Energy and Minerals Science at the U.S. Geological Survey

The economy, national security, and standard of living of the United States depend on adequate and reliable supplies of energy and mineral resources. Based on population and consumption trends, the Nation's and World's use of energy and minerals is expected to grow, driving the demand for scientific understanding of resource formation, location, and availability. The importance of environmental stewardship and human health in sustainable growth emphasizes the need for a broader understanding of energy and mineral resources. The U.S. Geological Survey (USGS) is a world leader in conducting research needed to address these challenges and to provide a scientific foundation for policy and decisionmaking with respect to resource use, sustainability, environmental protection, and an adaptive resource management approach.

Introduction

The United States produces and uses substantial amounts of energy and mineral resources each year, and faces critical decisions regarding growing challenges in meeting current (2013) and future needs (fig.1). Decisions at every scale will affect the availability of energy and minerals and have far-reaching economic, environmental, geopolitical, and social consequences.

The need for energy and mineral resources is driving exploration and production into geological settings with limited or no data, such as in the Arctic, deeper in the Earth's crust, and beneath deeper regions of the oceans. Interest in alternative energy and mineral resources may involve producing unconventional resources, mining lower concentration deposits, recovering resources from waste and recycling streams, and sourcing from countries with different political systems or environmental stewardship philosophies. These demands are met with the need to consider energy and mineral development amidst the effects of climate change, the comparative value of ecosystem services, and the risks associated with natural hazards to prevent or mitigate environmental degradation. The USGS serves the national interest by providing impartial scientific studies (fig. 2) and information that enable decisionmakers and society to make informed decisions and to understand potential outcomes.

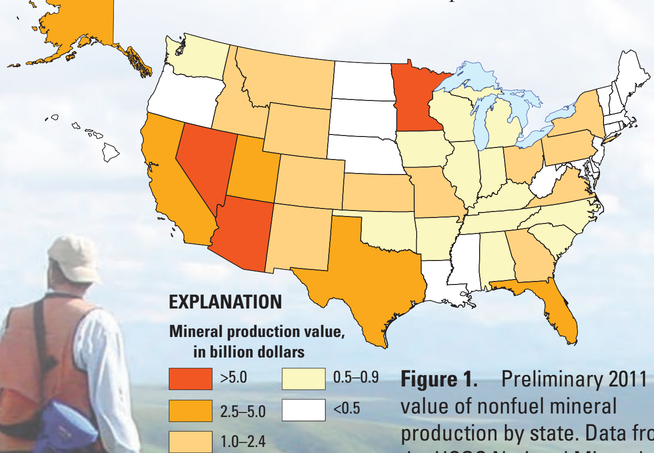

Figure 1. Preliminary 2011 value of nonfuel mineral production by state. Data from the USGS National Minerals Information Center.

Figure 2. USGS scientist collecting rock samples as part of a regional-scale, geologic framework study of the western Alaska Range.

The USGS Energy and Minerals Science Strategy

In the USGS Energy and Minerals Science Strategy (*http://pubs.usgs.gov/circ/1383d/*), we identified a set of overarching questions that drive the science needed to provide information on existing and emerging energy and minerals issues during the coming decade:

- How or where might energy and mineral commodities be obtained to meet present and future needs?
- What economic, environmental, geopolitical, and health consequences must also be considered in both the short term and the long term?
- How can decisions more effectively incorporate scientific complexity and uncertainty?
- What science is needed to anticipate and respond to future events?

Using these questions as a guide, five interdependent goals were identified that recommend actions to provide the needed scientific research, information, and analysis:

- *Goal 1.*—Understand fundamental Earth processes that form energy and mineral resources.
- *Goal 2.*—Understand the environmental behavior of energy and mineral resources and their waste products.
- *Goal 3.*—Provide inventories and assessments of energy and mineral resources.
- *Goal 4.*—Understand the effects of energy and mineral development on natural resources and society.
- *Goal 5.*—Understand the reliability and availability of energy and mineral supplies.

