Co. Ltd
Huaqi	China	No info	No info	Production	Rising Nonferrous Metals Share Co. Ltd
Huashan	China	IA deposit		Deposit	
Huishan	China	Other- magmatic	hus, mon, hui	Production	
Hukeng	China	Heavy mineral sand	xen, mon, eux	Deposit – no data	
Hunts Beach	New Zealand	Heavy mineral sand, shore deposits	hus, mon, bea	Deposit – no data	
Huong Dien	Vietnam	Heavy mineral sand, shore deposits	hus, mon, die	Deposit – no data	
Husky	US	Phosphorite	hus, mon, hus	Deposit – no data	
Hwajinpo	South Korea	Heavy mineral sand, shore deposits	hws, mon, hwa	Deposit – no data	
Høgtuva	Norway	Hydrothermal	all, mon, fer	Exploration	
Ibis-Alpha	Australia	Heavy mineral sand, shore deposits	ibs, mon, alp	Deposit – no data	
Ice River	Canada	No info	ics, mon, riv	Exploration	Eagle Plains Resources Ltd
Iditarod	US	Heavy mineral sand, river deposits	ids, mon, idi	Deposit – no data	
Idkerberget	Sweden	Iron-oxide-apatite	apa	Production – ceased	
Igaliko, Gardar	Greenland	Alkaline	eud, pyr, mon, bas	Prospect – on hold	Czech Geological Research Group Ltd
Iivaara	Finland	Alkaline		Deposit	
Ile (Namatuacatue)	Mozambique	Other- magmatic	ils, mon, nam	Deposit – no data	
Ilomba	Malawi	Alkaline	ils, mon, ilo	Deposit – no data	
Imotski	Croatia	Laterite	bas	Deposit – no data	
Imuruan Bay	Philippines	Heavy mineral sand, shore deposits	ims, mon, bay	Deposit – no data	
Inani	Bangladesh	Heavy mineral sand, shore deposits	ins, mon, ina	Deposit – no data	
Indian Creek District	US	Metamorphic	ins, mon, ind	Deposit – no data	
Ingischke	Uzbekistan	Metamorphic	ins, mon, ing	Deposit – no data	

Locality/project	Country	REE type	REE mineral	Status	License holder
Inuruwa	Sri Lanka	Heavy mineral sand, shore deposits	ins, mon, inu	Deposit – no data	
IRC	Canada	No info	irs, mon, irc	Prospect	Zimtu Capital Corp.; Gathro Resources Corp
Iron Hill	US	Carbonatite	irs, mon, hil	Deposit – no data	US Rare Earths Inc
Itanhaem	Brazil	Carbonatite	its, mon, ita	Deposit – no data	
Itapemirim	Brazil	Heavy mineral sand, shore deposits	mon	Production – by-product	
Itremo	Madagascar	Alkaline	its, mon, itr	Deposit – no data	
Ivigtut	Greenland	Alkaline		Deposit	
J6L 1	Canada	No info	j6s, mon, l 1	Prospect	Critical Elements Corp
Jabab Tawlah	Saudi Arabia	Alkaline	jas, mon, taw	Deposit – no data	
Jabal Ar Rabuts	Saudi Arabia	Other/ unknown	jas, mon, rab	Deposit – no data	
Jabal Archenu	Libya	Alkaline	jas, mon, arc	Deposit – no data	
Jabal Awja	Saudi Arabia	Other/ unknown	jas, mon, awj	Deposit – no data	
Jabal Ebed	Saudi Arabia	Other/ unknown	jas, mon, ebe	Deposit – no data	
Jabal Hamra	Saudi Arabia	Alkaline	jas, mon, ham	Deposit – no data	
Jabal Kuara	Saudi Arabia	Other/ unknown	jas, mon, kua	Deposit – no data	
Jabal Said	Saudi Arabia	Alkaline	jas, mon, sai	Deposit – no data	
Jacupiranga	Brazil	Alkaline	apa	Advanced explo. – by-product	
Jake Lee	Canada	No info	jas, mon, lee	Prospect	Cache Exploration Ind; Geodex Minerals
Jangardup	Australia	Heavy mineral sand, shore deposits	mon	Production – by-product	
Janghowon	South Korea	Heavy mineral sand, river deposits	jas, mon, jan	Deposit – no data	
Jarud Wi	China	Alkaline		Deposit – no data	
Jasimampa	Argentina	No info	jas, mon, jas	Prospect	Centenera Mining Corp.
Javorsky	Canada	No info	jas, mon, jav	Prospect	Arctic Star Exploration Corp.
Jiazhuang	China	IA deposit		Deposit	
Jinqiao	China	IA deposit		Advanced explo.	
John Galt	Australia	No info	jos, mon, gal	Prospect	Northern Minerals Ltd
Jokinkangas	Finland	No info	fer, ala, col	Deposit – no data	
Jongju	North Korea	No info	jos, mon, jon	Prospect	Pacific Century Rare Earth Minerals Ltd.
Jos Plateau	Nigeria	Heavy mineral sand, river deposits	jos, mon, pla	Deposit – no data	
Junguni	Malawi	Alkaline	jus, mon, jun	Deposit – no data	
Jurien Bay	Australia	Heavy mineral sand, shore deposits	jus, mon, bay	Production – by-product	
Kabengelwa	DRC	Heavy mineral sand, shore deposits	kas, mon, kab	Deposit – no data	
Kachin State	Myanmar	IA deposit	kas, mon, kac	Production	
Kaikawela	Sri Lanka	Heavy mineral sand, shore deposits	kas, mon, kai	Production – by-product	
Kaiserstuhl	Germany	Carbonatite		Deposit	
Kalkfeld	Namibia	Carbonatite	kas, mon, kal	Deposit – no data	
Kalutara	Sri Lanka	Heavy mineral sand, shore deposits	kas, mon, kal	Exploration	
Kaluwe	Zambia	Carbonatite (with residual enrichment)	kas, mon, kal	Deposit – no data	
Kamloops	Canada	Alkaline	kas, mon, kam	Deposit – no data	
Kanbauk	Myanmar	Heavy mineral sand, river deposits	kas, mon, kan	Deposit – no data	
Kangankunde	Malawi	Carbonatite (with residual enrichment)	mon, bas, flor	Exploration	Lindian Resources / Lynas/Rift Valley Ressource Development Ltd

Locality/project	Country	REE type	REE mineral	Status	License holder
Kap Parry	Greenland	Alkaline	kas, mon, par	Prospect	Czech Geological Research Group Ltd
Kap Simpson, Bjørnedal	Greenland	Hydrothermal	eux, sam, fer, mon, bas	Deposit	
Kapfrugwa (Gungwa)	Zimbabwe	Carbonatite	kas, mon, gun	Deposit – no data	
Kapiri	Malawi	Carbonatite (with residual enrichment)	kas, mon, kap	Deposit – no data	
Karamea	New Zealand	Heavy mineral sand, shore deposits	kas, mon, kar	Deposit – no data	
Karasu	Turkey	No info	kas, mon, kar	Prospect	Black Sea Metals Inc.
Karganskii	Kirgizstan	Alkaline	kas, mon, kar	Deposit – no data	
Karnasurt	Russia	No info	kas, mon, kar	Prospect	PJSC Solikansk Mangesium Works
Karonge	Burundi	Hydrothermal		Deposit	
Karsakpai	Kazakhstan	Alkaline	kas, mon, kar	Deposit – no data	
Kasagwe	Burundi	Other- magmatic	kas, mon, kas	Deposit – no data	
Katajakangas	Finland	Alkaline	fer, ala, col	Exploration	
Katete	Zimbabwe	Carbonatite	kas, mon, kat	Prospect	Premier African Minerals Ltd
Katugino	Russia	No info		Prospect	
Kavango	Botswana	No info	kas, mon, kav	Prospect	Kavango Resources Plc.
Ke Sung	Vietnam	Heavy mineral sand, shore deposits	kes, mon, sun	Deposit – no data	
Kelani River	Sri Lanka	Heavy mineral sand, shore deposits	kes, mon, kel	Deposit – no data	
Kembajan	Indonesia	Heavy mineral sand, shore deposits	kes, mon, kem	Deposit – no data	
Kerala	India	Heavy mineral sand	mon	Advanced explo.	Stateowned (Dep. Atomic Energy)
Kerr-McGee	US	Heavy mineral sand, shore deposits	kes, mon, gee	Deposit – no data	
Keshya	Zambia	Carbonatite	kes, mon, kes	Deposit – no data	
Khaldzan Burgtey	Mongolia	Carbonatite	khs, mon, bur	Deposit	
Khamna	Russia	Carbonatite	khs, mon, kha	Deposit – no data	
Khan Bogdo	Mongolia	Alkaline	khs, mon, bog	Deposit – no data	
Khanneshin	Afghanistan	Carbonatite	khs, mon, kha	Deposit – no data	Government of Islamic Republic of Afghanistan
Khibiny apatite deposti	Russia	Alkaline	apa, eud, bur, anc	Production	?
Khotgor	Mongolia	No info	khs, mon, kho	Exploration	Khotgor Minerals LLC
Kin	Canada	No info	kis, mon, kin	Prospect	Critical Elements Corp
King Sound	Australia	Heavy mineral sand, shore deposits	kis, mon, sou	Exploration	
Kingscliff	Australia	Heavy mineral sand, shore deposits	mon	Production – by-product	
Kinta Kellas Batu	Malaysia	Heavy mineral sand, river deposits	mon, xed	Production – by-product	
Kipawa (Zeus)	Canada	Alkaline	eud, mos, bri, git	Advanced explo.	Vital Metals Ltd/ Matamec Explorations Inc.
Kirra	Australia	Heavy mineral sand, shore deposits	kis, mon, kir	Deposit – no data	
Kiruna	Sweden	Iron-oxide-apatite	apa, mon	Advanced explo. – by-product	
Kiviniemi	Finland	No info	kis, mon, kiv	Prospect	Scandium International Mining Corp.
Kizilcaoren	Turkey	Hydrothermal	bas, bro, flo, mon	Advanced explo.	
Kluan Tong Mine	Thailand	Heavy mineral sand, river deposits	mon	Production – by-product	

Locality/project	Country	REE type	REE mineral	Status	License holder
Kodal	Norway	Alkaline	apa	Exploration	
Kokkilai	Sri Lanka	Heavy mineral sand, shore deposits	kos, mon, kok	Deposit – no data	
Koner	Russia	Alkaline	kos, mon, kon	Deposit – no data	
Kontioaho	Finland	No info	fer, ala, col	Prospect	
Koombana Bay	Australia	Heavy mineral sand, shore deposits	xen	Production – by-product	
Koppamurra	Australia	IA deposit		Prospect	Australian Rare Earths Ltd
Koppany	Australia	No info		Prospect	Hammer Metals Ltd
Korella	Australia	No info	kos, mon, kor	Exploration – ceased	Australian Venus Resources Pty Ltd
Korgeredaba	Russia	Alkaline	kos, mon, kor	Deposit – no data	
Korsnas Mine	Finland	Carbonatite	apa, mon	Exploration	Magnus Minerals Ltd
Korsun-Novomirorodskii	Ukraine	Alkaline	kos, mon, nov	Deposit – no data	
Kovdor Complex	Russia	Alkaline	kos, mon, com	Deposit – no data	
Kovela	Finland	No info	mon	Prospect	
Kpong	Ghana	Alkaline	kps, mon, kpo	Deposit – no data	
Kribi	Cameroon	Alkaline	krs, mon, kri	Deposit – no data	
Kringlerne	Greenland	Alkaline	eud, all	Advanced explo.	Rimbal Pty Ltd
Kriumba	DRC	Carbonatite	krs, mon, kri	Deposit – no data	
Krusne Hory	The Czech Republic	Alkaline		Deposit	
Kudraimozhi	India	Heavy mineral sand, shore deposits	mon	Exploration	
Kugda	Russia	Carbonatite	kus, mon, kug	Deposit – no data	
Kulwin	Australia	Heavy mineral sand, shore deposits	kus, mon, kul	Deposit – no data	
Kunyang	China	Phosphorite	kus, mon, kun	Deposit – no data	
Kusipo	South Korea	Heavy mineral sand, shore deposits	kus, mon, kus	Deposit – no data	
Kutessay II	Kirgizstan	Alkaline	mon, xen, Y-syn	Production	Neon Mining Company/Stans Energy Inc.
Kutessiask	Kirgizstan	Other/ unknown	Y-syn	Production	
Kutubdai Island	Bangladesh	Heavy mineral sand, shore deposits	kus, mon, isl	Deposit – no data	
Kutubjum	Bangladesh	Heavy mineral sand, shore deposits	kus, mon, kut	Deposit – no data	
Kuwn-Thong	Thailand	Heavy mineral sand, river deposits	kus, mon, tho	Deposit – no data	
Kvanefjeld (main)	Greenland	Alkaline	ste	Advanced explo. – on hold	Greenland Minerals A/S
Kvanefjeld (Sørensen)	Greenland	Alkaline	ste	Advanced explo. – on hold	Greenland Minerals A/S
Kvanefjeld (Zone 3)	Greenland	Alkaline	ste	Advanced explo. – on hold	Greenland Minerals A/S
Kwangsangun	South Korea	Heavy mineral sand, river deposits	kws, mon, kwa	Deposit – no data	
Kwyjibo	Canada	Iron-oxide-copper-gold	apa, bri, all	Advanced explo.	Investissement Quebec/Focus Graphite Inc.
Ky Khang	Vietnam	Heavy mineral sand, shore deposits	mon, xen	Production – by-product	
Ky Ninh	Vietnam	Heavy mineral sand, shore deposits	kys, mon, nin	Deposit – no data	
Kyan Chaung	Myanmar	Heavy mineral sand, river deposits	kys, mon, cha	Deposit – no data	
Kymi	Finland	No info	mon, ala, bas, xen	Deposit – no data	
Kyzul-Ompul	Kirgizstan	Alkaline	kys, mon, omp	Deposit – no data	
La Llacuma	Spain	Laterite	bastnäsit	Deposit	
La Paz	US	Hydrothermal	las, mon, paz	Exploration	American Rare Earth

