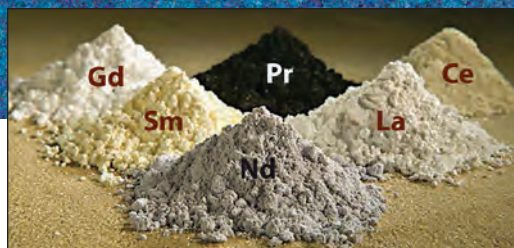


The Rare-Earth Elements— Vital to Modern Technologies and Lifestyles



As part of a broad mission to conduct research and provide information on nonfuel mineral resources, the U.S. Geological Survey (USGS) supports science to understand the following:

- Where and how concentrations of rare-earth elements form in the Earth's crust;
- Where undiscovered/undeveloped resources of rare-earth elements may occur;
- Trends in the supply and demand of rare-earth elements domestically and internationally;
- How undisturbed and mined rare-earth deposits interact with the environment.

List of the rare-earth elements found in natural deposits—the “lanthanides” plus yttrium.

[Average abundance (concentration) in the earth's crust (in parts per million) from Lide (2004, CRC handbook of physics and chemistry, 85th edition). For comparison, average crustal abundances for gold, silver, lead, and copper are 0.004, 0.075, 14, and 60 parts per million, respectively]

Element	Symbol	Atomic number	Crustal abundance
Light REEs			
Lanthanum	La	57	39
Cerium	Ce	58	66.5
Praseodymium	Pr	59	9.2
Neodymium	Nd	60	41.5
Samarium	Sm	62	7.05
Europium	Eu	63	2.0
Gadolinium	Gd	64	6.2
Heavy REEs			
Terbium	Tb	65	1.2
Dysprosium	Dy	66	5.2
Holmium	Ho	67	1.3
Erbium	Er	68	3.5
Thulium	Tm	69	0.52
Ytterbium	Yb	70	3.2
Lutetium	Lu	71	0.8
Yttrium	Y	39	33

Until recently, the rare-earth elements (REEs) were familiar to a relatively small number of people, such as chemists, geologists, specialized materials scientists, and engineers. In the 21st century, the REEs have gained visibility through many media outlets because (1) the public has recognized the critical, specialized properties that REEs contribute to modern technology, as well as (2) China's dominance in production and supply of the REEs and (3) international dependence on China for the majority of the world's REE supply.

Since the late 1990s, China has provided 85–95 percent of the world's REEs. In 2010, China announced their intention to reduce REE exports. During this timeframe, REE use increased substantially. REEs are used as components in high technology devices, including smart phones, digital cameras, computer hard disks, fluorescent and light-emitting-diode (LED) lights, flat screen televisions, computer monitors, and electronic displays. Large quantities of some REEs are used in clean energy and defense technologies. Because of the many important uses of REEs, nations dependent on new technologies, such as Japan, the United States, and members of the European Union, reacted with great concern to China's intent to reduce its REE exports. Consequently, exploration activities intent on discovering economic deposits of REEs and bringing them into production have increased.

What are the Rare-Earth Elements?

The REE group is composed of 15 elements that range in atomic number from 57 (lanthanum) to 71 (lutetium) on the periodic table of elements, and are officially referred to as the “lanthanoids,” although they are commonly referred to as the “lanthanides.” The rare-earth element promethium (atomic number 61) is not included in discussions of REE deposits because the element is rare and unstable in nature. Yttrium (atomic number 39) is commonly regarded as an REE because of its chemical and physical similarities and affinities with the lanthanoids, and yttrium typically occurs in the same deposits as REEs. Scandium (atomic number 21) is chemically similar to, and thus sometimes included with, the REEs, but it does not occur in economic concentrations in the same geological settings as the lanthanoids and yttrium and will not be discussed further.

Traditionally, the REEs are divided into two groups on the basis of atomic weight: (1) the light REEs are lanthanum through gadolinium (atomic numbers 57 through 64); and (2) the heavy REEs comprise terbium through lutetium (atomic numbers 65 through 71). [Note: Some authorities include europium and gadolinium within the group of heavy REEs.] Yttrium, although light (atomic number 39), is included with the heavy REE group because of its similar chemical and physical properties.