The unifying concept for these goals is a resource lifecycle for energy and minerals (fig. 3). The science actions developed in this strategy represent key components of integrated studies at multiple scales. When leveraged with expertise across the USGS and with partners, the actions in this strategy can provide a more comprehensive and integrated understanding of natural resources and facilitate the dissemination of science, information, and tools to a range of audiences, including policymakers, regulators, resource managers, scientists, and the public.

Providing a Scientific Foundation for Decisionmaking

The USGS, with its long history of important contributions to energy and mineral resources science, has a solid foundation of core capabilities. USGS scientists have broad expertise relevant to understanding energy and mineral formation and occurrence, resource assessment, environmental characterization, data collection, and analysis. Many congressional mandates and Executive orders recognize, support, and encourage USGS science. With this foundation and recognized expertise, the USGS is well positioned to continue providing cutting-edge science on current (2013) and future energy and mineral resources issues.

Mission and Vision.—The USGS energy and mineral resources mission is to provide impartial science and information for understanding the occurrence and distribution of national and global energy and mineral resources that may contribute to supplies; the potential environmental and socioeconomic effects associated with resource occurrence, extraction, and use; and the global supply and flow of nonfuel mineral commodities.

Over the coming decade, science leading to a broader understanding of the resource lifecycle will be a cornerstone for decisions supporting our Nation's economic vitality, protection of natural resources, security of resource supplies, and quality of life.

Science Linkages

Coordination within USGS and with partners is important to understand fully the breadth and magnitude of interactions among energy and mineral lifecycles and air, land, soil, water, ecosystem services (or natural capital), and human health from local, regional, national, and global perspectives. The USGS Energy and Minerals Science Strategy mirrors the reality that complex societal issues demand diverse capabilities from every corner of the USGS and its partner communities. Many science actions reflect the need for enlisting expertise across the USGS. Likewise, efforts precipitated by this strategy will contribute to other USGS science goals. An even broader range of linkages that includes partners, such as other DOI bureaus, Federal agencies, state geological surveys, and international organizations, is acknowledged and anticipated.