Locality/project	Country	REE type	REE mineral	Status	License holder
Lac Arques	Canada	No info	las, mon, arq	Prospect	Critical Elements Lithium Corp
Lac Henri	Canada	No info	las, mon, hen	Prospect	Ditem Exploration Inc.
Lackner Lake (Nemegos)	Canada	Alkaline	pyr	Exploration	6378366 Canada Inc.
laenaya Varaka	Russia	Carbonatite	las, mon, var	Deposit – no data	
Lahat Perak	Malaysia	Heavy mineral sand	las, mon, min	Production – ceased	Mentri Besar Incorp; Malaysian Rare Earth Corp.
Laishi (Luilong)	China	IA deposit		Deposit – no data	
Laivajoki	Finland	No info	las, mon, lai	Exploration	
Lake Innes	Australia	Laterite	las, mon, inn	Deposit – no data	
Lake Pythonga	Canada	No info	las, mon, pyt	Exploration	Cavan Ventures Inc
Lalande	Canada	No info	las, mon, lal	Exploration	Cavan Ventures Inc
Lamujärvi	Finland	Alkaline		Deposit	
Lamwpyin Shwedu Chaung	Myanmar	Heavy mineral sand, river deposits	las, mon, cha	Deposit – no data	
Langesundfjord	Norway	Alkaline	las, mon, lan	Deposit – no data	
Lanshan	China	IA deposit	las, mon, lan	Deposit – no data	
Laramie Anorthosite	US	Alkaline	las, mon, ano	Deposit – no data	
Las Chasras	Argentina	No info	las, mon, cha	Prospect	Golden Santa Cruz S.A.
Launceston	Australia	IA deposit		Deposit	Australian Bauxite Ltd
Lavergne-Springer	Canada	Carbonatite	las, mon, spr	Advanced explo.	Canada Rare Earths Corporation
Lavrent'evskii	Russia	Alkaline	las, mon, lav	Deposit – no data	
Layan	Thailand	Heavy mineral sand, river deposits	mon	Production – by-product	
Lemhi Pass	US	Hydrothermal	les, mon, pas	Prospect – on hold	US Rare Earths Inc
Letitia Lake	Canada	Alkaline	les, mon, lak	Prospect	Cornerstone Capital Resources Inc
Leveâniemi	Sweden	Iron-oxide-apatite	apa	Advanced explo. – by-product	LKAB
Leviathan	Australia	No info	les, mon, lev	Prospect	Strategic Elements Ltd
Liancheng	China	No info	No info	Production	Xiamen Tungsten Industry Co. Ltd
Lindsay	Canada	No info	lis, mon, lin	Exploration	X-Terra Resources Inc
Lintang	China	IA deposit		Deposit – no data	
Linwu	China	IA deposit	lis, mon, lin	Advanced explo. – former by-product	
Little Friar Mountain	US	Other- magmatic	all, fer	Advanced explo. – former by-product	
Lizhuang	China	Carbonatite		Deposit – no data	
Llano County	US	Other- magmatic	all, gad, fer	Advanced explo. – former by-product	
Loch Loyal	UK	Alkaline		Deposit	
Lofdal	Namibia	Carbonatite	bas, syn, par	Advanced explo.	Namibia Critical Metals
Lolekek	Uganda	Carbonatite	los, mon, lol	Deposit – no data	
Long Hai	Vietnam	Heavy mineral sand, shore deposits	los, mon, hai	Deposit – no data	
Long Valley	US	Heavy mineral sand, river deposits	mon	Advanced explo. – former by-product	
Longbaoshan	China	Carbonatite		Deposit – no data	
Longchuan Heping	China	IA deposit	los, mon, hep	Production	
Longnan (Zudong)	China	IA deposit	los, mon, zud	Production	People's Republic of China
Longonjo	Angola	Carbonatite	mon, bas	Advanced explo.	Pensana Rare Earths

Locality/project	Country	REE type	REE mineral	Status	License holder
Longyan, Jiangxi	China	IA deposit		Production	Xiamen Tungsten Industry Co. Ltd
Los Archipelago	Guinea	Alkaline	los, mon, arc	Deposit – no data	
Lovozero (loparit deposti)	Russia	Alkaline	loparit	Production	Lovozersky GOK
Ludlow	Australia	Heavy mineral sand, shore deposits	lus, mon, lud	Deposit – no data	
Lugeengol	Mongolia	No info	lus, mon, lug	Advanced explo.	Rare Earth Exporters of Mongolia
Lugin Gol	Mongolia	Carbonatite	bas, syn, par	Exploration	
Luicuisse	Mozambique	Carbonatite (with residual enrichment)	lus, mon, lui	Deposit – no data	
Luokeng	China	Heavy mineral sand	xen, mon, eux	Deposit – no data	
Lupongola	Angola	Carbonatite	lus, mon, lup	Deposit – no data	
Lutaia	Angola	Alkaline	lus, mon, lut	Deposit – no data	
Mabounie	Gabon	Carbonatite (with residual enrichment)	mon, xen, pyro	Exploration	
MacDonald Pegmatite	Canada	Other- magmatic	mas, mon, peg	Deposit – no data	
Macotaia	Mozambique	Other- magmatic	mas, mon, mac	Deposit – no data	
Mactacquac	Canada	No info	mas, mon, mac	Prospect	Edge Exploration
Madianhe	China	Heavy mineral sand, river deposits	mas, mon, mad	Deposit – no data	
Magang	China	Heavy mineral sand, river deposits	mas, mon, mag	Deposit – no data	
Mahgai Khuduk	Mongolia	Carbonatite	mas, mon, khu	Deposit – no data	
Maicuru	Brazil	Carbonatite (with residual enrichment)	mas, mon, mai	Deposit – no data	
Main Khao	Thailand	Heavy mineral sand, river deposits	mas, mon, kha	Deposit – no data	
Makonde	Tanzania	Carbonatite	mas, mon, mak	Deposit – no data	
Makuutu	Uganda	IA deposit	mas, mon, mak	Exploration	Rwenzori Rare Metals/Ionic Rare Earth Ltd
Malilongue	Malawi	No info	mas, mon, mal	Exploration	Great Western Mining Limitada (bancrupt?)
Malmberget	Sweden	Iron-oxide-apatite	apa	Advanced explo. – by-product	
Manavalakurichi	India	Heavy mineral sand, shore deposits	mon	Production	
Mangaroon	Australia	Carbonatite/Laterite			Dreadnought Resources Ltd
Manget Cove	US	Carbonatite (with residual enrichment)	eud, mon	Advanced explo. – former by-product	
Mangyshlak	Kazakhstan	Other – uranium		Deposit – no data	
Mantoushan	China	IA deposit		Deposit	
Maoniuping	China	Carbonatite	bas, mon, all, bri	Production	China Southern Rare Earth Group Co Ltd/ Sichuan Jiangtong Rare Earth Co. Ltd
Maraconai	Brazil	Carbonatite (with residual enrichment)	mas, mon, mar	Deposit – no data	
Marhuanta	Venezuela	Other/ unknown	mas, mon, mar	Deposit – no data	
Marikas Quellen	Namibia	Carbonatite	mas, mon, que	Deposit – no data	
Marion	US	Heavy mineral sand, river deposits	mas, mon, mar	Deposit – no data	
Martison Lake	Canada	Carbonatite (with residual enrichment)	apa	Exploration	
Mary Kathleen	Australia	Hydrothermal	mas, mon, kat	Deposit – no data	
Mashabuto	DRC	Heavy mineral sand, shore deposits	mas, mon, mas	Deposit – no data	
Massidon	Australia	Heavy mineral sand, shore deposits	mas, mon, mas	Deposit – no data	
Matara	Sri Lanka	Heavy mineral sand, shore deposits	mas, mon, mat	Deposit – no data	

Locality/project	Country	REE type	REE mineral	Status	License holder
Mataraca	Brazil	Heavy mineral sand, shore deposits	mas, mon, mat	Exploration	
Matchinskii	Kirgizstan	Carbonatite	mas, mon, mat	Deposit – no data	
Matka Zul	Brazil	No info	mas, mon, zul	Exploration	Canada Rare Earths Corporation
Mato Preto	Brazil	Carbonatite	mas, mon, pre	Deposit – no data	
Matoersyanskii	Ukraine	Alkaline	mas, mon, mat	Deposit – no data	
Matum	Brazil	Carbonatite (with residual enrichment)	mas, mon, mat	Deposit – no data	
Maxville	US	Heavy mineral sand, shore deposits	mas, mon, max	Deposit – no data	
Maybe Canyon	US	Phosphorite	mas, mon, can	Deposit – no data	
Mazurivske	Ukraine	Other- magmatic	mas, mon, maz	Exploration	
Mbeya (Panda Hill)	Tanzania	Carbonatite (with residual enrichment)	bas, mon	Exploration	
McArthur River	Canada	Other – uranium deposits	mcs, mon, riv	Deposit – no data	
McGreath	US	Heavy mineral sand, river deposits	mcs, mon, gre	Deposit – no data	
McLean Lake	Canada	Heavy mineral sand, fossil	mcs, mon, lak	Deposit – no data	
Megiscane Lake	Canada	Carbonatite	mes, mon, lak	Deposit – no data	
Mengwang	China	Heavy mineral sand	mes, mon, men	Deposit – no data	
Meponda	Mozambique	Alkaline	mes, mon, mep	Deposit – no data	
Mfouati	DRC	Other – lead deposit	mfs, mon, mfo	Deposit – no data	
Mi Tho	Vietnam	Heavy mineral sand, shore deposits	mis, mon, tho	Deposit – no data	
Mianning	China	Alkaline	bas, par, mon, cen	Production	Advanced Materials Resources
Miaoya	China	Carbonatite	mon,bas, par, bur	Advanced explo.	n.a.
Miask	Russia	Alkaline	mis, mon, mia	Deposit – no data	
Milenje Hill	Malawi	No info	mis, mon, hil	Prospect	Lotus Resources Ltd
Milne Land	Greenland	Heavy mineral sand	mon, ana, xen	Prospect – on hold	Czech Geological Research Group Ltd
Milo	Australia	Iron-oxide-apatite	app	Advanced explo.	GBM Resources
Minacu	Brazil	No info	mis, mon, min	Prospect	Mineracao Serra Verde
Minami-Tor-ishima	Japan	No info	mis, mon, tor	Prospect	Japan Oil, Gas and Metals National Corporation
Mineral Hill District	US	Metamorphic	mis, mon, dis	Deposit – no data	
Mineral X	US	Other- magmatic		Deposit – no data	
Mineville Dumps	US	Hydrothermal iron oxide	apa	Exploration	
Minniup	Australia	Heavy mineral sand, shore deposits	mon, xen	Production – by-product	
Misværdal	Norway	Alkaline	apa	Exploration	
Mitre Hill	Australia	IA deposit		Exploration	Australian Rare Earths Ltd
Mit-Thawi	Thailand	Heavy mineral sand, river deposits	mon	Production – by-product	
Modot Uul	Mongolia	No info	mos, mon, uul	Exploration	Ar Erkhes
Moebase	Mozambique	Heavy mineral sand, shore deposits	mos, mon, moe	Deposit – no data	
Mogok	Myanmar	Heavy mineral sand, river deposits	mos, mon, mog	Deposit – no data	
Mogwembo	Sierra Leone	Heavy mineral sand, shore deposits	mos, mon, mog	Deposit – no data	
Mokunui	New Zealand	Heavy mineral sand, shore deposits	mos, mon, mok	Deposit – no data	
Momi River	Indonesia	Heavy mineral sand, river deposits	mos, mon, riv	Deposit – no data	
Mong Kung	Myanmar	Heavy mineral sand, river deposits	mos, mon, kun	Deposit – no data	
Monte Muambe	Mozambique	Carbonatite		Deposit	Altona Rare Earths Pls

Locality/project	Country	REE type	REE mineral	Status	License holder
Monte Verde	Angola	Carbonatite	mos, mon, ver	Deposit – no data	
Montviel	Canada	Carbonatite	bas, mon	Exploration	GeoMega Resources
Monumental Summit	US	Metamorphic	mos, mon, sum	Deposit – no data	
Moquiquel	Mozambique	Heavy mineral sand, shore deposits	mos, mon, moq	Deposit – no data	
Morabisi	Guyana	No info	mos, mon, mor	Deposit – no data	
Moreton Island	Australia	Heavy mineral sand, shore deposits	mon	Advanced explo. – former by-product	
Morro dos Seis Lagos	Brazil	Carbonatite (with residual enrichment)	flo	Exploration	
Moshikeng	China	Other/ unknown	mos, mon, mos	Deposit – no data	
Motzfeldt	Greenland	Alkaline	mos, mon, mot	Prospect – on hold	Regenxy Mines Pl
Mount Clere	Australia	Heavy mineral sand	leu	Prospect	Krakatoa Resources Ltd
Mount Mansbridge	Australia	hydrothermal	xen	Prospect	Red Mountain Mining Ltd
Mount Prindle	US	Alkaline	mos, mon, pri	Deposit – no data	
Mount Ridley	Australia	IA deposit		Exploration	Mount Ridley Mines
Mount St. Hilaire	Canada	Alkaline	mos, mon, hil	Deposit – no data	
Mount Weld, Duncan	Australia	Carbonatite	mon, chu, xen, flor, goy	Production	Lynas Corporation
Mountain Fuel	US	Phosphorite	mos, mon, fue	Deposit – no data	
Mountain Pass	US	Carbonatite	bas, par, mon, sah, all	Production	MP Materials/ Bhang Inc
Mrima Hill	Kenya	Carbonatite	mon, gor, goy	Advanced explo.	Pacific Wildcat Resources Corp
Mt. Isa	Australia	No info	mts, mon, isa	Advanced explo.	Cloncurry Exploration and Development Pty Ltd
Mt. Mansbridge/ Killi-Kill	Australia	No info	xen	Exploration	Red Mountain Mining Ltd
M'Tomoti	Mozambique	Other - magmatic	m's, mon, tom	Deposit – no data	
Mulanje	Malawi	IA deposit	mus, mon, mul	Prospect	Altona Rare Earths Plc. Akatswiri Rare Earths
Mulas	Spain	No info	mon	Prospect	
Mullaittivu	Sri Lanka	Heavy mineral sand, shore deposits	mus, mon, mul	Deposit – no data	
Muluo	China	Carbonatite		Deposit – no data	
Muluo Diaolou Shang	China	No info	No info	Production	China Southern Rare Earth Group Co Ltd
Muluo Zhengjia Liangzi	China	No info	No info	Production	China Southern Rare Earth Group Co Ltd
Munmorah	Australia	Heavy mineral sand, shore deposits	mon	Advanced explo. – former by-product	
Muong Hum	Vietnam	Heavy mineral sand, river deposits	mus, mon, hum	Advanced explo.	Government of Vietnam
Mushgia Khudug	Mongolia	Carbonatite	mus, mon, khu	Advanced explo.	Mongol Group LLC (Mongolian Mining Co.)
Music Valley	US	Metamorphic	mus, mon, val	Deposit – no data	
Mutum	Brazil	Alkaline	mus, mon, mut	Deposit – no data	
Nabiac	Australia	Heavy mineral sand, shore deposits	mon	Advanced explo. – former by-product	
Naboomspruit	South Africa	Carbonatite	nas, mon, nab	Deposit – no data	
Nagyharsany	Hungary	Laterite	bas	Deposit – no data	
Nam Xe	Vietnam	Metamorphic/Laterite		Advanced explo.	Government of Vietnam
Nam Xe North (Mau Xe North)	Vietnam	Metamorphic	nas, mon, mau	Deposit – no data	
Namdaecheon River	South Korea	Heavy mineral sand, river deposits	nas, mon, riv	Deposit – no data	
Namo-Vara	Russia	Carbonatite	nas, mon, var	Deposit – no data	