Most REEs are not as rare as the group's name suggests. They were named “rare-earth elements” because most were identified during the 18th and 19th centuries as “earths” (originally defined as materials that could not be changed further by heat) and in comparison to other “earths,” such as lime or magnesia, they were relatively rare. Cerium is the most abundant REE, and is more common in the Earth's crust than copper or lead. All of the REEs, except promethium, are more abundant on average in the Earth's crust than silver, gold, or platinum. However, concentrated and economically minable deposits of REEs are unusual.

How Do We Use the Rare-Earth Elements?

Due to their unusual physical and chemical properties, such as unique magnetic and optical properties, REEs have diverse applications that touch many aspects of modern life and culture. Specific REEs are used individually or in combination to make phosphors—substances that emit luminescence—for many types of ray tubes and flat panel displays, in screens that range in size from smart phone displays to stadium scoreboards. Some REEs are used in fluorescent and LED lighting. Yttrium, europium, and terbium phosphors are the red-green-blue phosphors used in many light bulbs, panels, and televisions.

The glass industry is the largest consumer of REE raw materials, using them for glass polishing and as additives that provide color and special optical properties. Lanthanum makes up as much as 50 percent of digital camera lenses, including cell phone cameras.

Lanthanum-based catalysts are used to refine petroleum. Cerium-based catalysts are used in automotive catalytic converters.

Magnets that employ REEs are rapidly growing in application. Neodymium-iron-boron magnets are the strongest magnets known, useful when space and weight are limiting factors. Rare-earth magnets are used in computer hard disks and CD-ROM and DVD disk drives. The spindle of a disk drive attains high stability in its spinning motion when driven by a

Did you know....

Rare-earth magnets are stronger per unit weight and volume than any other magnet type. Clean energy technologies, such as large wind turbines and electric vehicles, use rare-earth permanent magnets (meaning permanently magnetized) that usually contain four REEs: praseodymium, neodymium, samarium, and dysprosium.

rare-earth magnet. These magnets are also used in a variety of conventional automotive subsystems, such as power steering, electric windows, power seats, and audio speakers.

Nickel-metal hydride batteries are built with lanthanum-based alloys as anodes. These battery types, when used in hybrid electric cars, contain significant amounts of lanthanum, requiring as much as 10 to 15 kilograms per electric vehicle.

Cerium, lanthanum, neodymium, and praseodymium, commonly in the form of a mixed oxide known as mischmetal, are used in steel making to remove impurities and in the production of special alloys.

The end use applications of REEs are detailed in USGS Scientific Investigations Report 2011–5094 (available at <http://pubs.usgs.gov/sir/2011/5094/>).



Rare-earth elements (REEs) are used in the components of many devices used daily in our modern society, such as: the screens of smart phones, computers, and flat panel televisions; the motors of computer drives; batteries of hybrid and electric cars; and new generation light bulbs. Lanthanum-based catalysts are employed in petroleum refining. Large wind turbines use generators that contain strong permanent magnets composed of neodymium-iron-boron. Photographs used with permission from PHOTOS.com.

Where Do Rare-Earth Elements Come From?

The REEs are commonly found together in the Earth's crust because they share a trivalent charge ($+3$) and similar ionic radii. In nature, REEs do not exist individually, like gold or copper often do, but instead occur in minerals as either minor or major constituents. In general, these minerals tend to be dominated by either light or heavy REEs, although each can be present. In igneous (magmatic) systems, the large sizes of the REE ions impede their ability to fit into the structure of common rock-forming minerals. As a result, when common silicate minerals crystallize—such as feldspars, pyroxenes, olivine, and amphiboles—most REEs tend to remain in the coexisting magma. Successive generations of this process increase REE concentrations in the residual magma until individual REE minerals crystallize. The REEs can substitute for one another in crystal structures, and multiple REEs typically occur within a single mineral.