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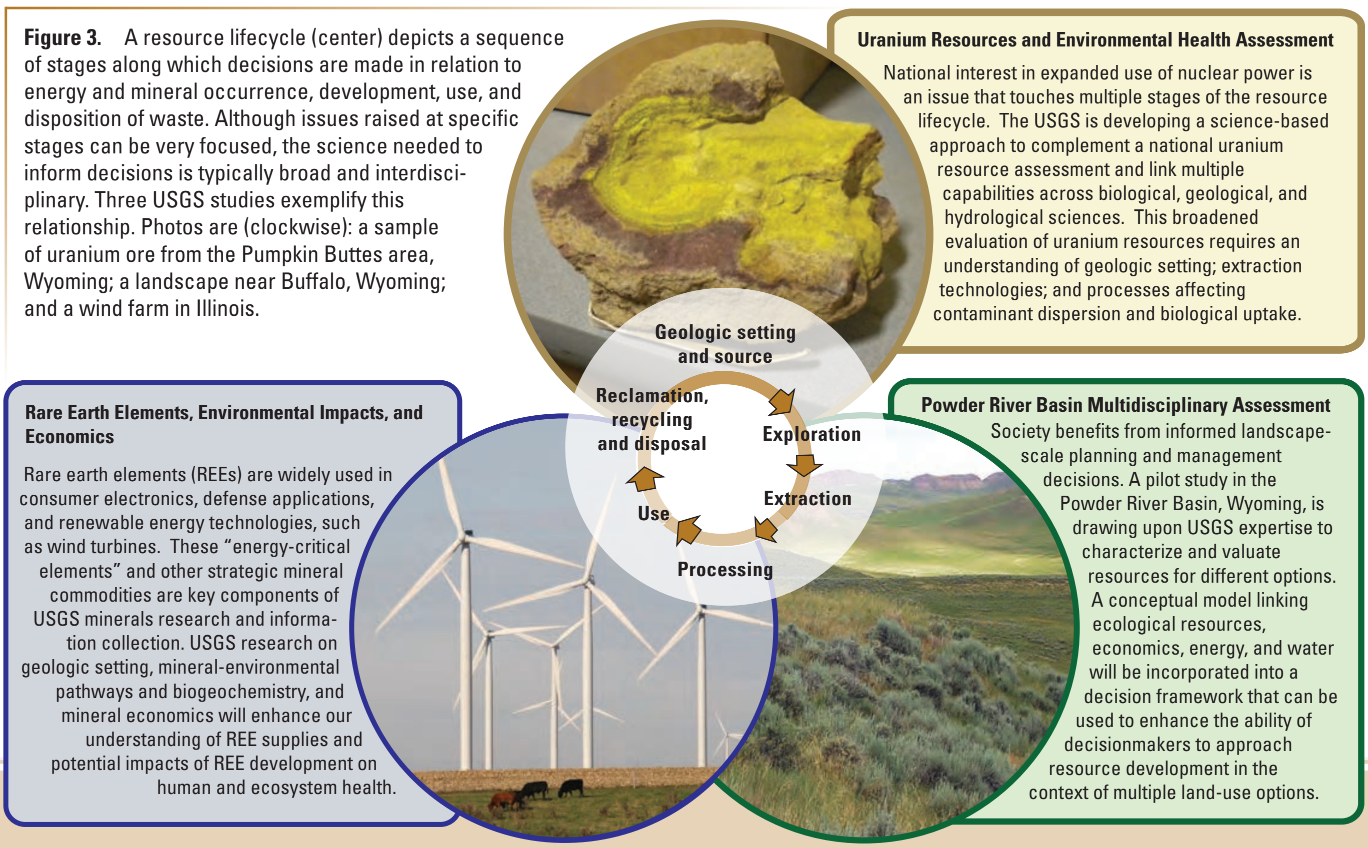

Figure 3. A resource lifecycle (center) depicts a sequence of stages along which decisions are made in relation to energy and mineral occurrence, development, use, and disposition of waste. Although issues raised at specific stages can be very focused, the science needed to inform decisions is typically broad and interdisciplinary. Three USGS studies exemplify this relationship. Photos are (clockwise): a sample of uranium ore from the Pumpkin Buttes area, Wyoming; a landscape near Buffalo, Wyoming; and a wind farm in Illinois.

For additional information:

- USGS Energy and Mineral Resources Mission Area web site—*http://www.usgs.gov/energy_minerals/*
- USGS Energy and Mineral Resources Science Strategy—*http://pubs.usgs.gov/circ/1383d/*

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USGS
science for a changing world

Do We Take Minerals for Granted?

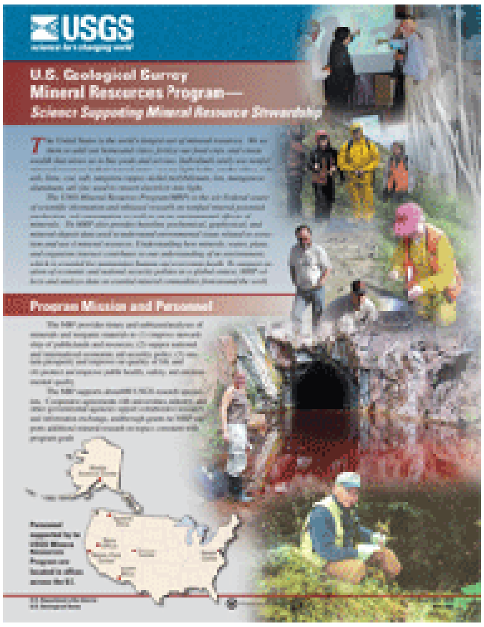
Did you know that the average automobile contains more than a ton of iron and steel, 240 lbs of aluminum, 50 lbs of carbon, 42 lbs of copper, 41 lbs of silicon, 22 lbs of zinc, and more than thirty other mineral commodities, including titanium, platinum, and gold? Do you know the cost of a pound of copper or an ounce of platinum? Though you are constantly reminded of the importance of gasoline, and its cost, to keep the car running, do you ever think about the importance and cost of the mineral materials that make up the car? Do we take minerals for granted?