Locality/project	Country	REE type	REE mineral	Status	License holder
Nanqiao	China	IA deposit		Deposit – no data	
Nanshanxia	China	Heavy mineral sand, shore deposits	mon, xen	Prospect	
Nanyang	China	Heavy mineral sand, shore deposits	mon, xen	Production	Peoples Republic of China
Naracoopa	Australia	Heavy mineral sand, shore deposits	nas, mon, nar	Deposit – no data	
Narngula	Australia	Heavy mineral sand, shore deposits	mon	Production – by-product	
Narraburra	Australia	No info	nas, mon, nar	Exploration	Paradigm Resources Pty Ltd
Nassuttutatasia	Greenland	No info		Deposit – no data	
Natchez	US	Heavy mineral sand, shore deposits	nas, mon, nat	Deposit – no data	
Nayaru	Sri Lanka	Heavy mineral sand, shore deposits	nas, mon, nay	Deposit – no data	
Nea Peramos	Greece	Heavy mineral sand	mon, all	Exploration	
Nechalacho (Thor Lake)	Canada	Alkaline	bas, mon, all, fer, eud	Advanced explo.	Avalon Advanced Materials
Nechalacho Upper	Canada	Alkaline	bas, mon, all, fer	Mine development	Vital Metals Ltd
Nejoio	Angola	Alkaline	nes, mon, nej	Deposit – no data	
Nemgosenda Lake	Canada	Alkaline	pyro	Exploration	
Nettuno	Italy	Heavy mineral sand		Deposit	
Newcastle	Australia	Heavy mineral sand, shore deposits	mon	Production – by-product	
Newybar	Australia	Heavy mineral sand, shore deposits	nes, mon, new	Deposit – no data	
Ngualla Hill	Tanzania	Carbonatite	bas, mon	Advanced explo.	Peak Resources Ltd
Nha Trang	Vietnam	Heavy mineral sand, shore deposits	nhs, mon, tra	Deposit – no data	
Niaqornakavsak	Greenland	Metamorphic	bas, mon, all	Prospect – on hold	
Nijhum Dwip	Bangladesh	Heavy mineral sand, shore deposits	nis, mon, dwi	Deposit – no data	
Niksic	Montenegro	Laterite	bas	Deposit – no data	
Niobec	Canada	Carbonatite	nis, mon, nio	Advanced explo.	Magris Resources Inc; Commerce Resources
Nipissis	Canada	Other- magmatic	nis, mon, nip	Deposit – no data	
Nisikkatch	Canada	Carbonatite		Deposit	
Niulanyong	China	Heavy mineral sand	mon	Deposit – no data	
Nizhenesaynskii	Russia	Carbonatite	nis, mon, niz	Deposit – no data	
Nkombwa Hill	Zambia	Carbonatite	bas	Advanced explo.	African Consolidated Resources ?/Vast?
No. 101	China	Other/ unknown	nos, mon, no.	Deposit – no data	
Nolans Bore	Australia	Hydrothermal/Carbonatite	all, apa, bas, mon	Advanced explo.	Arafura Resources
Nooitgedacht	South Africa	Carbonatite	nos, mon, noo	Deposit – no data	
Norberg	Sweden	Hydrothermal		Exploration	
Norra Kärr	Sweden	Alkaline	eud	Advanced explo. (on hold)	Leading Edge Materials Corp
North Camden	US	Heavy mineral sand, shore deposits	nos, mon, cam	Deposit – no data	
North Fork Area	US	Carbonatite	nos, mon, are	Deposit – no data	
North Henry	US	Phosphorite	nos, mon, hen	Deposit – no data	
North Stradbroke	Australia	Heavy mineral sand, shore deposits	mon	Advanced explo. – by-productFormer by-product	
Northeast Dunes	Brazil	Heavy mineral sand, shore deposits	nos, mon, dun	Exploration	
Nosy Komba	Madagascar	Alkaline	nos, mon, kom	Deposit – no data	
Nsengwa	Malawi	Carbonatite	nss, mon, nse	Deposit – no data	
Nungan Gilgai	Australia	No info	nus, mon, gil	Advanced explo.	
Nurra	Italy	Laterite	bas	Deposit	

Locality/project	Country	REE type	REE mineral	Status	License holder
Nuware Eliya	Sri Lanka	Other- magmatic	nus, mon, eli	Deposit – no data	
Naantali	Finland	Carbonatite		Deposit	
Oak Grove	US	Heavy mineral sand, fossil	oas, mon, gro	Deposit – no data	
Odegarden	Norway	Other- magmatic	ods, mon, ode	Deposit – no data	
Oka	Canada	Carbonatite (with residual enrichment)	bri, apa	Exploration – by-product	
Okarito	New Zealand	Heavy mineral sand, shore deposits	oks, mon, oka	Deposit – no data	
Okurusu Complex	Namibia	Carbonatite	syn, mon, Xen	Production	
Old Hickory	US	Heavy mineral sand, shore deposits	mon	Production – by-product	
Olety Ruchey	Russia	No info	ols, mon, ruc	Prospect	PJSC Acron
Olserum	Sweden	Hydrothermal	ols, mon, ole	Advanced explo.	Leading Edge Materials Corp
Olympic Dam	Australia	Iron-oxide-copper-gold	mon, bas, xen	Production – by-product	BHP
Ondurakorume	Namibia	Carbonatite		Deposit – no data	
Onemile Creek	US	Heavy mineral sand, fossil	ons, mon, cre	Deposit – no data	
Orissa	India	Heavy mineral sand	mon	Mine development	Indian Rare Earths Ltd. (IREL)
Otjiwarongo	Namibia	Carbonatite	ots, mon, otj	Prospect	Namibia Critical Metals Inc.
Owelle	Sri Lanka	Other/ unknown	ows, mon, owe	Deposit – no data	
Owendale	Australia	Laterite	ows, mon, owe	Exploration	Platina Resources Ltd
Pajarito Mountain	US	Alkaline	eud, mon, apa	Exploration	
Pang War	Myanmar	No info	pas, mon, war	Prospect	
Panichara	Bangladesh	Heavy mineral sand, shore deposits	pas, mon, pan	Deposit – no data	
Paranagua	Brazil	Heavy mineral sand, shore deposits	pas, mon, par	Deposit – no data	
Parnassus	Greece	Laterite	bas	Deposit – no data	
Pea Ridge	US	Hydrothermal Fe-oxide	pes, mon, red	Deposit – no data	
Pearsol Creek	US	Heavy mineral sand, river deposits	pes, mon, cre	Advanced explo.	n.a.
Pebane	Madagascar	Heavy mineral sand, shore deposits	mon	Production – by-product	
Peitungshanchow	Taiwan	Heavy mineral sand, shore deposits	pes, mon, pei	Deposit – no data	
Penco	Chile	IA deposit	pes, mon, pen	Exploration	Aclara / Hochschield Mining
Perak	Malaysia	Heavy mineral sand			
Petaca District	US	Other- magmatic	pes, mon, dis	Deposit – no data	
Petäiskoski	Finland	Carbonatite		Deposit	
Phalabowra	South Africa	Carbonatite	app	Advanced explo.	Rainbow Rare Earth
Phan thiet	Vietnam	Heavy mineral sand, shore deposits	phs, mon, pha	Deposit – no data	
Phuket	Thailand	Heavy mineral sand, shore deposits	mon, xen	Production – by-product	
Pi-In	South Korea	Heavy mineral sand, shore deposits		Deposit – no data	
Pilanesberg Complex	South Africa	Alkaline	eud, fer, bri	Prospect	n.a.
Pingyuan	China	IA deposit	pis, mon, pin	Production	
Pinkanba	Australia	No info	mon	Advanced explo. – former by-product	
Pitinga	Brazil	Heavy mineral sand, shore deposits	xe, Y-Nb	Advanced explo. – by-product	
Plavna	Romania	No info	mon	Prospect	
Ploskaya Mountain	Russia	Other- magmatic	pls, mon, mou	Deposit – no data	
Pocos de Caldas	Brazil	Alkaline	all, bas, eud, cer	Prospect	Industrias Nucleares Do Brasil SA
Poert Pirie	Australia	Other – uranium deposits	pos, mon, pir	Deposit – no data	

Locality/project	**Country**	**REE type**	**REE mineral**	**Status**	**License holder**
Polkotuwa	Sri Lanka	Heavy mineral sand, shore deposits	mon	Production – by-product	
Pomona Tile	US	Other- magmatic	pos, mon, til	Deposit – no data	
Ponoiskii	Russia	Alkaline	pos, mon, pon	Deposit – no data	
Ponton	Australia	No info	pos, mon, pon	Exploration	
Port Clarence	US	Heavy mineral sand, river deposits	pos, mon, cla	Deposit – no data	
Port Clinton	Australia	Heavy mineral sand, shore deposits	pos, mon, cli	Deposit – no data	
Porto Sequro	Brazil	Heavy mineral sand, shore deposits	mon	Advanced explo. – former by-product	
Prachuap Khiri Khan	Thailand	Heavy mineral sand, shore deposits	mon, xen	Production – by-product	
Prado Area	Brazil	Heavy mineral sand, shore deposits	prs, mon, pra	Deposit – no data	
Prairie Lake	Canada	Carbonatite	apa	Prospect	Nuinsco Resources Ltd
Prowse	Australia	Heavy mineral sand, shore deposits	prs, mon, pro	Deposit – no data	
Pudavakattu	Sri Lanka	Heavy mineral sand, shore deposits	pus, mon, pud	Deposit – no data	
Pulau Bangka	India	No info	pus, mon, ban	Prospect	Artisenal mining
Pump Lake	Canada	No info	pus, mon, lak	Exploration	Goldstar Minerals Corp.
Putaichow	Taiwan	Heavy mineral sand, shore deposits	pus, mon, put	Deposit – no data	
Puyi	China	Laterite		Advanced explo.	
Qaqarssuk	Greenland	Carbonatite	anc, bur, hua	Prospect – on hold	
Qeqertaasaq	Greenland	Carbonatite	qes, mon, qeq	Prospect – on hold	? Korea Resources Corp.
Qiganlaing	China	Alkaline	apa, all	Exploration	
Qingyuan	China	IA deposit	qis, mon, qin	Production	
Qinzhou	China	Heavy mineral sand, river deposits	mon	Production – by-product	
Quang Ngan	Vietnam	Heavy mineral sand, shore deposits	qus, mon, nga	Deposit – no data	
Quelemane	Mozambique	Heavy mineral sand, shore deposits	qus, mon, que	Deposit – no data	
Qui Nhon	Vietnam	Heavy mineral sand, shore deposits	qus, mon, nho	Deposit – no data	
Rainbow Beach	Australia	Heavy mineral sand, shore deposits	mon	Advanced explo. – former by-product	
Ramblas de las Granatillia	Spain	No info	mon, xen	Exploration	
Ramey Meadows	US	Heavy mineral sand, river deposits	ras, mon, mea	Deposit – no data	
Ranchi-Purulia	India	Heavy mineral sand, river deposits	mon	Advanced explo.	n.a.
Ranong	Thailand	Heavy mineral sand, shore deposits	mon, xen	Production – by-product	
Ravilii	US	Carbonatite	ras, mon, rav	Deposit – no data	
Red Wine	Canada	Alkaline	res, mon, win	Deposit – no data	
Renju	China	IA deposit	xen, zir	Advanced explo.	Rising Nonferrous Metals Share Co. Ltd
Revda, Murmansk	Russia	Alkaline	lop	Prospect	
Rexspar	Canada	Alkaline	res, mon, rex	Deposit – no data	
Richards Bay	South Africa	Heavy mineral sand, shore deposits	ris, mon, bay	Deposit – no data	
Riddarhyttan-Bastnäs	Sweden	Carbonatite		Deposit	
RioTercero	Argentina	Heavy mineral sand, river deposits	ris, mon, ter	Advanced explo.	n.a.
Rock Canyon Creen	Canada	Hydrothermal	ros, mon, cre	Deposit – no data	