REEs generally occur in uncommon geologic rock types and settings. As mentioned earlier, REEs are common in the Earth's crust but rarely in economic concentrations. Economic REE deposits occur primarily in four geologic environments: carbonatites, alkaline igneous systems, ion-adsorption clay deposits, and monazite-xenotime-bearing placer deposits. Even within these deposit types, minable (economic) concentrations of REEs are rare. For example, globally there are more than 500 known carbonatites but only 6 are currently mined for REEs.

Other deposit types can contain minor amounts of REEs but have not been important REE sources thus far. One example is the giant Olympic Dam iron oxide-copper-uranium-gold-silver deposit in Australia, the world's largest single uranium deposit, which also contains REE enrichments. So far it has not proven economical to recover REEs from this deposit.

Carbonatites host the world's largest REE deposits and are typically most enriched in the light REEs. Carbonatites are unusual igneous rocks derived from carbonate-rich magmas, in contrast to the more common silica-rich magmas. Carbonatites are igneous rocks with more than 50 percent carbonate minerals, usually calcite and dolomite. As a group, carbonatites have the highest REE concentrations of all igneous rocks. Carbonatites have been the world's main source for light REEs since the 1960s. Currently, REEs are mined from large carbonatite bodies in California (Mountain Pass) and in China (Bayan Obo, Maoniuping, Daluxiang, and Weishan). The Mount Weld mine in Western Australia, Australia, produces REEs from a weathered zone that overlies a carbonatite.

Alkaline igneous rocks comprise a group of uncommon igneous rock types generally deficient in silica, relative to

sodium, potassium, and calcium. Many current (2014) advanced exploration projects are focused on large bodies of alkaline igneous rocks, with some finding significant REE concentrations (0.3–2.6 percent total REE oxide). These deposit types are sought because they are often enriched in the important heavy REEs.

Ion-adsorption clay deposits in southern China are the world's primary source of heavy REEs. This deposit type is informally referred to as “south China clays.” Thick clay accumulations that host low concentrations of REEs (from about 0.04 to 0.25 percent total REE oxides) form in tropical regions with moderate to high rainfall through successive processes:

1. REEs are leached by groundwater from granite bedrock;
2. thick zones of clay-rich soils develop above the granites; and
3. mobilized REEs become weakly fixed (by ion-adsorption) onto clays in the soils.

Despite their low concentrations in REEs, the clay deposits of south China are economic because the REEs can be easily extracted from the clays with weak acids, the deposits are often enriched in high-value heavy REEs, and labor costs are low.

A pilot project in Jamaica is evaluating the recovery of REEs from tailings of red mud produced by bauxite (aluminum ore) mining, which could be considered a form of ion-adsorption clay deposit.

Monazite-xenotime-bearing placer deposits were important REE sources prior to the mid-1960s. From some modern and ancient beach deposits, the REE-thorium-phosphate mineral monazite $[(\text{REEs,Th})\text{PO}_4]$ can be recovered as a by-product during the extraction of the targeted heavy minerals, ilmenite (FeTiO_3), rutile (TiO_2), and zircon (ZrSiO_4). Ilmenite and rutile—the principal minerals of value as in these deposits—are mechanically separated from sand-silt deposits. Monazite can be recovered simultaneously if desired. The separated ilmenite and rutile are then chemically processed to remove titanium; ilmenite and rutile are the primary source of the titanium used in paint pigments. Monazite is recovered as a byproduct mineral from beach sands along the southern coasts of India, where it is sought as a source of light REEs and thorium. The recovered thorium is stockpiled for future use as fuel material in thorium-based nuclear power, which is under development. Xenotime (YPO_4), a less common mineral, has been recovered as a source of yttrium and other REEs as a byproduct of mining tin placers.



The mineral bastnäsite is an important source of the REEs. Bastnäsite, a REE-carbonate-fluorine mineral, is the primary ore mineral in the world's largest REE deposits. Photograph courtesy of Rob Lavinsky, www.iRocks.com.



The mineral monazite is an important source of the REEs. Monazite, a REE-thorium-phosphate mineral, has been separated from some ancient and modern beach sands as a coproduct to the recovery of economic titanium (Ti) minerals. Photograph courtesy of www.geology.com.