When the power goes out, few of us give a second thought about the copper and aluminum needed to carry electricity from the power plant to our homes or offices. When the battery dies, you do not automatically think about the lead, nickel, cadmium, or lithium used to make the batteries that store power for our cell phones, MP3 players, or hybrid cars, because you do not buy minerals, you buy products that have been manufactured using mineral materials. But without these nonfuel mineral commodities, many things that we take for granted would not work.

Minerals in the environment and products manufactured from mineral materials are all around us and we use and encounter them every day. They impact our way of life and the health of all that lives. Minerals are critical to the Nation's economy and knowing where future mineral resources will come from is important for sustaining the Nation's economy and national security.

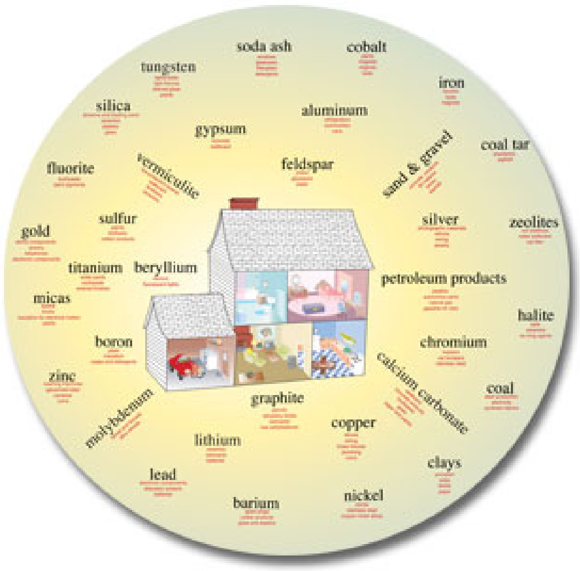
The USGS Mineral Resources Program (MRP) supports science used to understand:

- How and where nonfuel mineral resources form and are concentrated in the Earth's crust,
- Where mineral resources might be found in the future,
- How mineral materials interact with the environment to affect human and ecosystem health, and
- The usage and production of about 100 different mineral commodities in the U.S. and nearly 180 countries throughout the world.



Why is it important to understand the science of mineral resources and materials? Because we are increasingly dependent on mineral materials to create products that support our way of life, our health, and the global economy.

Minerals Everywhere and Everyday



Our homes and office buildings contain many mineral materials:

- Drywall is made from gypsum,
- Concrete in the foundation is made with limestone and aggregate reinforced with steel rebar,
- Bricks are made from clay,
- Titanium oxide is used to make paint,
- Silica is used to make windows,
- Electrical wiring is made from copper,
- Iron and copper are used to make pipes for plumbing, and
- Faucets contain various combinations of iron, chromium, nickel, and molybdenum combined to make stainless steel.

Some things we use for our favorite hobbies and recreation also rely on mineral materials to make them stronger, lighter, and more flexible. Advances in materials science have allowed bicycles, once largely made of steel, to incorporate parts made of aluminum, carbon fiber, magnesium, and titanium that make them lighter and more durable. Aluminum, fiberglass, graphite, titanium, zirconium, beryllium, copper, tungsten, and steel have replaced wood in baseball bats, tennis racquets, and golf clubs to make them lighter and stronger. Race tracks, as well as playing surfaces for baseball and tennis, are a prescribed mixture of clay, sand, and silt. Calcined clay (a clay that has been heated) readily absorbs water to dry wet spots on fields and it is used to reduce soil compaction. It is also used on infield areas of baseball diamonds and on fields and tracks because it does not stick to cleats or hooves.