Locality/project	Country	REE type	REE mineral	Status	License holder
Rodeo de Los Molles	Argentina	Other/ unknown	ros, mon, mol	Advanced explo.	Wealth Minerals Ltd
Ross	New Zealand	Heavy mineral sand, shore deposits	ros, mon, ros	Deposit – no data	
Round Top	US	Alkaline	bas, xen	Advanced explo.	US Rare Earth (80 %) JV Texas Rare Earth Resources (20 %)
Ruby Meadows	US	Heavy mineral sand, river deposits	rus, mon, mea	Deposit – no data	
Rudnica	Croatia	Laterite	bas	Deposit – no data	
Ruri Complex	Kenya	Carbonatite (with residual enrichment)	mon, bas, eud	Exploration	
Rusheng	China	IA deposit	rus, mon, rus	Deposit – no data	
Sai-Chon	Thailand	Heavy mineral sand, river deposits	sas, mon, cho	Deposit – no data	
Sai-Lao	China	Heavy mineral sand, shore deposits	mon	Production – by-product	
Saima	China	Alkaline	rin,mos, kop, eud	Exploration	
Saint Honore	Canada	Carbonatite	sas, mon, hon	Prospect	Magris Resources Inc/Niobec Inc./ Commerce Resources
Sakagyi	Myanmar	Heavy mineral sand, river deposits	sas, mon, sak	Deposit – no data	
Sakhariokskii	Russia	Alkaline	sas, mon, sak	Deposit – no data	
Salitre I	Brazil	Carbonatite		Deposit – no data	
Sallanlatvi	Russia	Carbonatite (with residual enrichment)	sas, mon, sal	Deposit – no data	
Salmon Bay	US	Carbonatite	sas, mon, bay	Deposit – no data	
Samcheon	North Korea	No info	sas, mon, sam	Deposit – no data	No info
San Antonio	Venezuela	Other/ unknown	sas, mon, ant	Deposit – no data	
San Giovanni Rotondo	Italy	Laterite	bas	Deposit – no data	
San Venanzo	Italy	Carbonatite		Deposit – no data	
Sanchahe	China	Carbonatite	No info	Production	n.a.
Sandalwood	Australia	Heavy mineral sand, shore deposits	mon	Production – by-product	
Sangu	Tanzania	Carbonatite	sas, mon, san	Deposit – no data	
Sanlangyan	China	Other/ unknown	sas, mon, san	Deposit – no data	
Sanming	China	No info	sas, mon, san	Prospect	Xiamen Tungsten Industry Co. Ltd
Sao Goncalo do Sapucai	Brazil	Heavy mineral sand, river deposits	sas, mon, sap	Exploration	
sao Joao de Barr	Brazil	Heavy mineral sand, shore deposits	sas, mon, bar	Exploration	
Sao Meteus	Brazil	Heavy mineral sand, shore deposits	sas, mon, met	Deposit – no data	
Sao Sebastio de Bela Vista	Brazil	Other/ unknown	sas, mon, vis	Deposit – no data	
Sarakiniko	Greece	Laterite	mon, all	Exploration	
Sarfartoq	Greenland	Carbonatite	bas, syn, mon	Exploration - on hold	Hudson Resources
Sarnu	India	Carbonatite	sas, mon, sar	Deposit – no data	
Saulia	DRC	Other/ unknown	sas, mon, sau	Deposit – no data	
Schevchenko	Kazakhstan	Phosphorite	scs, mon, sch	Production – by-product	
SCONI	Australia	No info		Exploration	Metallica Minerals Ltd/ Australian Mines Ltd
Scrup Oaks	US	Hydrothermal iron oxide	scs, mon, oak	Deposit – no data	
Se Petiba	Brazil	Heavy mineral sand, shore deposits	ses, mon, pet	Deposit – no data	
Sebi Yavr	Russia	Carbonatite (with residual enrichment)	ses, mon, yav	Deposit – no data	
Sedisehir	Turkey	Laterite	bas	Deposit – no data	
Seligdar	Russia	Carbonatite	apa, mon, all	Exploration	

Locality/project	Country	REE type	REE mineral	Status	License holder
Serra Jacareipe	Brazil	Heavy mineral sand, shore deposits	ses, mon, jac	Deposit – no data	
Serra Negra	Brazil	Carbonatite (with residual enrichment)	apa, ana	Advanced explo. – by-product	
Serra Verde	Brazil	IA deposit	ses, mon, ver	Exploration	Mining Vent ures Brasil Ltda/ Innovation Metals Corp (CND)
Shallow Lake	Canada	Alkaline	shs, mon, lak	Deposit – no data	
Shanghang	China	No info	shs, mon, sha	Prospect	Xiamen Tungsten Industry Co. Ltd
Shartolgoi	Mongolia	Alkaline	shs, mon, sha	Deposit – no data	
Shatou	China	IA deposit		Deposit – no data	
Sheep Creek	US	Metamorphic	shs, mon, cre	Advanced explo. – former by-product	
Shenggonzhai	China	No info	shs, mon, she	Prospect	Minmetals Rare Earth Co. Ltd
Shengtieling	China	Metamorphic	shs, mon, she	Deposit – no data	
Shilhali	Bangladesh	Heavy mineral sand, shore deposits	shs, mon, shi	Deposit – no data	
Shuitai	China	Other/ unknown	shs, mon, shu	Deposit – no data	
Shvanidzorksi	Armenia	Alkaline	shs, mon, shv	Deposit – no data	
Sichuan	China	Carbonatite	sis, mon, sic	Exploration	
Sierra de Tamulipas	Mexico	Alkaline	sis, mon, tam	Deposit – no data	
Silinjarvi	Finland	Carbonatite	apa	Exploration	Magnus Minerals Ltd
Simon's Find	Australia	Carbonatite/Laterite	mon	Exploration	Hastings Technology Metals
Singkep	Indonesia	Heavy mineral sand, shore deposits	mon, xen, all	Advanced explo. – former by-product	
Sin-Krasom	Thailand	Heavy mineral sand, river deposits	sis, mon, kra	Deposit – no data	
Sishui	China	IA deposit		Deposit	
Sitaduwei	China	Carbonatite		Deposit	
Skjoldungen	Greenland	Alkaline		Deposit	
Slupsk	Poland	Heavy mineral sand, shore deposits	sls, mon, slu	Deposit – no data	
Smoky Canyon	US	Phosphorite	sms, mon, can	Deposit – no data	
Snowbird	US	Hydrothermal	sns, mon, sno	Deposit – no data	
Sofular	Turkey	Carbonatite		Exploration	
Sokli	Finland	Carbonatite (with residual enrichment)	anc, bas, all	Advanced explo.	
Sokolo	Kenya	Carbonatite	sos, mon, sok	Deposit – no data	
Soledad	US	Heavy mineral sand, shore deposits	sos, mon, sol	Deposit – no data	
Songwe Hills	Malawi	Carbonatite	bas, mon, syn, par	Exploration	Mkango Resources
Soroy	Norway	Carbonatite	sos, mon, sor	Deposit – no data	
Soun-Miyan	South Korea	Heavy mineral sand, river deposits	sos, mon, miy	Deposit – no data	
South Ham Tam	Vietnam	Heavy mineral sand, shore deposits	sos, mon, tam	Deposit – no data	
South Platte District	US	Other- magmatic	sos, mon, dis	Deposit – no data	
Southeast Guangdong	China	No info	Xenotim	Deposit – no data	
Southern Malyan Batu Gajah Mine	Malaysia	Heavy mineral sand, river deposits	mon	Production – by-product	
Springer Lavergne	Canada	Carbonatite	sps, mon, lav	Deposit – no data	
Srednetatarskii	Russia	Alkaline	srs, mon, sre	Deposit – no data	
Srednevorogovskii	Russia	Alkaline	srs, mon, sre	Deposit – no data	
St. Honore (Niobec)	Canada	Carbonatite	bas, pyro, par, mon	Advanced explo. - by-product	IAMGOLD Ltd

Locality/project	Country	REE type	REE mineral	Status	License holder
Steenkampskral	South Africa	Hydrothermal	mon	Advanced explo.	Great Western Minerals /Steenkampskraal Monazite Mine Ltd
Stepnogorsk	Kazakhstan	Uranium mine – tailings	sts, mon, ste	Production	JV: Sumitomo + Kazatomprom
Stjernoy	Norway	Carbonatite	sts, mon, stj	Exploration	
Stockton	Australia	Heavy mineral sand, shore deposits	mon	Advanced explo. – former by-product	
Storkwitz (Delizsch)	Germany	Carbonatite	par, ron, apa	Advanced explo.	Deutsche Rohstoff AG
Strange Lake	Canada	Alkaline	all, bas, mon, pyr	Advanced explo.	Quest Rare Minerals Ltd/Tongat Metals Inc.
Stratham South	Australia	Heavy mineral sand, shore deposits	mon	Advanced explo. – former by-product	
Subrang	Bangladesh	Heavy mineral sand, shore deposits	sus, mon, sub	Deposit – no data	
Sucunduri	Brazil	Alkaline	sus, mon, suc	Deposit – no data	
Sudbury	Canada	Other/ unknown	sus, mon, sud	Deposit – no data	
Sugar Loaf	Zambia	Alkaline	sus, mon, loa	Deposit – no data	
Sukulu	Uganda	Carbonatite (with residual enrichment)	apa, mag	Exploration	
Swan Lake Gulch	US	Phosphorite	sws, mon, gul	Exploration	
Synnyr	Russia	Alkaline	sys, mon, syn	Deposit – no data	
Sæteråsen	Norway	Alkaline	eux, fer, apa	Exploration	
Tajno	Poland	Carbonatite		Deposit	
Takua Pa	Thailand	Heavy mineral sand, shore deposits		Deposit – no data	
Tamezeght	Morocco	Alkaline	tas, mon, tam	Deposit – no data	
Tanami	Australia	No info		Prospect	PVW Resources Ltd
Tanmen	China	Other/ unknown	tas, mon, tan	Deposit – no data	
Tantalus	Madagascar	Iron-oxide-apatite	bas, syn, pa.	Advanced explo.	Tantalus Rare Earths AG/Reenova Investment Holding Ltd
Taohualashan	China	Other/ unknown	tas, mon, tao	Deposit – no data	
Taohulashan	China	Carbonatite	tas, mon, tao	Exploration	
Tapira	Brazil	Carbonatite (with residual enrichment)	ana, hap	Advanced explo. - by-product	
Tareietau	Guyana	Carbonatite (with residual enrichment)	tas, mon, tar	Deposit – no data	
Tchivira	Angola	Carbonatite (with residual enrichment)	tcs, mon, tch	Deposit – no data	
Teknaf	Bangladesh	Heavy mineral sand, shore deposits	tes, mon, tek	Deposit – no data	
Teldeniya	Sri Lanka	Other- magmatic	tes, mon, tel	Deposit – no data	
Telixlahuaca	Mexico	Other- magmatic	tes, mon, tel	Deposit – no data	
Tezhsar	Armenia	Alkaline	tes, mon, tez	Deposit – no data	
Thawi-thap	Thailand	Heavy mineral sand, river deposits	mon	Production – by-product	
Tianzhuping Sha'ebo	China	No info	tis, mon, sha	Advanced explo.	Ganzhou Mining Group
Tie Siding	US	Other- magmatic	tis, mon, sid	Deposit – no data	
Tiejincun	China	Laterite		Deposit	
Tigusmat el akhdar	Mauritania	Alkaline	tis, mon, tig	Deposit – no data	
Tiiembetskii	Kazakhstan	Alkaline	tis, mon, tii	Deposit – no data	
TikiUSaq	Greenland	Carbonatite	tis, mon, tik	Prospect - on hold	
Tikshozerskii	Russia	Carbonatite	tis, mon, tik	Deposit – no data	
Timukkovil	Sri Lanka	Heavy mineral sand, shore deposits	tis, mon, tim	Deposit – no data	
Tingtouechow	Taiwan	Heavy mineral sand, shore deposits	tis, mon, tin	Deposit – no data	

Locality/project	Country	REE type	REE mineral	Status	License holder
Toisuk	Russia	Carbonatite	tos, mon, toi	Deposit – no data	
Tolgnaro	Madagascar	Heavy mineral sand, shore deposits	mon	Exploration	
Tolovana	US	Heavy mineral sand, river deposits	tos, mon, tol	Deposit – no data	
Tomago	Australia	Heavy mineral sand, shore deposits	mon	Advanced explo. – former by-product	
Tommot	Russia	Alkaline	tos, mon, tom	Deposit – no data	
Tomtorskoye	Russia	Carbonatite (with residual enrichment)	flo, mon, xen, bas	Advanced explo.	ThreeArc Mining LLC
Tongsalin	China	IA deposit	tos, mon, ton	Production	
Topsails	Canada	Alkaline	tos, mon, top	Deposit – no data	
Toscanni	Namibia	Heavy mineral sand, shore deposits	tos, mon, tos	Deposit – no data	
Trail Creek	US	Phosphorite	trs, mon, cre	Deposit – no data	
Trail Ridge	US	Heavy mineral sand, shore deposits	trs, mon, rid	Deposit – no data	
TRE Project	Madagascar	Alkaline/Laterite		Exploration	Tantalus Rare Earths AG/Reenova Investment Holding Ltd
Trebic	The Czech Republic	Alkaline		Deposit	
Trivandrum	India	Heavy mineral sand, shore deposits	trs, mon, tri	Deposit – no data	
Tronoh Mines	Malaysia	Heavy mineral sand, river deposits	mon	Production – by-product	
Tsakhirt	Mongolia	Alkaline	tss, mon, tsa	Deposit – no data	
Tuanshuitou	China	Laterite		Advanced explo.	
Tundulu	Malawi	Carbonatite	tus, mon, tun	Deposit – no data	
Tungshanchow	Taiwan	Heavy mineral sand, shore deposits	tus, mon, tun	Deposit – no data	
Tupertalik	Greenland	Carbonatite		Deposit	
Tutunup	Australia	Heavy mineral sand, shore deposits	tus, mon, tut	Deposit – no data	
Two Tom (Red Wine)	Canada	Alkaline	mon; fer	Exploration	Canada Rare Earths Corporation
Tysfjord	Norway	Alkaline		Deposit	
Tåsjö	Sweden	Other – uranium	apa	Prospect	
Ulkanshoe	Russia	Alkaline	uls, mon, ulk	Deposit – no data	
Ulug-Tanzek	Russia	Hydrothermal		Prospect	
Ulaan Tolgoi	Mongolia	Alkaline	uls, mon, tol	Deposit – no data	
Umgaba	South Africa	Other/ unknown	ums, mon, umg	Deposit – no data	
Umm al Birak	Saudi Arabia	Alkaline	ums, mon, bir	Deposit – no data	
Unsan	North Korea	Other/ unknown	uns, mon, uns	Deposit – no data	
Urumqi	China	Other/ unknown	urs, mon, uru	Deposit – no data	
Usssangoda	Sri Lanka	Heavy mineral sand, shore deposits	uss, mon, uss	Deposit – no data	
Uyaynah	United Arab Emirates	Carbonatite	uys, mon, uya	Deposit – no data	
Valle Fertil	Argentina	Other- magmatic	vas, mon, fer	Deposit – no data	
Vedi-Azatskii	Armenia	Alkaline	ves, mon, aza	Deposit – no data	
Vekhnesayanskii	Russia	Carbonatite	ves, mon, vek	Deposit – no data	
Venturi	Canada	Carbonatite	ves, mon, ven	Deposit – no data	
Vero Beach	US	Heavy mineral sand, shore deposits	mon, xen	Advanced explo. – former by-product	
Vichada project	Columbia	Heavy mineral sand	n.a.	Prospect	Auxico Resources Canada Inc.
Viney Creek	Australia	Heavy mineral sand, shore deposits	vis, mon, cre	Deposit – no data	
Vinh Cam Ranh	Vietnam	Heavy mineral sand, shore deposits	vis, mon, ran	Deposit – no data	
Vinh Giat	Vietnam	Heavy mineral sand, shore deposits	vis, mon, gia	Deposit – no data	
Virulundo	Angola	Carbonatite	vis, mon, vir	Deposit – no data	