Worldwide Supply and Demand for Rare-Earth Elements

As noted earlier, in recent years Chinese production has accounted for about 95 percent of the REE global market. Citing a need to retain their limited REE resources for domestic requirements and concerns for environmental effects of mining, China has restricted the supply of REEs through quotas, licenses, and taxes. As a result, the REE industry outside of China increased REE stockpiling, explored for deposits in many locations, and promoted new efforts to conserve, recycle, and find substitutes for REEs. New mine production has begun in Australia (Mount Weld) and the United States (Mountain Pass, California).

In recent years, expert panels convened by research institutes and government agencies highlighted specific REEs as raw materials critical to evolving technologies, such as clean-energy applications, high-tech military components, and electronics (Long and others, 2010). These reports suggest that a high potential exists for disruptions in REE supplies. As a result, several expert panel analyses rank REEs high on the “criticality” factor of raw materials, meaning they are of high technological and economic importance and have high supply-side risk (National Research Council, 2008). Panels and agencies that assessed the criticality of REEs and other raw materials include the National Research Council, U.S. Department of Energy, European Commission, American Physical Society (APS) and Materials Research Society (MRS), and the Resnick Institute.

Worldwide explorations for economic deposits of REEs and efforts to bring them into production have increased substantially since 2000. More than 400 rare-earth projects were in progress during 2012, including many projects in advanced stages of exploration, meaning that the deposit sizes and REE concentrations were announced based on detailed drilling. One important aspect in the development of a property for REE mining is the cost and complexity of processing the REE ores. Recovery of REEs can be complex because they occur in minerals as a group of similar elements, and at many deposits the REEs are hosted within more than one mineral. Not only do REE-rich minerals need to be concentrated, but the actual elements must be separated from each other, usually as oxide compounds (for example, lanthanum oxide). The success and timeliness of rare-earth mining projects, and the rare-earth elements industry in general, is difficult to predict and will be continuously monitored and studied by the USGS.



The Mountain Pass mine of Molycorp, Inc., southeastern California, is the only active producer of REEs in the United States (2014). The ore body is a carbonatite intrusion, thought to be the largest REE resource in the United States.

Did you know....

In the 1940s, as part of the Manhattan Project that created the nuclear bomb, Frank Spedding and others in the United States developed chemical ion exchange procedures that could separate and purify individual REEs. This method was first used to separate plutonium-239 and neptunium from uranium, thorium, and actinium in materials generated by nuclear reactors.

How Do We Ensure Adequate Supplies of Rare-Earth Elements for the Future?

Global REE resources are estimated to be 110 million metric tons of rare-earth oxide, which primarily occur, in descending order, in China, Russia, the United States, India, and Australia. Exploration for additional REE deposits is ongoing; therefore, the world's known in-the-ground resources (endowment) of REEs are likely to increase. Despite many known REE deposits, the global supply of REEs is limited by the cost and complexity of exploring REE deposits and developing REE mines, including REE extraction and separation facilities. These factors are discussed in USGS Scientific Investigations Report 2010–5220 (available at <http://pubs.usgs.gov/sir/2010/5220/>).

In addition to bringing more REE deposits into production, other methods may help offset REE supply restrictions. Examples include new efforts to recycle REEs, research to find substitute materials for REEs, and efforts to recover REEs as coproducts of mineral deposits. These efforts may eventually offset some of the demand for REEs.

References

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- Long, K.R., Van Gosen, B.S., Foley, N.K., and Cordier, Daniel, 2010, The principal rare earth elements deposits of the United States—A summary of domestic deposits and a global perspective: U.S. Geological Survey Scientific Investigations Report 2010–5220, 96 p. [Also available at <http://pubs.usgs.gov/sir/2010/5220/>.]
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For More Information

On production and consumption of rare-earth elements:
http://minerals.usgs.gov/minerals/pubs/commodity/rare_earths/

On historical statistics of rare-earth elements:
<http://minerals.usgs.gov/ds/2005/140/>

On end use and recycling of rare-earth elements:
<http://pubs.usgs.gov/sir/2011/5094/>

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