The USGS MRP studies these and many more commodities to provide the critical mineral resource information required by policy makers, industry and the public to make informed decisions regarding minerals issues important to the Nation. The range of MRP research is described in USGS Circular 1289. The MRP also compiles information on known mineral resources and makes these data and information available to the public. To find out where various mineral materials occur in the U.S. and around the world, visit the MRP Spatial Data site.

We use minerals every day to grow, prepare, and eat our food. Much of our food is grown using fertilizers made from phosphate and potash. Meat and poultry come from animals that eat fodder grown with mineral-based fertilizers that may be supplemented with selenium, phosphorus, or zinc. Modern tools for safe food storage and preparation (such as, refrigerators and stoves) are made from many mineral commodities and rely on copper wires for electric power or copper pipe for natural gas. At the table, salt is used for seasoning, cutlery is made from stainless steel or may be silver plated, plates are made from clays, and glassware is made from silica (or perhaps on special occasions it is lead crystal).

1. RADIO: Includes aluminum, copper, gold, iron, and petroleum products.
2. TOASTER: Includes copper, iron, nickel, mica, chromium, and petroleum products.
3. ELECTRICAL WIRING: Includes copper, aluminum, and petroleum products.
4. MICROWAVE: Includes copper, gold, iron, nickel, and silica.
5. STOVE: Includes aluminum, copper, iron, nickel, and silica.
6. REFRIGERATOR: Includes aluminum, copper, iron, nickel, petroleum products, and zinc.
7. TABLE SALT: Includes halite; light salt can be made from sylvite. Most salt has added iodine.
8. PLATES: Includes clays, silica, and feldspar.
9. CUTLERY: Includes iron, nickel, silver, and chromium.
10. CLOCK: Includes iron, nickel, petroleum products, and silica.
11. STAINLESS STEEL SINK: Includes iron and nickel.
12. BLACKBOARD: Includes clays. Chalk includes limestone or petroleum products.
13. MAGNET: Includes cobalt.
14. DISH RACK: Made of petroleum products.

Minerals and the Environment

Many of the minerals that our bodies require for good health, such as calcium, magnesium, iron, potassium, and zinc, we get from food. And while we need an adequate supply of many different minerals, there are negative health consequences resulting from exposure to some mineral materials or elevated levels of otherwise good minerals. Some of these minerals come from our everyday contact with the air, water, and ground in our surroundings. Some of them we are exposed to by man-made disturbances to the natural environment or as a result of a wide range of natural disasters.

Whether it is research on

- Asbestos in California soils,
- Dust from black shale landscapes in Colorado and Utah,
- Mercury from abandoned mines in Big Bend National Park, Texas,
- Mud deposited during flooding in New Orleans after Hurricanes Katrina and Rita,
- Dust from the collapse of the World Trade Center in New York, or
- Effects of recent wild fires on soils and runoff waters in southern California.

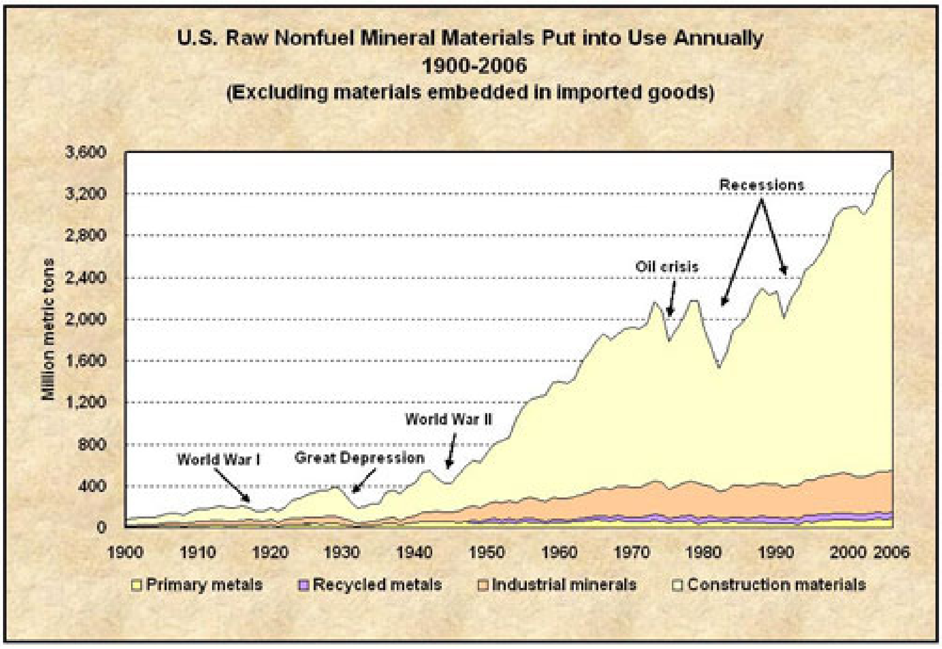
MRP science helps local, State, and Federal agencies develop land management plans to minimize effects of mineral-borne contaminants on human and ecosystem health.