Locality/project	Country	REE type	REE mineral	Status	License holder
Vishnevye	Russia	Carbonatite	vis, mon, vis	Deposit – no data	
Vitoria District	Brazil	Heavy mineral sand, shore deposits	mon	Production – by-product	
Vlsenica	Bosnia-Herzegovina	Laterite	bas	Deposit – no data	
Vohibarika	Madagascar	Heavy mineral sand, shore deposits	vos, mon, voh	Deposit – no data	
Vung Tau	Vietnam	Heavy mineral sand, shore deposits	vus, mon, tau	Deposit – no data	
Vuoriyarvi	Russia	Carbonatite	vus, mon, vuo	Deposit – no data	
Västervik	Sweden	Heavy mineral sand		Deposit	
Västervik	Sweden	Heavy mineral sand		Deposit – no data	
Wadi el Sahrm	Egypt	Other/ unknown	was, mon, sah	Deposit – no data	
Waisantingchow	Taiwan	Heavy mineral sand, shore deposits	was, mon, wai	Deposit – no data	
Wajilitage	China	Carbonatite	mon, bas	Exploration	
Wako Bussan Co	India	Heavy mineral sand	mon	Mine development	Toyota Tsusho Corp.
Wan Hapalam	Myanmar	Heavy mineral sand, river deposits	was, mon, hap	Deposit – no data	
Wangtzeliaochow	Taiwan	Heavy mineral sand, shore deposits	was, mon, wan	Deposit – no data	
Wangu Hill	South Africa	Alkaline	was, mon, hil	Deposit – no data	
Wangyehchow	Taiwan	Heavy mineral sand, shore deposits	was, mon, wan	Deposit – no data	
Warm Spring Creek	US	Heavy mineral sand, river deposits	was, mon, cre	Deposit – no data	
Waroona	Australia	Heavy mineral sand, shore deposits	mon	Advanced explo. – former by-product	
Wedderburn	Australia	Heavy mineral sand	mon	Exploration	WIM Ressource Pty
Weishanhu	China	Alkaline	bas, par, bri, cer, mon, anc	Production	
Weishanhu, Shandong	China	Alkaline	bas	Exploration	
Wemen	Australia	Heavy mineral sand, shore deposits	mon	Exploration	
Weres, Seigneurie, Sophie, Reine J6L1	Canada	No info		Prospect	
Westcriffe	US	Carbonatite	wes, mon, wes	Deposit – no data	
Westen Keiv	Russia	Alkaline	wes, mon, kei	Deposit – no data	
Wet Mountains	US	Carbonatite	wes, mon, mou	Advanced explo.	U.S. Rare Earths Inc.
Wheeler River	Canada	Heavy mineral sand, fossil	whs, mon, riv	Deposit – no data	
Whiste Tundra	Russia	Alkaline	whs, mon, tun	Deposit – no data	
Wicheeda	Canada	Carbonatite	wis, mon, wic	Exploration	Defense Metals Corp/Marvel Discovery Corp.
Wigu Hill	Tanzania	Carbonatite (with residual enrichment)	bas, mon, syn, par	Exploration	Montero Mining & Exploration /Vital Metals
Williams Lake	Canada	Heavy mineral sand, fossil	wis, mon, lak	Deposit – no data	
Williamstown	Australia	Heavy mineral sand, shore deposits	wis, mon, wil	Deposit – no data	
WIM 150	Australia	Heavy mineral sand, shore deposits	mon, xen	Advanced explo.	Murray Zircon Pty Ltd
Wimmera	Australia	Heavy mineral sand	mon	Exploration	Iluka Resources
Wind Mountain	US	Alkaline	wis, mon, mou	Deposit – no data	
Witchit	Thailand	Heavy mineral sand, river deposits	wis, mon, wit	Deposit – no data	
Witwatersrand	South Africa	Heavy mineral sand, fossil	wis, mon, wit	Deposit – no data	
Wlgevonden	South Africa	Carbonatite	wls, mon, wlg	Deposit – no data	
Wolf Mountain	US	Other- magmatic	wos, mon, mou	Deposit – no data	
Wolverine (Browns Range)	Australia	Hydrothermal	xen	Mine development	Northern Minerals

Locality/project	Country	REE type	REE mineral	Status	License holder
Wonneup	Australia	Heavy mineral sand, shore deposits	wos, mon, won	Deposit – no data	
Wooley Valley	US	Phosphorite	wos, mon, val	Deposit – no data	
Woornack	Australia	Heavy mineral sand, shore deposits	wos, mon, woo	Exploration	
Wufang	China	IA deposit		Deposit	
Wuhe	China	Metamorphic	wus, mon, wuh	Deposit – no data	
Wuzhaung (Baoding)	China	Heavy mineral sand, shore deposits	mon	Production – by-product	
Wuzhou	China	Other/ unknown	wus, mon, wuz	Deposit – no data	
Xiangwang	China	Laterite (bauxite)		Production ??	
Xihuashan	China	Other - magmatic	gad, fer, mon, eux	Production	
Xiluvo	Mozambique	Carbonatite	mon	Advanced explo.	Promac Lda/Southern Crown Resources JV-partner Galileo Resources ????
Xinfeng, Jiangxi	China	IA deposit		Production ??	
Xing'an	China	Other/ unknown	xis, mon, xin	Deposit – no data	
Xinglong	China	Heavy mineral sand, shore deposits	mon	Production – by-product	
Xinhua	China	Phosphorite	xis, mon, xin	Deposit – no data	
Xintou	China	Heavy mineral sand, river deposits	xis, mon, xin	Deposit – no data	
Xishan	China	No info	No info	Production	No info
Xitou	China	Heavy mineral sand, shore deposits	mon	Production – by-product	
Xiuwen	China	Laterite	xis, mon, xiu	Deposit – no data	
Xuanwu 1	China	IA deposit	xus, mon, xua	Production	Ganzhou Mining Group
Xuanwu 2	China	IA deposit	xus, mon, xua	Production	Ganzhou Mining Group
Xueshan	China	Other/ unknown	xus, mon, xue	Deposit – no data	
Xun Jiang	China	Heavy mineral sand, river deposits	xus, mon, jia	Exploration	
Xunwun/Longnan	China	IA Deposit	xus, mon, xun	Deposit – no data	
Yadanabon Mine	Myanmar	Heavy mineral sand, river deposits	yas, mon, min	Deposit – no data	
Yangdun	China	Carbonatite	yas, mon, yan	Deposit – no data	
Yangibana North	Australia	Carbonatite/Laterite	bas, mon, syn, par	Advanced explo.	Hastings Technology Metals/Cadence Minerals Plc
Yangpokeng	China	IA deposit		Advanced explo.	
Yanjiang (Nanshanhai)	China	Heavy mineral sand, shore deposits	mon, xen	Production – by-product	
Yarega	Russia	No info		Prospect	
Yarloop	Australia	Heavy mineral sand, shore deposits	mon	Exploration	
Yarraman	Australia	Heavy mineral sand, shore deposits	mon, xen	Exploration	
Yastrebets	Ukraine	Alkaline	yas, mon, yas	Deposit – no data	
Yeehaw	Canada	No info	yes, mon, yee	Prospect	Lithium Corporation
Yen Phu	Vietnam	Heavy mineral sand	xen	Advanced explo.	Government of Vietnam
Yinachange	China	Carbonatite	yis, mon, yin	Deposit – no data	
Yoganup	Australia	Heavy mineral sand, shore deposits	mon	Advanced explo. – former by-product	
Yongfeng	China	IA deposit		Deposit	
Yongsanpo	South Korea	Heavy mineral sand, river deposits	yos, mon, yon	Deposit – no data	
Yousuobao	China	Alkaline	apa, all	Exploration	
Ytterby	Canada	No info	yts, mon, ytt	Prospect	Midland Exploration
Yueyang	China	Heavy mineral sand, river deposits	yus, mon, yue	Deposit – no data	
Yukeng	China	IA deposit			

Locality/project	Country	REE type	REE mineral	Status	License holder
Zandkopdrift Mineral Ressource	South Africa	Carbonatite	mon	Advanced explo.	Frontier Rare Earth Ltd /Korea Resources Corp
Zhangjiang	China	Heavy mineral sand, shore deposits	mon, xen	Production – by-product	
Zhangoing (Longian)	China	IA deposit	zhs, mon, lon	Deposit – no data	
Zhanjiang	China	Heavy mineral sand, river deposits	zhs, mon, zha	Deposit – no data	
Zhijin	China	Phosphorite	zhs, mon, zhi	Deposit – no data	
Zijingshan	China	Carbonatite	zis, mon, zij	Deposit – no data	
Zixing	China	IA deposit	zis, mon, zix	Advanced explo.	
Zudong	China	IA deposit		Production ??	
Zunwu, Jiangxi ???	China	IA deposit		Deposit	
Zuokeng	China	IA deposit		Deposit	

Appendix II

Mineral abbreviations

Abbreviations for minerals that are primarily used in Appendix I are shown in the table below.

Abbreviation	Mineral name
all	Allanite
ana	Anatase
anc	Ancylite
apa	Apatite
bad	Baddeleyite
bas	Bastnäsite
bra	Brannerite
bri	Britholite
bur	Burbankite
cas	Cassiterite
col	Columbite
eud	Eudialyte
eux	Euxenite
fer	Fergosonite
flo	Florencite
gad	Gadolinite
ger	Gerenite
goy	Goyazite
hua	Huanghoite
kar	Karnasurtite
kas	Kainosite
lop	Loparite
mon	Monazite
mos	mosandrite
nio	Niobite
par	Parisite
pyr	Pyrochlore
rin	Rinkite
sam	Samarskite
ste	Steenstrupine
syn	Synchysite
xen	Xenotime
zir	Zircon

Appendix III

REE grades (%) for selected projects

Sources: Miscellaneous, collected November 2021.

Locality	Country	La_2O_3	Ce_2O_3	Pr_2O_3	Nd_2O_3	Sm_2O_3	Eu_2O_3	Gd_2O_3	Tb_2O_3	Dy_2O_3	Ho_2O_3	Er_2O_3	Tm_2O_3	Yb_2O_3	Lu_2O_3	Y_2O_3
Aksu Diamas	Turkey	25.3	43.7	4.5	15.5	2.2	0.6	1.4	0.2	0.9	0.1	0.4	0.1	0.4	0.1	4.8
Araxa	Brazil	28.1	49.4	4.5	13.9	1.5	0.3	0.7	0.1	0.3	0.0	0.1	0.0	0.0	-	1.1
Ashram (Total Resource)	Canada	26.1	46.6	4.8	16.6	2.0	0.5	1.1	0.1	0.4	0.1	0.1	0.0	0.1	0.0	1.6
Bayan Obo (Main and West)	China	25.0	50.0	4.0	17.0	1.5	0.2	0.4	0.1	0.1	-	-	-	-	-	0.3
Bear Lodge	US	27.0	43.0	5.0	18.0	3.0	1.0	2.0	0.0	0.0	-	0.0	-	-	-	1.0
Buckton	Canada	19.0	32.9	4.1	15.7	3.1	0.7	2.6	0.4	2.3	0.5	1.3	0.2	1.3	0.2	15.8
Canakli I	Turkey	25.3	44.5	4.5	14.5	2.0	0.5	1.4	0.2	0.9	0.2	0.5	0.1	0.4	0.1	5.2
Capel North	Australia	23.9	46.0	5.0	17.4	2.5	0.1	1.5	0.0	0.7	0.1	0.2	-	0.1	-	2.4
Changling	China	20.9	1.8	5.6	20.5	5.0	0.9	5.6	0.8	5.0	0.9	2.4	0.3	2.1	0.3	27.8
Charley Creek	Australia	18.1	38.6	4.2	14.9	2.8	0.6	2.4	0.4	2.1	0.4	1.2	0.2	1.0	0.2	12.9
Chongzou	China	19.5	5.3	5.9	22.4	4.6	0.7	4.6	0.8	4.3	0.9	2.1	0.3	1.5	0.3	26.9
Clay-Howells	Canada	25.1	43.6	4.4	15.1	2.3	0.6	1.5	0.6	1.0	0.1	0.4	-	0.4	-	4.9
Cummins Range	Australia	26.9	46.8	4.8	15.7	1.9	0.4	1.1	-	0.5	-	0.0	-	-	-	2.0
Dong Pao	Vietnam	32.0	50.4	4.0	10.7	0.9	-	-	-	-	-	-	-	-	-	2.0
Dubbo	Australia	19.6	36.9	4.0	14.1	2.2	0.1	2.2	0.3	2.0	0.4	1.2	0.2	1.0	0.2	15.8
Eco Ridge	Canada	23.9	45.3	4.5	14.6	2.5	0.1	1.7	0.3	1.1	0.2	0.5	0.1	0.3	0.1	4.9
Eldor	Canada	26.0	46.5	4.8	16.6	2.1	0.5	1.1	0.1	0.4	0.1	0.1	0.0	0.1	0.0	1.7
Elliott Lake Teasdale	Canada	25.0	46.4	4.5	14.5	2.4	0.1	1.5	0.2	0.8	0.1	0.3	0.1	0.3	0.1	3.8
Fen	Norway	15.2	64.3	3.6	13.4	-	-	-	-	-	-	-	-	-	-	3.6
Foxtrot (Port Hope Simpson)	Canada	18.1	38.5	4.4	15.8	2.9	0.1	2.2	0.4	2.1	0.4	1.4	0.2	1.0	0.2	12.7
Gakara (Karonge)	Burundi	30.6	48.1	4.4	14.8	-	-	-	-	-	-	-	-	-	-	-
Glenover	South Africa	16.2	44.6	5.9	22.5	3.7	0.9	2.1	0.2	0.8	0.1	0.2	0.0	0.1	0.0	2.6
Grande-Vallee	Canada	17.6	38.2	4.0	17.1	3.5	-	2.0	-	2.0	-	2.0	-	1.5	-	12.1
Green Cove Springs	US	17.5	43.7	5.0	17.5	4.9	0.2	6.6	0.3	0.9	0.1	-	-	0.2	-	3.2
Guandong	China	30.4	1.9	6.6	24.4	5.2	0.7	4.8	0.6	3.6	-	1.8	-	-	-	20.0