The MRP supports research to better understand the environmental impact of abandoned mines, which reduces the cost of cleanup. For example, studies of old mining areas in the Animas River watershed in southwestern Colorado helped other agencies plan and carry out effective reclamation activities. The USGS MRP is a leader in the investigation and analysis of:

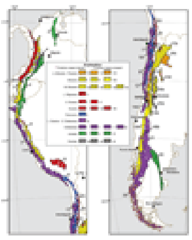
- Natural background levels of minerals in the environment,
- Mechanisms of mineral breakdown, and
- Transport of mineral components that may be sources of contaminants.

Future Mineral Supplies

As standards of living rise around the world, there is greater demand for durable goods and products manufactured from mineral materials. As large emerging economies, such as China and India, increase their participation in the global economy, demand for critical mineral resources is increasing at a rapid rate. That means that we are depleting our known mineral deposits at an increasing rate, requiring that new deposits be found and put into production.



Every year, each person in the U.S requires more than 25,000 pounds of new nonfuel minerals to make the items we use every day. Where are the world's future supplies of important mineral resources located? The USGS MRP assessment of Global Mineral Resources and a new assessment of U.S. mineral resources will help answer this question. Recently MRP completed an assessment of copper resources in the Andes of South America. The study found that there likely is more copper (approx. 690 million tons) remaining in undiscovered deposits than has been produced and currently exists in known deposits in the Andes (590 million tons).

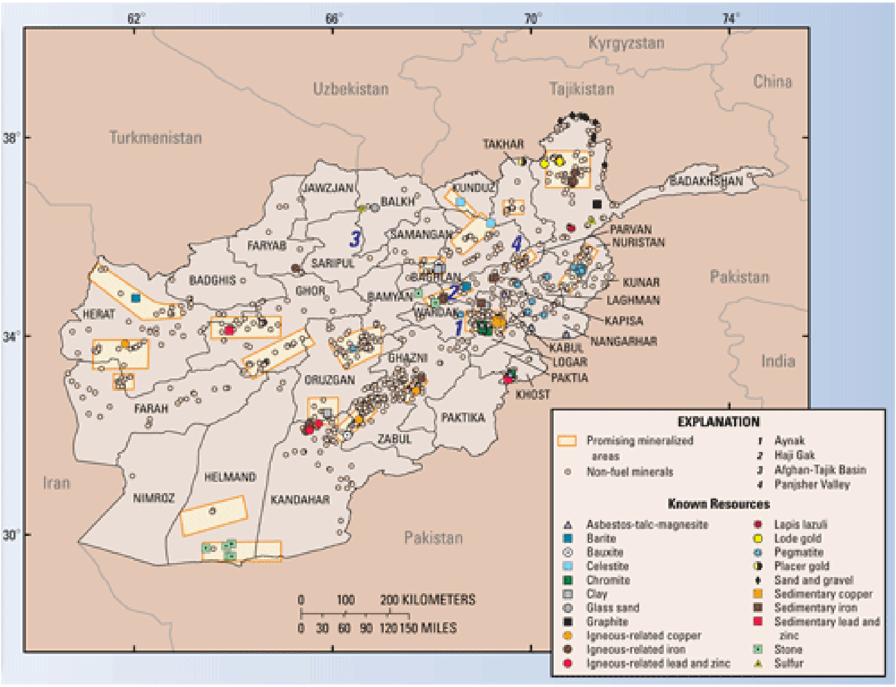


Every American born in 2008 is estimated to use the following amounts of nonfuel mineral commodities in their lifetime for their necessities, lifestyles, and health.	
Mineral commodity	Amount required over a lifetime
Aluminum (bauxite)	5,677 pounds
Cement	65,480 pounds
Clays	19,245 pounds
Copper	1,309 pounds
Gold	1,576 ounces
Iron ore	29,608 pounds
Lead	928 pounds
Phosphate rock	19,815 pounds
Stone, sand, and gravel	1.61 million pounds
Zinc	671 pounds
Data from U.S. Geological Survey and U.S. Energy Information Administration; statistical analysis by National Mining Association. Source of information: http://www.mii.org/pdfs/CalculationofmiiBaby.pdf.	

MRP is currently preparing for a new national assessment of mineral resources of the United States. Assessments of undiscovered resources require state-of-the-art methodologies and up-to-date background information. In preparation for the new assessment MRP is currently:

- Identifying mineral materials that will be important for emerging technologies and the future U.S. and global economy,
- Refine techniques to decrease uncertainty of new estimates of the location, quantity, and quality of undiscovered mineral resources,
- Refine ways to identify resources not directly exposed at the Earth's surface, and
- Enhancing our ability to identify potential environmental consequences of developing mineral resources.

MRP expertise in mineral resource and mineral environmental assessments is recognized by the international community and by U.S. governmental agencies that provide assistance to developing countries. Mineral resource assessments of Afghanistan and Madagascar are examples of USGS mineral resource science aiding economic development of countries around the world. The MRP has also provided expertise to assist with the identification of possible mine-related environmental issues in the Philippines.



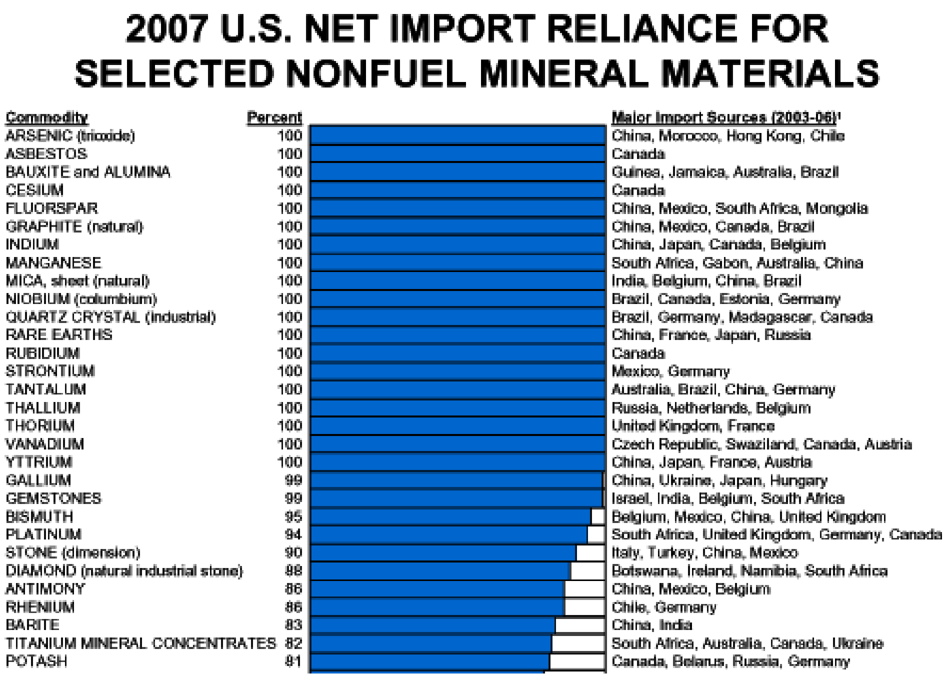
Minerals and the Economy

A recent study by the National Research Council (NRC) of the National Academies highlights the importance of minerals to the U.S. economy and provides a means to characterize how critical a mineral commodity might be by asking:

- How important is a particular commodity to our economy?
- What is the risk that the supply of an important commodity might be interrupted?