Locality	**Country**	**La_2O_3**	**Ce_2O_3**	**Pr_2O_3**	**Nd_2O_3**	**Sm_2O_3**	**Eu_2O_3**	**Gd_2O_3**	**Tb_2O_3**	**Dy_2O_3**	**Ho_2O_3**	**Er_2O_3**	**Tm_2O_3**	**Yb_2O_3**	**Lu_2O_3**	**Y_2O_3**
Hastings	Australia	1.6	6.0	0.9	3.5	2.2	0.1	3.6	1.1	8.9	2.1	8.2	1.1	6.6	0.9	53.3
Hoidas Lake (Nisikkatch)	Canada	20.4	46.8	6.0	20.6	2.7	0.5	1.2	0.1	0.4	-	0.2	-	0.1	-	1.2
Kangankunde	Malawi	29.8	49.7	4.7	14.0	1.1	0.2	0.4	0.1	0.1	0.0	0.0	-	0.0	-	-
Khibiny (apatite deposit)	Russia	25.8	46.2	4.0	14.4	1.6	0.5	0.1	1.0	0.1	0.2	-	-	-	-	6.1
Kipawa (Zeus)	Canada	14.3	29.1	3.6	13.4	3.0	0.4	2.9	0.5	3.6	0.8	2.5	0.4	2.3	0.3	23.0
Kringlerne	Greenland	17.8	33.3	3.2	12.2	2.3	0.3	2.6	0.5	2.9	0.6	2.4	0.3	2.0	0.3	19.4
Kutessay II	Kirgisistan	16.8	20.0	3.8	8.3	4.2	0.2	3.7	1.6	6.2	0.6	3.3	0.3	3.3	0.5	27.2
Kvanefjeld (main)	Greenland	26.4	44.1	4.3	13.2	1.4	0.1	1.0	0.1	1.0	0.2	0.5	-	0.3	-	7.3
La Paz	US	17.2	38.3	4.4	16.4	3.1	0.8	2.7	0.4	2.1	0.4	1.1	0.2	0.9	0.1	11.9
Lavergne-Springer	Canada	26.7	46.1	4.7	15.9	1.9	0.5	1.1	0.1	0.5	0.1	0.2	-	0.1	-	2.3
Lofdal	Namibia	5.4	9.8	1.1	4.0	1.6	0.8	4.0	1.0	7.4	1.6	4.8	0.7	4.4	0.6	52.8
Longonjo	Angola	23.9	45.9	4.9	17.2	2.5	0.6	1.2	0.1	0.6	0.1	0.2	0.0	0.1	0.0	2.6
Longyan, Jiangxi	China	2.2	1.0	1.1	3.5	2.3	0.3	5.7	1.1	7.5	1.6	4.3	0.6	3.3	0.5	64.9
Lovozero (loparit deposit)	Russia	28.0	57.5	3.8	8.8	1.0	0.1	0.2	0.1	0.1	-	-	-	-	-	-
Makuutu	Uganda	19.4	30.3	4.8	17.0	3.6	0.6	2.4	0.4	2.4	0.5	1.2	0.2	1.2	0.1	15.8
Manavalakurichi	India	23.0	47.0	5.5	20.0	2.5	0.0	1.2	0.1	0.2	0.0	0.0	-	-	-	0.5
Maoniuping	China	29.5	47.6	4.4	15.2	1.2	0.2	0.7	0.1	0.2	0.1	0.1	0.0	0.1	0.0	0.7
Milo	Australia	24.3	42.1	3.9	13.0	2.0	0.7	1.7	0.3	1.3	0.3	0.8	0.2	1.0	0.2	8.4
Montviel	Canada	25.6	49.2	5.0	15.8	1.7	2.4	0.6	0.1	0.2	-	0.0	-	0.0	-	-
Motzfeldt	Greenland	22.0	41.0	4.0	14.0	3.0		2.0	-	2.0	1.0	-	-	-	-	11.0
Mount Weld, Duncan	Australia	23.9	47.5	5.2	18.1	2.4	0.5	1.1	0.1	0.3	0.0	0.1	0.0	0.0	-	0.8
Mountain Pass, CA	US	34.0	48.8	4.2	11.7	0.8	0.1	0.2	-	-	-	-	-	-	-	0.1
Mrima Hill	Kenya	27.5	43.2	4.5	14.9	2.0	0.5	1.4	0.2	0.8	0.1	0.3	-	0.2	-	4.2
Nanyang	China	23.0	42.7	4.1	17.5	3.5	0.1	2.0	0.7	0.8	0.1	0.3	-	2.4	0.1	2.4
Nechalacho (Thor Lake)	Canada	15.3	34.0	4.3	17.0	3.9	0.5	3.5	0.7	1.7	0.2	1.7	0.2	1.4	0.2	15.5
Ngualla Hill	Tanzania	27.6	48.3	4.8	16.5	1.6	0.3	0.6	0.1	0.1	0.0	0.0	-	0.0	-	0.2
Niobec	Canada	24.5	47.9	5.3	18.5	2.1	0.4	1.0	0.1	0.3	-	-	-	-	-	-
Nolans Bore	Australia	19.1	48.7	5.9	20.6	2.3	0.4	1.0	0.1	0.3	0.0	0.1	0.0	0.1	0.0	1.4
Norra Kärr	Sweden	9.5	21.2	2.8	11.0	3.0	0.4	3.3	0.7	4.5	1.0	3.1	0.5	2.8	0.4	36.0
North Stradbroke	Australia	21.5	45.5	5.3	18.6	3.1	0.8	1.8	0.3	0.6	0.1	0.2	-	0.1	0.0	2.6
Olserum	Sweden	13.5	30.7	3.8	14.6	3.4	0.2	3.5	0.7	3.5	0.7	2.0	0.3	1.8	0.3	21.0
Penco	Chile	16.0	-	4.0	19.0	3.0	-	5.0	1.0	5.0	1.0	3.0	-	2.0	-	41.0

Locality	Country	La_2O_3	Ce_2O_3	Pr_2O_3	Nd_2O_3	Sm_2O_3	Eu_2O_3	Gd_2O_3	Tb_2O_3	Dy_2O_3	Ho_2O_3	Er_2O_3	Tm_2O_3	Yb_2O_3	Lu_2O_3	Y_2O_3
Phalabowra	South Africa	18.5	40.0	5.8	23.5	4.4	0.9	3.2	-	1.1	0.1	0.2	-	-	-	2.0
Revda, Murmansk	Russia	25.0	50.5	5.0	15.0	0.7	0.1	0.6	-	0.6	0.7	0.8	0.1	0.2	0.2	1.3
Round Top	US	3.8	15.0	2.0	5.4	2.0	0.0	1.9	0.7	5.9	1.5	6.2	1.4	10.9	1.7	41.8
Sarfartoq	Greenland	19.5	51.5	5.9	19.2	1.9	0.4	1.1	0.1	0.2	-	-	-	-	-	0.4
Serra Verde	Brazil	22.6	32.9	4.1	13.4	2.4	0.2	2.2	0.4	2.4	0.5	1.6	0.2	1.6	0.2	15.3
Sichuan	China	29.0	47.0	5.0	13.0	1.7	0.4	0.9	0.2	0.2	0.2	0.2	0.2	-	-	0.8
Songwe Hills	Malawi	24.6	44.6	4.8	16.4	2.4	0.6	1.4	0.2	0.8	0.1	0.3	0.0	0.2	0.0	3.7
Southeast Guangdong	China	1.2	3.0	0.6	3.5	2.2	0.2	5.0	1.2	9.1	2.6	5.6	1.3	6.0	1.8	57.3
Steenkampskral	South Africa	20.8	45.2	5.1	18.0	2.9	0.1	2.0	0.2	1.0	0.1	0.3	0.0	0.1	0.0	4.1
Storkwitz (Delizsch)	Germany	27.4	48.7	5.1	14.2	1.4	0.3	1.1	0.1	0.2	0.1	0.1	0.0	0.1	0.0	1.2
Strange Lake	Canada	12.1	28.0	3.1	11.2	2.6	0.1	2.7	0.6	4.0	0.9	2.9	0.5	3.0	0.4	28.2
Tantalus	Madagascar	7.0	1.0	19.0	33.0	-	7.0	2.0	5.0	16.0	-	1.0	1.0	1.0		7.0
Two Tom (Red Wine)	Canada	24.4	46.0	4.7	15.9	2.7	0.3	1.6	0.2	0.7	0.1	0.2	-	0.1	-	3.2
Vichada Project	Columbia	16.6	54.7	4.3	16.7	3.2	-	1.3		1.3	-	0.4	-	0.7	-	0.9
Weishanhu, Shandong	China	35.5	47.8	4.0	10.9	0.8	0.1	0.5	0.1	-	-	-	-	0.0	-	0.8
Weres, Seigneurie, Sophie, Reine J6L1	Canada	32.0	49.0	4.0	11.5	1.4	0.2	0.4	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.2
Wicheeda	Canada	36.9	48.8	3.8	10.8	1.0		-	-	-	-	-	-	-	-	-
Wigu Hill	Tanzania	39.0	47.5	3.6	9.0	0.5	0.1	0.2	0.0	0.1	0.0	0.0	-	-	-	0.2
Wolverine (Browns Range)	Australia	2.5	6.0	0.8	3.8	2.1	0.4	5.5	1.2	8.4	1.8	5.2	0.7	4.3	0.6	56.7
Xiluvo	Mozambique	22.0	46.0	4.9	17.0	2.4	0.7	1.7	0.2	0.9	0.1	0.3	0.0	0.2	0.0	4.0
Xinfeng, Jiangxi	China	27.3	3.2	5.6	17.6	4.5	0.9	6.0	0.7	3.7	0.7	2.5	0.3	1.1	0.2	24.3
Xuanwu 1	China	35.0	3.5	7.4	30.2	5.3	0.5	4.2	0.5	1.8	0.3	0.9	0.1	0.6	0.1	10.1
Xuanwu 2	China	29.8	7.2	7.1	30.2	6.3	0.5	4.2	0.5	1.8	0.3	0.8	0.1	0.6	0.1	10.1
Yangibana North	Australia	11.7	43.9	7.8	32.4	3.6	0.1	0.2	0.2	0.1	-	0.0	0.0	-	-	0.1
Zandkopdrift Mineral Resource	South Africa	26.2	44.1	4.6	15.7	2.2	0.6	1.3	0.1	0.7	0.1	0.3	0.1	0.2	0.1	3.7
Zunwu, Jiangxi?	China	38.0	3.5	7.4	27.2	5.3	0.5	4.2	0.5	1.8	0.3	0.9	0.1	0.6	0.1	10.1

Appendix IV

Resource volumes for selected projects with rare earth elements

Sources: Miscellaneous, collected November 2021.

Locality/projects	Country	REE-type	Measured/proven ton TREO	Indicated ton TREO	Inferred ton TREO
Aksu Diamas	Turkey	Heavy mineral sand	-	-	350,000
Alces Lake	Canada	No info	-	-	20,000
Amba Dongar	India	Carbonatite	-	3,150,000	-
Araxa	Brazil	Carbonatite	30,000	530,000	880,000
Ashram (Total Resource)	Canada	Carbonatite	30,000	530,000	4,130,000
Bayan Obo (Main and West)	China	Carbonatite	3,440,000	-	-
Bayan Obo (surrounding)	China	Carbonatite	330,000	-	-
Bayan Obo (West)	China	Carbonatite	1,210,000	-	-
Bear Lodge	US	Carbonatite	110,000	450,000	-
Belaya Zima	Russia	No info	-	10,000	-
Bokan Mountain	US	Alkaline/hydrothermal?/Alkaline?	-	30,000	30,000
Brockmans	Australia	Alkaline	-	70,000	-
Buckton	Canada	Carbonatite	-	-	150,000
Canakli I	Turkey	Heavy mineral sand	-	-	350,000
Charley Creek	Australia	Heavy mineral sand	-	240,000	-
Chuktukun	Russia	No info	-	40,000	-
Clay-Howells	Canada	Alkaline	-	-	60,000
Cummins Range	Australia	Carbonatite	-	150,000	90,000
Daluhala	China	Carbonatite	-	220,000	-
Dubbo	Australia	Alkaline	140,000	650,000	-
Eco Ridge	Canada	Carbonatite (with residual enrichment)	-	40,000	90,000
Elliott Lake Teasdale	Canada	Heavy mineral sand (conglomerate,)	-	480,000	-
Fen	Norway	Carbonatite	-	-	910,000
Foxtrot (=Port Hope Simpson)	Canada	Alkaline	-	50,000	60,000
Gakara (Karonge)	Burundi	Carbonatite (with residual enrichment)	-	-	30,000
Glenover	South Africa	Carbonatite	-	240,000	120,000
Grande-Vallee	Canada	IA deposit	-	610,000	-
Gupsehan	China	IA deposit	-	-	-
Hastings	Australia	Alkaline	-	60,000	20,000
Hoidas Lake (Nisikkatch)	Canada	Hydrothermal	20,000	70,000	10,000
Høgtuva	Norway	Hydrothermal	-	-	-
Jongju	North Korea	No info	-	-	59,840,000
Kangankunde	Malawi	Carbonatite (with residual enrichment)	-	110,000	-
Katajakangas	Finland	Alkaline	-	-	10,000
Katugino	Russia	No info	-	-	-
Khaldzan Burgtey	Mongolia	Carbonatite	-	-	290,000
Khibiny apatite deposti	Russia	Alkaline	40,000	-	-
Khotgor	Mongolia	No info	-	-	490,000

Locality/projects	Country	REE-type	Measured/proven ton TREO	Indicated ton TREO	Inferred ton TREO
Kipawa (Zeus)	Canada	Alkaline	-	80,000	-
Kiruna	Sweden	Iron-oxide-apatite	-	-	19,800,000
Kizilcaoren	Turkey	Hydrothermal	-	-	10,000
Kodal	Norway	Alkaline	-	-	60,000
Kontioaho	Finland	No info	-	-	30,000
Korsnas Mine	Finland	Carbonatite	-	-	10,000
Kovela	Finland	No info	-	-	90,000
Kringlerne	Greenland	Alkaline	-	27,950,000	-
Kutessay II	Kirgizstan	Alkaline	40,000	50,000	-
Kvanefjeld (main)	Greenland	Alkaline	1,590,000	3,610,000	810,000
Kwyjibo	Canada	IOCG	70,000	120,000	-
La Paz	US	Hydrothermal	-	300,000	-
Lavergne-Springer	Canada	Carbonatite	-	50,000	150,000
Leveâniemi	Sweden	Iron-oxide-apatite	-	-	1,950,000
Lizhuang	China	Carbonatite	-	-	-
Lofdal	Namibia	Carbonatite	-	10,000	10,000
Longonjo	Angola	Carbonatite	-	1,110,000	2,220,000
Lovozero (loparit deposti)	Russia	Alkaline	60,000	10,000,000	-
Lugin Gol	Mongolia	Carbonatite	-	-	10,000
Makuutu	Uganda	IA deposit	-	50,000	150,000
Malmbjerget	Sweden	Iron-oxide-apatite	-	-	7,980,000
Maoniuping	China	Carbonatite	1,430,000	2,120,000	940,000
Miaoya	China	Carbonatite	-	10,000	1,220,000
Milo	Australia	Iron-oxide-apatite	-	110,000	110,000
Misværdal	Norway	Alkaline	-	-	20,000
Montviel	Canada	Carbonatite	-	1,240,000	2,630,000
Moreton Island	Australia	Heavy mineral sand, shore deposits	-	-	30,000
Motzfeldt	Greenland	Alkaline	-	-	880,000
Mount Weld, Duncan	Australia	Carbonatite	1,400,000	660,000	-
Mountain Pass, CA	US	Carbonatite	1,330,000	-	-
Mrima Hill	Kenya	Carbonatite	-	2,140,000	4,000,000
Mushgia Khudug	Mongolia	Carbonatite	-	3,150,000	-
Nam Xe	Vietnam	Metamorphic/Laterite	-	7,800,000	-
Narraburra	Australia	No info	-	-	30,000
Nechalacho (Thor Lake)	Canada	Alkaline	60,000	250,000	-
Nechalacho Upper	Canada	Alkaline	20,000	120,000	-
Ngualla Hill	Tanzania	Carbonatite	900,000	90,000	20,000
Niaqornakavsak	Greenland	Metamorphic	-	-	240,000
Niobec	Canada	Carbonatite	-	18,320,000	-
Nkombwa Hill	Zambia	Carbonatite	-	-	260,000
Nolans Bore	Australia	Hydrothermal/Carbonatite	140,000	550,000	530,000
Norra Kärr	Sweden	Alkaline	-	190,000	190,000
Olserum	Sweden	Hydrothermal	-	-	50,000
Phalabowra	South Africa	Carbonatite	-	160,000	-
Round Top	US	Alkaline	-	-	-
Sarfartoq	Greenland	Carbonatite	-	100,000	40,000
Seligdar	Russia	Carbonatite	20,000	-	-
Serra Verde	Brazil	IA deposit	50,000	550,000	450,000
Simon's Find	Australia	Carbonatite/Laterite	-	-	10,000
Songwe Hills	Malawi	Carbonatite	-	210,000	140,000
Steenkampskral	South Africa	Hydrothermal	90,000	70,000	-
Storkwitz (Delizsch)	Germany	Carbonatite	-	-	20,000

Locality/projects	**Country**	**REE-type**	**Measured/proven ton TREO**	**Indicated ton TREO**	**Inferred ton TREO**
Strange Lake	Canada	Alkaline	-	2,590,000	1,820,000
Tantalus	Madagascar	Iron-oxide-apatite	40,000	-	-
Tomtorskoye	Russia	Carbonatite (with residual enrichment)	920,000	-	-
Two Tom (Red Wine)	Canada	Alkaline	-	-	480,000
Tåsjö	Sweden	Other - uranium	-	-	110,000
Ulug-Tanzek	Russia	Hydrothermal	-	-	-
Wicheeda	Canada	Carbonatite	-	150,000	350,000
Wigu Hill	Tanzania	Carbonatite (with residual enrichment)	-	-	50,000
Wolverine (Browns Range)	Australia	Hydrothermal	-	20,000	20,000
Xiluvo	Mozambique	Carbonatite	-	20,000	-
Yangibana North	Australia	Carbonatite/Laterite	10,000	30,000	10,000
Yarega	Russia	No info	-	-	-
Zandkopdrift Mineral Resource	South Africa	Carbonatite	480,000	330,000	20,000
Total			**14,000,000**	**92,010,000**	**115,870,000**

Appendix V

The Big Six and subsidiaries

Subsidiary structure for “The Big Six”, the list is not complete.

Sources: Miscellaneous, collected November 2021.

China Northern Rare Earth Group	**China Northern Rare Earth (Group) High-Tech Co. Ltd**	
Gansu		Baogang Rare Earth Metallugical Factory
Inner Mogolia		Baogang Rare Earth Separation Factory
Shandong		Baotou Feida Rare Earth Co. Ltd
		Baotou Hontianyu Rare Earth Magnet Company
		Baotou Huamei Rare Earth Hi-Tech Comp.
		Baotou JinMeng Rare Earth Co. Ltd.
		Baotou Rare Magnet Materials
		Baotou Zinyuan Rare Earth Hi-tech Newly-material Co. Ltd
		Beijing Sanjili New Materials
		Gansu Rare Earth New Material Co. Ltd
		Inner Monglia Aerospace Kinxia Chemical Industry Co. Ltd
		Inner Mongolia Baotou Steel Rare Earth (Group) Hi-Tech Co. Ltd.
		Jiangxi Xinfeng Baogangxinli Rare Earth Co. Ltd
		Quannan Baogang Jinghuan Rare Earth Comp.
		Wuyan Runze Rare Earth Co. Ltd
		Zibo BaoSteel Lingzhi Rare Earth Hi-tech Co. Ltd

China Southern Rare Earth Group (CSREG)	**China Southern Rare Earth Group Co. Ltd**	Udgøres af Ganzhou Rare Earth Group (60 %) + Jiangxi Copper Group (35 %) + Jianngxi Rare Earth & Rare Metal Tungsten Group Comp. (5 %)
Sichuan		Ganzhou Rare Earth Longnan Smelting Separation Com
Jiangxi		Ganzhou Rare Earth Minerals Industry Co. Ltd
		Jiangxi Golden Century Advanced Materials Co. Ltd
		Longnan Longyi Heavy Rare-Earth Technology Co. Ltd
		Quannan New Ressource Rare Earth Co. Ltd
		Sichuan Jiangxi Copper Rare Earth Co. Ltd
		Sichuan Mianning County Fangxing Rare Earth Co. Ltd
		Wan'an Jiangwu REE Mineral Co. Ltd.

China Aluminium Group (Chinalco)	**China Xiyou Rare Earths Corp. (China Aluminium)**	Central Iron & Steel Research Institute
Sichuan		China Steel Research Technology Group Co. Ltd
Guangxi		China Guangxi Hezhou Rare Earth Development Co. Ltd
Jiangsu		China Guangxi Nonferrous Metals Chongzuo Rare Earth Development Co. Ltd
Shandong		China Guangxi Wuxhou Rare Earth Development Co. Ltd
		Chinalco Guangxi Nonferrous Rare-Earth Development Co Ltd
		Chinalco Sichuan Rare Earth Co. Ltd
		Chinalco Rare Earth (Chanzhou) Co. Ltd
		Dechang Houdi Rare Earth Mining Co. Ltd
		Hunan Research Institute of Rare Earth Metals
		Jiangsu Guosheng Rare Erath Co. Ltd
		Jiangyin Jiahua Advanced Material Resources Co. Ltd
		Leshan Shenghe Rare Earth Co. Ltd
		MianNing MianLi Rare Earth Mineral Co Ltd

		Shandong Weishan Lake Rare Earth Co. Ltd
		Shandong Zhongkai Rare Earth Material Co. Ltd
		Sichuan Hanxin Mineral Development Co. Ltd
		Xian Xijun New Material Co. Ltd
		Zibo Jiaua Advanced Materials Resources Co. Ltd

Xiamen Tungsten Co. Ltd	**Mining Division**	Louyang Yulu Tungsten Mining Co. Ltd
		Ningshua Xingluckeng Tungsten Mining Co. Ltd
		Jiangxi Duchang Jinding Tungsten Molybdenum Mining Co. Ltd
		Xiamen Tungsten Co. Ltd. Haicang Branch
		Xiamen Minglu International Trading Comp.
		Xiamen Tungsten (H.C.) Co. Ltd
		Malipo Haiyu Tungsten (H.C.) Co. Ltd
		Xiamen Golden Egret Special Alloy Co. Ltd
		Jiujang Golden Egret Hard Metal Co. Ltd
		Luoyang Golden Egret Geotools co. Ltd
		Bestool Co. Ltd
		Xiamen Honglu Tungsten & Molybdenum Industry Co. Ltd
		Chengdu Hongbo Industrial Co. Lt
		Ganzhou Hongei Tungsten & Molybdenum Material Co. Ltd
	Rare Earth Division	Changting Jinlong Rare-Earth Co. Ltd
		Longyan Rare-Earth Development Co. Ltd
		Guangzhou Zhujang Photoelectric Materials Co. Ltd
		Sanming Rare-Earth Development Co. Ltd
		Rare-Earth Magnetic Materials Research Centre
		Longyan Rare-Earth Industrial Zone Development
		Suzhou Aizh Gaosi elextric Machinery Co. Ltd
		Baotou Rare-Earth Products Exchange Co. Ltd
		Beijing Huixi Zhiding consulting co. Ltd
		Jialu (Hongkong) Ltd. Company
		Xiamen Ousilo Technology Co Ltd
		Xiamen Townowner Real Estate Co. Ltd

Guangong Rare Earth Group (omtaltes også: Guangsheng Nonferrous Metals Group)	**Guangdon Rare Earth Industry Co Ltd**	
Guangdong		Bading Huabao Rare Earth Co. Ltd
		Baotou Xinyuan Rare Earth Hi-Tech and New Material Co. Ltd
		China Nonferrous Metals Construction Co. Ltd
		Dapu Xinchengji Industry Co
		Deqing Xingbang Rare Earth New Materials Co. Ltd
		Guangdon Fuyuan Rare Earth New Material Co. Ltd
		Jintan Hailin Rare Earth Co. Ltd
		Longnan County Heli Rare Earth Smelting Co. Ltd
		Pingyuan Huaqi Rare Earth Industrial Co. Ltd
		Qinggyuan Jiahe Rare Metal Co. Ltd
		Varda Group Heyuan City Dongyuan Guyun Rare Earth Ore Mining Ltd.
		Yunnan Aosi Dilong Mineral Development Co. Ltd.

China Minmetals	**Minmetals Rare Earth Group Co. Ltd**	
Yunnan		China Minmetals Rare Earth Jianghua Co. Ltd
Guangzi		China Steel Research Technology Group Co. Ltd
Guangdong		Conghua Jiangeng Rare Earth Co. Ltd.
Hunan		Dingnan Dahua New Materials Resources Co. Ltd
Fujian		Dingnan Southern Rare Earth Co. Ltd
Jiangxi		Fujian SanMing Rare Earth Co. Ltd
		Ganxian Hongijn Rare Earth Co. Ltd
		Jianghua Rare Earths facility (started 2020)
		Jianghua Yao Nationality Autonomous County Xinghua Rare Earth Co. Ltd
		Shenggongzhai Rare Earth Mine (ny Minedevelopment)
		Xunwu South Rare Earth Co. Ltd

Appendix VI

Members of Rare Earth Industry Association (REIA)

Source: www.global-reia.org, December 2021.

Member organisation	Country	Activity
Appia Energy Corp.	Canada	Exploration (Elliot Lake, Canada (REE+U))
Arafura	Australia	Exploration (Nolans Bore, Australia)
Auxico Resources	Canada	MineralExploration (fokus on niobium, tantal) inMexico (Zamora)
B&C Speakers	Spain	Manufacturer of speakers)
BEC Gesellschaft für Produktmanagement	Germany	Production (magnets)
British Geological Survey	UK	R&D (ressources)
Brugger Magnetsysteme	Germany	R & D (magnets)
Carester	France	Consultant (mining and metallurgy)
Central America Nickel	Canada	Oreprocessering
E-TECH Resources	Canada	Exploration (Eurika, Namibia)
Fraunhofer IWKS	Germany	R & D; Consultant
Greenland Minerals Ltd.	Australia	Exploration, t (Kvanefjeld, Greenland)
Grundfos	Danmark	Manufacture (pumps)
HS PF	Germany	Training
Institute of Urban Environment (IUE)	China	R & D
Ionic Rare Earths	Australia	Exploration, (Makuutu, Uganda)
JL MAG Rare-Earth Co Ltd	China	Manufacturer (NdFeB-magnets)
JOGMEC	Japan	Exploration, mining, trade
Jozef Stefan Institute	Slovenien	R & D; consultant (functionel ceramics, sensorer etc.)
JSNM Japan	Japan	Manufacturer (magnets, flourescence, ceramic condensators, catalysators)
KU Leuven	Belgium	R & D
Leading Edge Materials	Canada	Exploration, (Norra Kärr, Sweden)
Medallion Resources	Canada	Exploration, udvinding, processering (from monazite)
MINVIRO	UK	Consultant – Life Cycle Analysis
Mkango Resources	Canada	Exploration (Songwe Hill, Malawi), mining, separation, refinery, alloying, and recycling
MTC rare earths solutions	UK	Trade
Namibia Critical Metals Inc.	Canada	Exploration (Namibia)
Natural Resources Canada	Canada	R & D; exploration, mining,
Pensana Plc	UK	Exploration (Longonjo, Angola)
Peak Rare Earths	Australia	Exploration (Ngualla, Tanzania), malmprocessering (UK)
Phoenix Tailings	US	Mining of tailings
Rare Earths Norway	Norway	Mining (industrial mineraler)
REE Minerals	Norway	Exploration (Fen, Norway)
Rock Link Rare Metals Recycling	Germany	Trade (chemicals and metals); recycling
Roskill	UK	Market survey
Saskatchewan Research Council	Canada	R & D
Ucore Rare Metal	US	Exploration (Bokan), separation (RapidSX™-methods).
UMAG	China	Production (magnets)
University of Exeter	UK	R & D

Appendix VII

Members of European Raw Material Alliance (ERMA)

Source: www.erma.eu September 2021.