Commodities identified as being among the most critical included platinum-group metals and rare-earths. Platinum-group metals are essential components of pollution control systems (catalytic converters) in both gasoline- and diesel-powered vehicles, where they facilitate reduction in carbon monoxide, hydrocarbon, and nitrogen oxide emissions. Rare-earths are used in the manufacture of high-strength magnets, lasers, high-temperature metal alloys, and refractory ceramics which are strategic to the defense industry. The USGS MRP conducts research on these commodities to better understand how they occur and to decrease uncertainty in estimates of future resources both in the U.S. and around the globe.

As with petroleum resources, the U.S. increasingly relies on foreign sources for many mineral commodities that are important to the economy. The NRC report concludes that “decision makers in both the public and private sectors need continuous, unbiased, and thorough mineral information provided through a federally funded system of information collection and dissemination” and recommends that “Federal agencies, …including the USGS…should develop and fund activities, including basic science,… to encourage U.S innovation in the areas of critical minerals and materials and to enhance understanding of global mineral availability.”



The Mineral Commodity Summaries report, published annually, is the earliest Government publication to furnish estimates covering nonfuel mineral industry data.

The USGS MRP is the sole Federal provider of objective mineral resource science and information. The MRP's unbiased research on mineral resource potential and mineral environmental issues and the collection, analysis, and dissemination of domestic and international mineral commodity information on production and consumption represent one-stop access for public and private users of mineral resource science and information.

As the global economy grows and evolves in the 21st century, emerging technologies will require mineral commodities on a greater scale and in a larger number of applications than ever before. Advances in alternative energy technologies, nanotechnology, telecommunications, and in the aerospace and defense industries have all been made possible by incorporating new applications of mineral materials. Some mineral commodities used in emerging technologies are rare and their known resources limited. The USGS MRP is conducting research to better understand the character of known resources for these rare and scarce commodities and is developing criteria to assess the possibility of undiscovered resources required to sustain emerging technology industries.

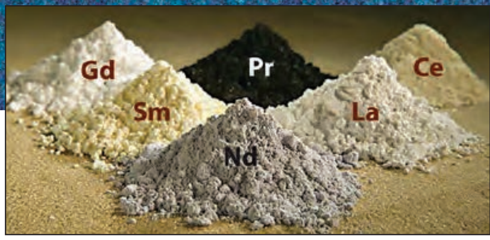
Minerals—Want to Learn More?

The next time you pick up that stainless steel fork, use your cell phone, replace the batteries in your remote control, or use your keys to start the car or open a locked door, take a moment to think about how important minerals are to your way of life. Then visit the USGS MRP Web site to learn more about what our Federal government is doing to ensure we have the mineral resources we need. The USGS Mineral Resources Program provides objective science and unbiased information at local to global scales so that the general public, government agencies, and industry can make informed decisions on minerals issues in land-use planning, national security, and economic policy, because mineral resources are vital to our nation.

http://minerals.usgs.gov/granted.html

USGS
science for a changing world

USGS Mineral Resources Program



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.

U.S. Department of the Interior
U.S. Geological Survey

Fact Sheet 2014–3078
November 2014

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 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/*).

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 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 crystalize. 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-absorption 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 [$(REEs,Th)PO_4$)] 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

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.

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.

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.

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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/

The USGS Mineral Resources Program is the sole Federal provider of research and information on rare-earth elements and other nonfuel mineral resources. For more information, please contact:

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