Company	Country
Alligator Energy	Australia
Alta Zinc Limited	Australia
Arafura Resources	Australia
Argosy Minerals Limited	Australia
Australian Trade and Investment Commission (Austrade)	Australia
Core Lithium Limited	Australia
Diversified Asset Holdings Pty Ltd	Australia
Essential Metals Limited	Australia
Government of Western Australia	Australia
Greenfields Exploration Limited	Australia
Hastings Technology Metals	Australia
International Graphite Limited	Australia
Ionic Rare Earths Limited	Australia
Mineral Commodities	Australia
Neometals Ltd.	Australia
Renascor Resources Limited	Australia
Speciality Metals International Ltd	Australia
Syrah Resources	Australia
University of Adelaide	Australia
Volt Resources Limited	Australia
Walkabout Resources LTD	Australia
Behault Mining BV	Belgium
Centre for Research in Metallurgy (CRM Group)	Belgium
Cobalt Institute	Belgium
CTP	Belgium
DEME Group	Belgium
EuroGeoSurveys	Belgium
European Association for Coal and Lignite AISBL (EURACOAL)	Belgium
European Lithium Institute eLi	Belgium
Ghent University	Belgium
industriAll European Trade Union	Belgium
Minister of Economy, Research and Innovation	Belgium
Prayon	Belgium
SoilWatch	Belgium
Solvay	Belgium
SQM Europe NV	Belgium
Umicore	Belgium
WalZinc srl	Belgium
CBMM	Brazil
Smartway Brasil Minerio de Ferro	Brazil
KCM 2000 Group	Bulgaria
Adamas Intelligence	Canada
Canada EU Trade and Investment Association	Canada
Commerce Resources Corp.	Canada
Euro Lithium	Canada
Fortune Minerals Limited	Canada
Global Energy Metals Corporation	Canada
Greenland Resources Inc.	Canada
Innovation Metals Corp.	Canada
Leading Edge Materials	Canada
Lundin Mining	Canada
Mkango Resources	Canada
Natural Resources Canada	Canada
Neo Performance Materials	Canada
NextSource Materials Inc.	Canada
Québec Ministry of Energy and Natural Resources	Canada
Rock Tech Lithium	Canada
Search Minerals Inc.	Canada
Sherritt International Corporation	Canada
The Metals Company	Canada
Torngat Metals	Canada
Trinity Management Ltd.	Canada
WT&C Innovates Inc.	Canada
BioLantanidos	Chile
Hellenic Minerals	Cypern
Confederation of Danish Industry	Danmark
FLSmidth	Danmark
Geological Survey of Denmark and Greenland	Denmark
Ministry of Climate, Energy and Utilities	Denmark
BiotaTec	Estonia
Geological Survey of Estonia	Estonia
UP Catalyst	Estonia
Critical Raw Materials Alliance	EU
CSR Europe	EU
ECGA - European Carbon and Graphite Association	EU
EFG - European Federation of Geologists	EU
EPMF - European Precious Metals Federation	EU
EUMICON	EU
Euroalliages - Association of European ferro-alloy producers	EU
EUROGYPSUM	EU
Eurometaux – European Association of Metals	EU
Euromines - European Association of Mining Industries, Metal Ores & Industrial Minerals	EU
European Aluminium	EU
European Copper Institute	EU
European Geothermal Energy Council	EU
European Industrial Hemp Association	EU
European Technology Platform on Sustainable Mineral Resources	EU

Company	Country
Industrial Minerals Association Europe	EU
PERC - Pan-European Reserves and Resources Reporting Committee	EU
PROMETIA	EU
TECHNIP Energies	EU
UEPG - European Aggregates Association	EU
FinnAust Mining Finland	Finland
Finnish Minerals Group	Finland
Finnish Mining Association (FinnMin)	Finland
Geological Survey of Finland	Finland
Keliber	Finland
Lappeenranta-Lahti University of Technology LUT	Finland
Mawson	Finland
Metso Outotec	Finland
Rovjok	Finland
S3P Mining Industries and global value chain	Finland
University of Lapland	Finland
University of Oulu	Finland
Aalto University	Finland
45-8 Energy	France
A3M - Alliance des Minerais, Minéraux et Métaux	France
Adionics	France
AT-IPIC	France
BRGM	France
Carester	France
CEA	France
DCX Chrome	France
Eramet	France
Extracthive	France
Fonroche Géothermie	France
France Industrie	France
French Ministry for the Economy and Finance	France
GEOLITH	France
Géosciences Conseils Catura Geoprojects	France
Grenoble INP Institute of Engineering and Management	France
IFREMER	France
Imerys	France
International Chromium Development Association	France
iUMTEK	France
MagREEsource	France
Orano	France
pôle AVENIA	France
Polymeris	France
PREDICT	France
Rare Earth Advisory	France
Sudmine	France
TERREMYS	France
Tokai COBEX Savoie SAS	France
Université de Lorraine	France
Vermilion REP SAS	France

Company	Country
WEEECycling	France
Ecoresources IKE	Greece
GRawMat Innovation Cluster	Greece
Hellas Gold	Greece
Hellenic Survey of Geology and Mineral Exploration	Greece
Metallon Ecosystems IKE	Greece
Mytilineos	Greece
National Technical University of Athens	Greece
ORYKTON Consulting MON.I.K.E	Greece
Vlysis	Greece
Dundas Titanium	Greenland
Greenland Minerals A/S	Greenland
Hudson Resources Inc.	Greenland
Ministry of Mineral Resources	Greenland
Tanbreez	Greenland
Delf University of Technology	The Netherlands
Durapower Technology Group B.V.	The Netherlands
Elewaut@efm	The Netherlands
IHC Mining B.V.	The Netherlands
JLMAG Rare Earth Co Europe BV	The Netherlands
Nyrstar	The Netherlands
Spectral Industries	The Netherlands
WMC Energy	The Netherlands
Epsilon Advanced Materials	India
i2a - International Antimony Association	International
International Platinum Group Metals Association	International
INTRAW, International Raw Materials Observatory	International
Nickel Institute	International
REIA - Global Rare Earth Industry Association	International
Vanitec	International
Zircon Industry Association (ZIA)	International
Geoscience Ireland	Ireland
Institute of Geologists of Ireland	Ireland
Irish Centre for Research in Applied Geosciences (iCRAG)	Ireland
LONGFORD ZINC MINING LIMITED	Ireland
Minco Exploration	Ireland
Resource 500 Fevti	Ireland
TechMet Limited	Ireland
TH Consulting and Training	Ireland
Adaci Ass. It. Acquisti e Supply Management	Italy
Consorzio SPRING - Strategic Partnership for Research based Innovative and Networked Growth	Italy
Contento Trade S.r.l.	Italy
Fondazione Bruno Kessler	Italy

Company	Country
La Mla Energia Scarl	Italy
MINERARIA GERREI SRL	Italy
Politecnico di Milano	Italy
SERENGEO S.R.L	Italy
Spacearth Technology Srl	Italy
STAM S.R.L.	Italy
University of Milano Bicocca	Italy
University of Padua	Italy
Veneta Mineraria	Italy
National Mining Company Tau-Ken Samruk JSC	Kasakhstan
Geological Survey of Croatia	Croatia
Adianano	Latvia
ArcelorMittal	Luxembourg
Eco-Connections Sàrl	Luxembourg
Euronickel Industries	Macedo-niaMacedonia
Lynas Corporation	Malaysia
Suricate Minerals	Mauretania
Managem	Marocco
Metalex Commodities Inc	Nigeria
Arctic Economic Council	Norway
Battery Norway	Norway
Federation of Norwegian Industries (Norsk Industri)	Norway
Geological Survey of Norway	Norway
Hydro	Norway
Institute for Energy Technology (IFE)	Norway
Metamorphic AS	Norway
Nordic Mining ASA	Norway
Norway Mining PLC	Norway
Rare Earth Norway (REN) AS	Norway
REEtec	Norway
SINTEF AS	Norway
ABC A HEAD	Poland
AGH University of Science and Technology in Cracow	Poland
Instytut Chemicznej Przeróbki Węgla	Poland
Jastrzębska Spółka Węglowa S.A.	Poland
KGHM Cuprum Research and Development Centre	Poland
KGHM Polska Miedź S.A	Poland
Ministry of Climate and Environment	Poland
Polish Geological Institute-National Research Institute	Poland
SGPR.TECH	Poland
Sieć Badawcza Łukasiewicz – Instytut Metali Nieżelaznych	Poland
Wroclaw University of Science and Technology (WUST)	Poland
Cluster Portugal Mineral Resources	Portugal
Institute for Systems and Computer Engineering, Technology and Science	Portugal
Lusorecursos Portugal Lithium	Portugal
Pegmatítica Sociedade Mineira de Pegmatites	Portugal

Company	Country
Quercus - ANCN	Portugal
ALRO	Romania
AMV Beta	Romania
AMV Magnum	Romania
MINISTERUL ECONOMIEI, ANTREPRENORIATULUI ȘI TURISMULU	Romania
National Research&Development Institute for Non-ferrous and Rare Metals - IMNR	Romania
LuNa Smelter Ltd.	Rwanda
Euro Lithium Balkan	Serbia
Ekolive s.r.o.	Slovakia
grantUP	Slovakia
OFZ	Slovakia
Technical University of Kosice - Faculty of Mining, Ecology, Process Control and Geotechnologies	Slovakia
Geological Survey of Slovenia	Slovenien
Acuvet Biotech SL	Spain
AEDIVE	Spain
ALS	Spain
ANCADE - Spanish Lime Manufacturers Association	Spain
ANEFA, Asociación Nacional de Empresarios Fabricantes de Áridos	Spain
Arcillas Refractarias S.A.	Spain
Atlantic Copper	Spain
CEINNMAT (INNCEINNNAT SL)	Spain
CETIM	Spain
CIC energiGUNE	Spain
Cobalt and Nickel Mines	Spain
Cobre Las Cruces	Spain
COMINROC - Confederación Española de Industrias Extractivas de Rocas y Minerales Industriales	Spain
Confedem - CONFEDERACIÓN NACIONAL DE EMPRESARIOS DE LA MINERÍA Y DE LA METALURGIA	Spain
CRS Ingeniería	Spain
Economía Recursos Naturales, S.L. (ecoNatura)	Spain
EURECAT	Spain
FdA - Federación de Áridos	Spain
FUNDACION GOMEZ PARDO	Spain
Fundación TECNALIA Research & Innovation	Spain
Ilustre Colegio Oficial de Geólogo	Spain
IMDEA Nanociencia	Spain
Infinity Lithium Corporation Limited	Spain
Ingenieria Magnetica Aplicada S.L.	Spain
ISMC - Iberian Sustainable Mining Cluster	Spain
MAGES - Asociación Española de Fabricantes de Magnesia	Spain
Magnesitas Navarras	Spain
MATSA	Spain

Company	Country
OFICEMEN - Agrupación de Fabricantes de Cemento de España	Spain
Orovalle Minerals, S.L.	Spain
Pasek	Spain
PRIMIGEA - Confederación Española de las Industrias de las Materias Primas Minerales	Spain
QBIS Resources S.L.	Spain
Quantum Minería	Spain
Rio Tinto Proyectos y Desarrollos, S.L.	Spain
Spanish Ministry for the Ecological Transition and the Demographic Challenge	Spain
Strategic Minerals Spain, S.L.	Spain
Tharsis Mining	Spain
Worldsensing	Spain
Anglo American	UK
Bluejay Mining	UK
British Geological Survey	UK
Disko Exploration	UK
European Bank for Reconstruction and Development	UK
Everledger	UK
Fauna & Flora International	UK
Ferrexpo PLC	UK
Ferroglobe	UK
Fibre Technologies Ltd	UK
Hypromag	UK
ICD Europe, LTD	UK
International Lithium Association (ILiA)	UK
Less Common Metals	UK
Minexx	UK
Mining & Sustainable Development Ltd	UK
Mitsui & Co Europe Plc	UK
nmcn	UK
One Cycle Ltd.	UK
Pensana Plc	UK
Polar Research and Policy Initiative	UK
Rainbow Rare Earths	UK
Resources Computing International Ltd	UK
Rio Tinto	UK
Rockmate	UK
Savannah Resources	UK
Sazani Associates	UK
Strategic Materials Advisiors Ltd.	UK
University College London	UK
Epiroc Rock Drills	Sweden
Eurobattery Minerals	Sweden
FAMMP – Fennoscandian Association for Metals and Minerals	Sweden
Geological Survey of Sweden	Sweden
Holmasjön Prospectering AB	Sweden
LKAB	Sweden
LTU Business	Sweden
Luleå University of Technology	Sweden
Sencept AB	Sweden

Company	Country
Sotkamo Silver	Sweden
Svemin	Sweden
Talga AB	Sweden
Vargön Alloys	Sweden
Vinnova	Sweden
Volvo Group	Sweden
Woxna Graphite	Sweden
Zinkgruvan Mining	Sweden
Boliden	Sweden
ARCORE Ltd.	Schweiz
Belenos Clean Power Holding	Schweiz
gaiffi international GmbH	Schweiz
Glencore	Schweiz
Minespider AG	Schweiz
MTO AG - Nornickel Group	Schweiz
Responsible Mining Foundation	Schweiz
Swatch Group Research and Development Ltd – Division CDNP	Schweiz
Manganese Metal Company	South Africa
ČEZ	Czech Republic
Geomet s.r.o.	Czech Republic
Kutahya Dummlupinar University	Turkey
Meta Nikel Kobalt Madencilik ve San. ve Tic. A.Ş.	Turkey
AMG Lithium GmbH	Germany
Aurubis	Germany
Ayni Verein für Ressourcengerechtigkeit e. V.	Germany
Beak Consultants GmbH	Germany
Coftech GmbH	Germany
Cronimet Holding	Germany
DeepSea Mining Alliance (DSMA)	Germany
Deutsche Lithium	Germany
DGWA GmbH	Germany
DMT Group	Germany
ECTerra	Germany
Fraunhofer Institute for Solar Energy Systems ISE	Germany
Fraunhofer-Gesellschaft	Germany
G.E.O.S. ingenieurgesellschaft	Germany
German Mining and Minerals (GM2)	Germany
Graphit Kropfmühl GmbH	Germany
Helmholtz-Zentrum Dresden-Rossendorf	Germany
HESSE & ASSOCIATES	Germany
HiTech Materials Advisory	Germany
Indurad GmbH	Germany
Iphigenie Bergbau GmbH	Germany
J&C Bachmann GmbH	Germany
Karlsruhe Institute of Technology	Germany
Metalshub	Germany
Projekt-Consult GmbH	Germany
Quarzwerke GmbH	Germany
Saxore Bergbau GmbH	Germany
SBI Sons of Bavaria Investment AG	Germany
TRIMET Aluminium	Germany
TU Bergakademie Freiberg	Germany

Company	Country
TU Darmstadt	Germany
Vulcan Energy Resources	Germany
WirtschaftsVereinigung Metalle	Germany
BGV Group Management	Ukraine
Institute of Geology, Taras Shevchenko National University of Kyiv	Ukraine
Mine Extraction LLC	Ukraine
National Extractive Industry Association of Ukraine (NEIAU)	Ukraine
Nonferrous Metals of Ukraine LLC	Ukraine
RM Minings LLC	Ukraine
State Service for Geology and Subsoil of Ukraine	Ukraine
Ukrainian Association of Geologists	Ukraine
UkrLithiumMining LLC	Ukraine

Company	Country
Albemarle Corporation	US
Amerocap Mining Ventures	US
Asbury Carbons	US
Controlled Thermal Resources	US
Emerson Electric	US
Piedmont Lithium Limited	US
US Rare Earth, LLC	US
Prospect Resources Ltd.	Zimbabwe
3GSM GmbH	Austria
euroMinerals	Austria
Montanuniversität Leoben	Austria
Austrian Mining and Steel Association	Austria
Austrian Non-Ferrous Metals Federation	Austria

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